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Analysis of Vegetation Diversity and Emission Absorption Sufficiency on the Pandaan-Malang Green Toll Road

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Abstract. Green corridors on toll roads are a natural strategy designed to reduce transportation emissions while maintaining the ecological function of the area. This study aims to assess the ability of vegetation to absorb carbon along the Pandaan–Malang Green Toll Road by comparing the total emissions produced by passing vehicles. The method employed is a quantitative descriptive approach with a bottom-up methodology to calculate carbon emissions and estimate CO_2 absorption, utilizing existing vegetation data. The research data revealed that the total annual emissions reached 63.32 million kg, while the total vegetation absorption was only 51.08 million kg or 19.33%, resulting in a deficit of 12.24 million kg (80.67%). Trembesi trees dominate, contributing around 90% of the total absorption, but dependence on this monoculture poses ecological risks due to pest attacks and climate pressure. Therefore, a species diversification strategy that focuses on zoning and strengthening technical regulations on green belts is needed. The policy implications aim to transform green highways from aesthetic elements into sustainable ecological infrastructure that actively functions in climate change mitigation and improves ecosystem service quality.

Keywords: Vegetation; Green Toll Road; Emissions; Pandaan-Malang Toll Road; Transportation

INTRODUCTION

The toll road is a highway designed to facilitate the mobility of motor vehicles between cities or regions, with a specific payment system in place. [1]. Motor vehicles on toll roads, which run on fossil fuels (gasoline and diesel), produce exhaust emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides (NO_x) [2]. The interconnection between toll roads, motor vehicles, and carbon emissions is strong, as the high number of vehicles on toll roads can lead to higher fuel consumption, thereby increasing the amount of carbon emissions released into the atmosphere. Some studies indicate that around 23% of total CO_2 emissions and 28% of total greenhouse gas emissions come from the transportation sector. [3], [4]. In Indonesia, this issue is exacerbated by the annual increase in the number of vehicles on toll roads, which reaches 9.2% [5]. In this context, a specific study on toll road infrastructure in Indonesia becomes crucial for understanding the local dynamics of carbon emissions and mitigation efforts.

The Green Toll Road (GTR) concept, which utilizes green corridors as nature-based solutions, is being implemented as an ecosystem-based mitigation strategy that not only enhances biodiversity but also aims to reduce carbon emissions from motor vehicle activities [6], [7]. However, the effectiveness of green corridors in absorbing carbon varies, with absorption capabilities ranging from 5% to 40% of total carbon emissions produced by vehicles along the road [8]. This indicates that the management and design of green corridors play a crucial role in the effectiveness of emission reduction. With an average daily vehicle volume of 42,150 units [9], the Pandaan-Malang Toll Road becomes one of the sections with high carbon emission potential. To meet the needs of environmentally friendly infrastructure, this toll road is designed as a Green Toll, equipped with a green area of 83 hectares and a vegetation density of approximately 450 plants per kilometer [10].

However, several previous studies have identified weaknesses that hinder the optimization of green corridors as carbon absorbers in toll road areas. [11], [12]. There is a lack of research employing approaches that consider carbon absorption data from urban green open spaces along main roads, which have different environmental characteristics than toll roads. [11]. The unique conditions along or near toll roads, such as higher levels of air pollution, noise, constant traffic disturbances, and variations in soil fertility, require tailored and more appropriate measurement and modeling methods for toll roads. [12]. This shortcoming can lead to carbon absorption estimates that do not accurately reflect reality and cannot serve as a basis for the best decision-making. In addition to identifying structural and methodological weaknesses, research remains lacking on analyzing vegetation composition and its relationship with carbon absorption effectiveness, specifically in toll road areas. Previous research has generally focused more on physical characteristics (such as lane width) or used general data regarding carbon absorption from other types of green spaces that do not face as high environmental pressures as toll road areas [11], [12].This highlights a lack of in-depth studies on the variation (type and arrangement) of adaptive vegetation in green spaces along toll roads and its quantitative relationship with the capacity to absorb carbon emissions from vehicles in those locations. Research on plants under stress near toll roads, such as sustained exposure to air pollutants (NO_x, PM, O_3), is still minimal [13]. Additionally, comprehensive field information regarding the actual performance of various types of vegetation and shrubs in carbon absorption at specific locations, especially on the Pandaan-Malang Toll Road, has not been extensively studied [14].

Based on this identification, this study addresses explicitly the gaps through a direct approach at the Pandaan-Malang Toll Road. The main objective of this research is to identify and comprehensively analyze the various types of vegetation found along the Pandaan-Malang Toll Road, including inventorying species, vegetation structure (height, trunk diameter, leaf area index), and the physiological conditions of plants in response to environmental stress along the toll road. This study is designed to measure the actual effectiveness of each identified type of vegetation in absorbing carbon emissions from motor vehicles by using an integrative approach that combines biomass estimation (stored carbon) with CO_2 measurements [15], [16]. Thus, this research is expected to provide a scientific foundation for toll managers and policymakers to transform green corridors along toll roads into practical and sustainable carbon-absorbing infrastructure, thereby contributing directly to climate change mitigation in the transportation sector.

METHODOLOGY

Research Design

This study applies a descriptive quantitative method to evaluate vehicle emissions and carbon sequestration by vegetation on the Pandaan-Malang Toll Road. The calculation framework employs a bottom-up process that accumulates emissions from individual vehicle activities, using the Vehicle Kilometers Travelled (VKT) formula multiplied by specific emission factors, as outlined in the EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023 [17]. A spatiotemporal design was employed by dividing the toll road into five segments based on road geometric characteristics and vegetation distribution, and analyzing monthly dynamics from January to December 2024 to identify seasonal variations and traffic patterns [18]. Vegetation data were calculated using allometric formulas with biophysical parameters such as Leaf Area Index (LAI) and biomass, referring to the Global Forest Resources Assessment guidelines [19], [20].

Research Location and Time

This study was conducted on the 38.49 km Pandaan–Malang Toll Road, which spans the districts of Pasuruan and Malang, as well as the city of Malang, in East Java Province. Based on the geometric characteristics of the road, topography, and vegetation cover patterns as stated in the 2023 maintenance document of PT Jasamarga Pandaan Malang, the toll road is divided into five operational segments. Segment I (Pandaan–Purwodadi, 15.475 km) is dominated by low-lying agricultural areas, Segment II (Purwodadi–Lawang, 8.05 km) has moderate slopes and diverse vegetation, Segment III (Lawang–Singosari, 7.1 km) which crosses a densely populated residential area, Segment IV (Singosari–Pakis, 4.75 km) as a suburban transition area, and Segment V (Pakis–Malang, 3.113 km) which enters the city center with high traffic levels [21]. The research was conducted over 12 months, from January to December, using research data collected from secondary sources, PT Jasa Marga Tbk., and literature studies related to vegetation [22]. The selection of location and time considered the availability of historical traffic flow data, plant phenology variations, and compatibility with the plant growth cycle along the toll road, as per the Ministry's technical guidelines [23]. The entire research duration was integrated and organized into a single method, as shown in Figure 1.

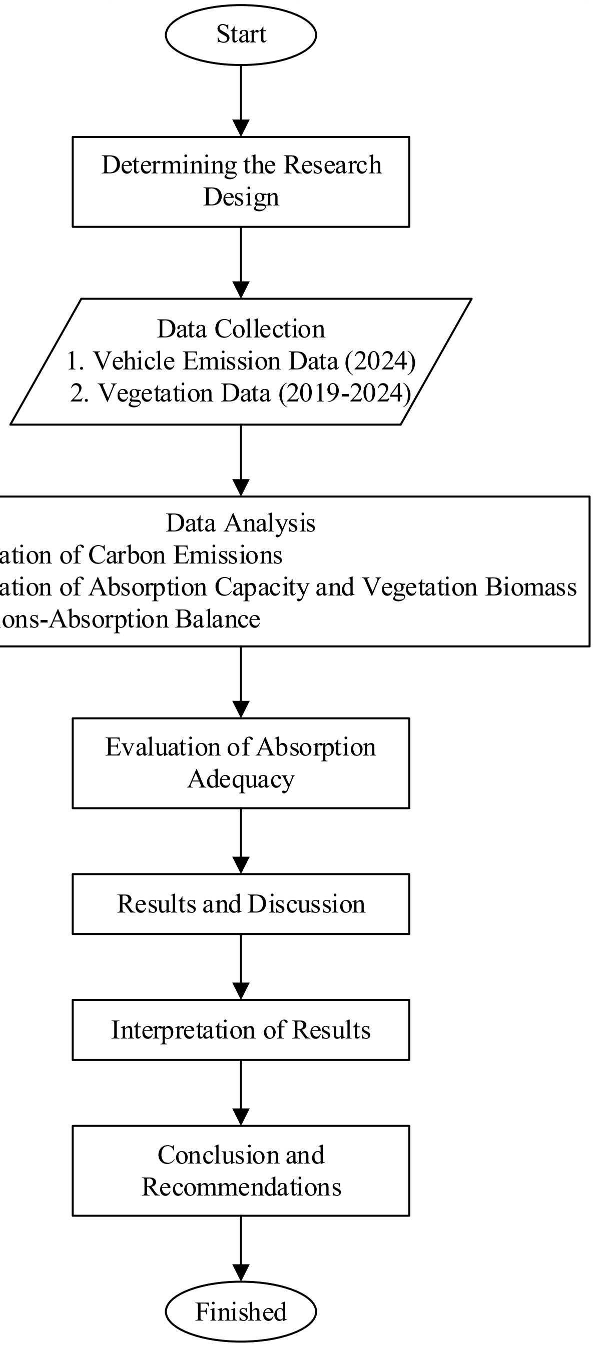

FIGURE 1. Flowchart Metodologi Penelitian

Data Collection

1. Vehicle Emission Data

Vehicle emission data collection begins with determining the transportation sector's contribution to air pollution, where exhaust emission estimates require verified activity data and technical parameters. Key activity information is obtained from PT. Jasa Marga Tbk.'s Average Daily Traffic (ADT) statistics classify vehicles into five categories: Category I (light vehicles such as sedans and jeeps), Category II (two-axle trucks), Category III (three-axle heavy vehicles), Category IV (four-axle trucks), and Category V (five-axle trucks). The technical parameters applied in the emission calculations include the Emission Factor (EF) referring to the IPCC 2006 methodology guidelines, along with energy consumption data (Ki) per vehicle category, based on the results of a study by the Agency for the Assessment and Application of Technology (BPPT) in 2019 [17].

2. Vegetation Data

Vegetation data was taken from PT. Jasa Marga's existing vegetation inventory for the period 2022–2024. This data includes various plant types, such as trees, flowers, and fruit plants. Some of the vegetation types listed include Trembesi (Samanea saman), Tabebuya (Tabebuia rosea/alba/aurea), Cemara Angin (Casuarina equisetifolia), Flamboyan (Delonix regia), Ketapang Kencana (Terminalia catappa), Pule (Trema orientalis), and fruit plants such as Mango (Mangifera indica) and Water Apple (Syzygium samarangense). The carbon dioxide (CO_2) absorption capacity of various vegetation types was determined through a literature study examining natural solutions for urban sustainability. [24]. PT Jasa Marga's vegetation inventory served as the primary data source and verified the vegetation's condition and presence at the study site. Although it does not cover all facts, this verification provides evidence that the second-level data is representative. The parameters of stem circumference (girth) and diameter at breast height (DBH) were obtained from field inventories conducted by PT Jasa Marga between 2022 and 2024. The values listed are averages for each species, which were used in allometric comparisons to determine biomass.

Data Analysis

1. Carbon Emission Load Calculation

As a reference for evaluating the balance between emissions and carbon absorption capacity on the Pandaan–Malang Green Toll Road, calculating carbon dioxide (CO_2) emissions is a crucial step. This estimate aims to calculate the total emission load generated by motor vehicles based on traffic volume and emission factors, categorized by vehicle type. The output of this calculation will be compared with the existing vegetation absorption capacity, thereby identifying potential absorption deficiencies and informing the formulation of more effective vegetation-based mitigation strategies. Carbon emission calculations in this study were conducted using an activity-based approach, following the emission inventory methods established by the Intergovernmental Panel on Climate Change [25]. The IPCC 2006 method is based on international standards adopted by the Indonesian National Greenhouse Gas Inventory. Additionally, this method provides consistent and verifiable emission factors for vehicle categories in developing countries, allowing for a comparison of study results with those of the transportation sector. However, several updates have been made, such as the IPCC 2019 Refinement; the 2006 guidelines remain more relevant to the availability of vehicle data in Indonesia. The formula applied is:

$$Q = Ni \times FEi \times Ki \times L$$

Description:
Q = CO2 emissions (kilograms)
Ni = Number of vehicles in class i
Fei = Emission factor for class i
Ki = Energy consumption for class i (liters/100 km)
L = Segment length (km)

The emission factor (EF) and fuel consumption (Ki) values shown in Table 1 indicate that the higher the vehicle category, the greater the emissions produced per liter of fuel. The total CO_2 emissions for each road segment can be estimated using these values in the formula. These findings form the basis for assessing the effectiveness of existing vegetation in absorbing emissions and designing strategies to reduce carbon deficits by adding green cover in a measured and spatial manner.

TABLE 1. Emissions Data Based on Vehicle Class

Class	FE (kg CO_2 / liter)	Ki (liter/ 100 km)
I	0.1179	1,297.86
II	0.1304	2,924.89
III	0.1689	2,924.90
IV	0.1515	2,924.90
V	0.1582	2,924.90

Source:[9]

Table 1 presents information on emission factors (EF) and energy consumption (Ki) by vehicle type category, highlighting a significant difference between the light and heavy vehicle categories. Vehicles in Class I (sedans, jeeps, and single-axle private cars) have a significantly lower energy consumption rate of 1,297.86 liters per 100 km, with an emission factor of 0.1179 kg CO_2 per Liter. Conversely, vehicles in Groups II to V, which include trucks with two to five axles, show higher energy consumption and gradually increasing emission factors, with energy consumption values ranging from 2,924.89 to 2,924.90 liters per 100 km and emission factors between 0.1304 and 0.1582 kg CO_2/liter. This difference indicates that heavy vehicles typically emit higher carbon emissions per unit of distance traveled compared to light vehicles. This data is crucial in measuring the environmental impact of highway transportation activities and as a strategic factor in formulating emission reduction policies based on vehicle type.

2. Calculation of Vegetation Absorption Capacity

Carbon absorption by plants is a crucial natural process for mitigating climate change [26]. This activity focuses on photosynthesis, the process by which plants take carbon dioxide from the air and use sunlight to convert it into organic matter, such as sugar and cellulose. Most of the captured carbon is then utilized for biomass growth, which includes roots, stems, branches, leaves, and fruits [27]. In other words, carbon from CO_2 in the atmosphere is stored and accumulated in the physical form of plants as biomass over a long period. This storage capacity, known as carbon sequestration, is greatly influenced by the plants' type, age, density, and health. To assess the contribution of vegetation in reducing carbon emissions along the Pandaan–Malang Green Toll Road, the total carbon dioxide (CO_2) absorption capacity was calculated based on existing vegetation inventory data. This calculation uses the following formula: [28]

$$\text{Total Absorption} = \Sigma(\text{Number of Vegetation x Absorption Capacity})$$

This formula calculates the total absorption capacity of each plant species by multiplying the number of individuals per species by the specific absorption capacity (in kg/year), as reported in relevant scientific literature [28]. The number of vegetation and types of vegetation are obtained from the inventory of PT. Jasa Marga, and every kind of plant has a different absorption value, depending on its morphological and physiological characteristics, such as canopy area, photosynthesis rate, and biomass growth rate [9]. This cumulative calculation forms the basis for assessing the adequacy of vegetative capacity to absorb emissions generated by motor vehicle activity along the toll road.

3. Emissions-Absorption Balance

In an effort to achieve sustainable development in the transportation sector, balancing carbon emissions and absorption is a key factor in assessing the environmental performance of Green Toll Roads. Recent studies show that the effectiveness of environmentally friendly toll roads is highly dependent on the ratio between emissions produced by vehicles and the absorption capacity of surrounding vegetation [29]. On the Pandaan-Malang Toll Road, maintaining this balance is crucial to ensure that the ecological function of the toll road aligns with the Sustainable Development Goals [30]. An analysis was conducted to determine the difference between total emissions and total vegetation absorption capacity to calculate the balance between vehicle carbon emissions and vegetation absorption capacity along the Pandaan-Malang Green Toll Road. This calculation uses the following formula: [31]

$$\text{Residual emissions} = \text{Total Emissions} - \text{Total Absorption}$$

This formula describes the deficit or excess of carbon emissions that remain in the environment after being compensated for by existing plants. If the residual emission value is positive, there are excess emissions that plants cannot fully absorb, indicating an ecological imbalance. Conversely, if the number is negative, it means that the absorption capacity of plants exceeds the total emissions produced [31].

Evaluation of Emission Absorption Adequacy

The evaluation began with the collection of data on green elements along the toll road, including plant species, number of individuals, and estimated annual carbon sequestration capacity based on scientific references and empirical data [32]. Each species was evaluated based on its CO_2 absorption capacity. Total absorption accumulation was calculated by multiplying the population of each plant by its average annual absorption, then summing to determine the overall emission absorption capacity. This method applied a bottom-up approach [30]. The difference between emissions produced and absorption capacity indicates the carbon balance, revealing whether there is a surplus or deficit in absorption. This research provides a basis for assessing the effectiveness of green corridors in supporting climate change mitigation and a foundation for formulating further management strategies, such as adding plants with high absorption capacity, restructuring vegetation distribution, and maintaining the sustainability of green corridor ecological functions [33].

RESULT AND DISCUSSION

Carbon Emissions on the Pandaan-Malang Toll Road

Carbon emissions (CO_2) release carbon compounds into the air, resulting from human activities, particularly motor vehicle-related ones. As the number of vehicles increases, greenhouse gas emissions, especially carbon dioxide, also increase. [34]. Table 2 presents the total carbon emissions (CO_2) generated in each segment of the Pandaan–Malang Toll Road based on segment length and emission estimates using the IPCC 2006 method and BPPT energy consumption data [17].

TABLE 2. Total Emissions per Segment

Segment	Length (km)	Total Emissions (kg/tahun)
Segment I Pandaan - Purwodadi	15.48	27,779,332.05
Segment II Purwodadi - Lawang	8.05	14,847,568.17
Segment III Lawang - Singosari	7.10	14,153,651.63
Segment IV Singosari - Pakis	4.75	4,551,468.84
Segment V Pakis - Malang	3.11	1,988,290.35
Total	**38.49**	**63,320,311.04**

Source:[21]

The data in Table 2 shows that the total carbon (CO_2) emissions on the Pandaan-Malang toll road reached 63,320,311.04 kg/hour. These findings indicate that the distribution of emissions among the segments reveals an inequality in the concentration of emissions. Segment I (Pandaan–Purwodadi) has the highest emission record of 27,779,332.05 kg/year. This is due to the length of the segment, which is 15.48 km, exceeding that of the other segments, causing vehicles to travel longer distances in a single trip and accumulate greater emissions [31]. The high volume of vehicles, especially Class I vehicles such as sedans and private cars, also contributes to this uneven distribution of emissions. On the other hand, segment V (Pakis–Malang), with a length of 3.11 km, has the lowest emissions at 1,988,290.35 kg/year. This is due to the smaller road capacity, which limits the number of vehicles passing through. The short distance can reduce the total kilometers traveled and the average speed, which tends to be lower because it is close to the city center, thereby reducing fuel consumption per kilometer [35]. The combination of short distances, low vehicle volume, and stable speeds can create a more optimal situation on longer and busier segments, and CO2 emissions become much more controllable [36].

Spatial and operational factors in each toll road segment significantly affect emission variations. Segments with constant traffic flow allow vehicles to run with more optimal fuel efficiency, thereby reducing energy consumption per kilometer. Stable traffic conditions can reduce emissions by 20–40% compared to traffic that experiences frequent acceleration and deceleration during congestion [37]. Optimal vehicle speeds in the 50–80 km/h range can reduce emission levels because the engine operates at maximum thermal efficiency [38]. On the other hand, in segments with high density and variable speeds, emissions tend to increase dramatically due to inefficient fuel combustion. Vehicle operating patterns impact emission intensity more than segment length alone [39]. Therefore, sustainable toll road management demonstrates that emission control strategies must consider the dynamic characteristics of traffic.

Carbon Absorption Capacity of Existing Vegetation on the Pandaan-Malang Toll Road

The green vegetation growing along the Pandaan–Malang Toll Road plays a crucial role in supporting the ecological function of the toll road, especially concerning carbon absorption. As an element of sustainable infrastructure, this vegetation is designed to balance the carbon emissions produced by motor vehicles [40]. Table 3 presents information on the carbon absorption capacity of the vegetation along the Pandaan-Malang toll road, encompassing 19 types of vegetation with a total population of 48,358 units [41]. The results of the study indicate that the total annual absorption capacity of all vegetation is 48,358.02 kg/unit/year, with a total cumulative absorption capacity of 51,080,719.78 kg/year.

TABLE 3. Absorption Capacity of Existing Vegetation

Species	Number (unit)	Absorption Capacity (kg/unit/year)	Contribution (%)
Rain tree	1,616	28,448.49	90.00
Pink/White Trumpet tree	515	320	0.32
Australian pine	285	60	0.03
Flamboyan	738	42.20	0.06
Yellow Trumpet tree	1,698	211.99	0.71
Terminalia mantaly	103	24.16	0.01
African tulip	515	569.42	0.57
Damar gum	200	24.956	0.01
Syzygium myrtifolium	520	100.02	0.10
Blackboard tree	326	11.565,49	7.38
Bougenville	720	45.44	0.06
Tropical almond	50	60	0.01
Java plum	50	5,997	0.59
Rose apple	50	250	0.02
Guava crystal	50	94.65	0.01
Mango	120	455.11	0.11
Sirsak	50	75.29	0.01
Soursop	50	1.46	0.0001
Longan	50	12.35	0.001
Total		**48,358.02**	**100**

Table 3 illustrates the dominant presence of Trembesi (Samanea saman) in carbon sequestration along the Pandaan–Malang Toll Road, accounting for 90% of the total sequestration capacity of 48,358 kg/year. This is related to the large trunk diameter (average DBH of 400 cm) and the number of trees reaching 1,616. The biological characteristics of Trembesi enable it to dominate 90% of the total carbon amount. This species has a larger trunk diameter, a more expansive canopy, and a longer lifespan, resulting in its biomass being significantly greater than other species. Previous studies have shown that Trembesi has the capacity to produce 287.65 kg of carbon per person per year [42] and a biomass potential of up to 2 tons per person [43]. Other studies have also shown that Samanea saman is included in the priority tree green belt due to its ability to adapt to higher carbon pollution and its absorption capacity compared to slower-growing vegetative populations [40].

In addition to Trembesi, several other species contribute, albeit on a smaller scale. Despite having only 326 units, the Pule species (Ficus spp.) contributes about 7.38% of the total absorption, indicating a relatively high absorption capacity per individual [44]. As a key component of tropical ecosystems, dea (Pterocarpus indicus) shows an average of 569 kg/unit/year, highlighting the importance of this species [45]. In contrast, Tabebuya and several other species, such as Cemara Angin, Ketapang, and Jambu Air, contribute less than 1% of the total population due to their small size and low biomass [46]. This suggests that vegetative morphological variations, such as canopy length and stem diameter, have a significant impact on variations in carbon sequestration capacity worldwide [47].

TABLE 4. Vegetation Biomass Calculation

Species	**Circumference of the Trunk (centimeter)**	**DBH (centimeter)**	**W (kilogram)**	**Contribution (%)**
Rain tree	1,256	400	257,766.718	62.98
Pink/White Trumpet tree	314	100	7,727.074	1.89
Australian pine	251	79.94	4,384.879	1.07
Flamboyan	377	120.06	12,272.320	3.00
Yellow Trumpet tree	251	79.94	4,384.879	1.07
Terminalia mantaly	188	59.87	2,110.583	0.52
Damar gum	471	150	21,553.904	5.27
Syzygium myrtifolium	126	40.13	766.868	0.19
Blackboard tree	314	100	7,727.074	1.89
Bougenville	94	29.94	365.424	0.09
Tropical almond	471	150	21,553.904	5.27
Java plum	314	100	7,727.074	1.89
Rose apple	251	79.94	4,384.879	1.07
Guava crystal	188	59.87	2,110.583	0.52
Mango	628	200	44,629.390	10.90
Sirsak	157	50	1,337.855	0.33
Soursop	126	40.13	766.868	0.19
Longan	314	100	7,727.074	1.89
Total Vegetation Weight			**409,297.346 kg**	**100**
Total Vegetation Biomass (Weight / Area)			**409.297 kg/m^2**	
Total Vegetation Biomass			**4,092.973 ton/ha**	
Carbon Stock (Total Biomass x 0.46)			**1,882.768 ton/ha**	

Based on Table 4, the total vegetation biomass in the Pandaan–Malang Toll Road area reaches 4,092,973 tons per hectare, with a carbon content of 1,882,768 tons per hectare. Meanwhile, motor vehicle emissions are estimated to reach 63,320,311.04 kg of CO_2 per year, while the annual CO_2 absorption capacity is 51,080,719.78 kg of CO_2. This condition indicates an absorption deficit of 12,239,591.26 kg of CO_2, equivalent to approximately 19.33% of total emissions. The biomass composition shows an uneven distribution, with the most significant biomass coming from Trembesi. This species is known to have a large trunk diameter and a long life span, resulting in high biomass [42], [43]. In addition, several other species, such as Mango, damar, Flamboyant, and Ketapang, also made significant contributions (approximately 2–11% of total biomass), consistent with the theory that medium-sized trees with moderate growth can be an essential component in green ecosystems [40]. Conversely, small species such as Tabebuya, Cemara Angin, and Jambu Air contribute less than 2%, which is consistent with studies showing that small species have lower carbon deposition rates [44].

A trembesi dependency rate exceeding 60% of total biomass indicates ecological risk. Monoculture conditions are vulnerable to microclimates, environmental disturbances, and disease. Previous studies have also shown that the dominance of a single species in forests can increase vulnerability to all living things and reduce ecological stress [45], [46]. Therefore, vegetation diversification is necessary to make ecosystems more resilient and healthy. Diversification can be achieved by increasing the number of species with slow-growing biomass, such as mango, damar, and flamboyant, which have the potential to reduce carbon emissions and thus reduce ecological risk. Several studies show that local species and introduced fast-growing species can increase carbon sequestration capacity by 30–40% compared to monoculture systems [47], [46]. Therefore, a more balanced vegetation composition is essential to maximize the ecological function of green corridors.

Emissions Absorption Analysis and Vegetation Absorption Capacity Evaluation

The emissions absorption deficit analysis evaluates how vegetation absorption capacity can offset carbon emissions generated on the Pandaan-Malang Toll Road, particularly from motor vehicle activity. Figure 2 compares total annual emissions, vegetation absorption capacity, and the carbon absorption deficit. The graph shows that the yearly emission value of 63,320,311.04 kg/year far exceeds the total absorption capacity of the existing vegetation, which is 51,080,719.78 kg/unit/year, resulting in a significant carbon absorption deficit of 12,239,591.26 kg/year, equivalent to 19.33%. This situation demonstrates that the carbon emissions produced far exceed the absorption capacity of vegetation, rendering the toll road a source of net emissions rather than a carbon sink [48]. A similar study reveals a comparable pattern, where absorption by vegetation and soil (9,518 tons/year) is significantly lower than vehicle emissions, resulting in a substantial carbon deficit for that road segment [49]. These findings suggest that urban toll roads often generate emissions that exceed the surrounding vegetation's ability to absorb. Carbon absorption deficits were also detected on several other toll road sections. Research on the Waru–Sidoarjo Toll Road shows that CO_2 emissions from cars far exceed the absorption capacity of existing vegetation, necessitating the addition of green areas [50]. A study on the Jagorawi Toll Road reveals the same finding: the green open spaces in the corridor are insufficient to offset vehicle emissions [51]. Similar results were observed on the Romokalisari–Tandes Toll Road, where vehicle emissions exceeded the vegetation's ability to absorb them, necessitating further planning [52]. Supported by international research in China, the absorption capacity of roadside vegetation can only absorb a small portion of traffic emissions, resulting in a continuing carbon deficit [53].

In a broader context, measuring the balance between carbon sources and sinks is a crucial indicator of global ecosystem health [54]. When green systems, such as toll roads, have net carbon sources, vegetation management and expansion strategies must be designed to achieve a balanced or positive carbon balance. In the case of the Pandaan–Malang Toll Road, the deficit figure shows that although vegetation has developed quite well, there is still a lack of absorption capacity to offset total vehicle emissions.

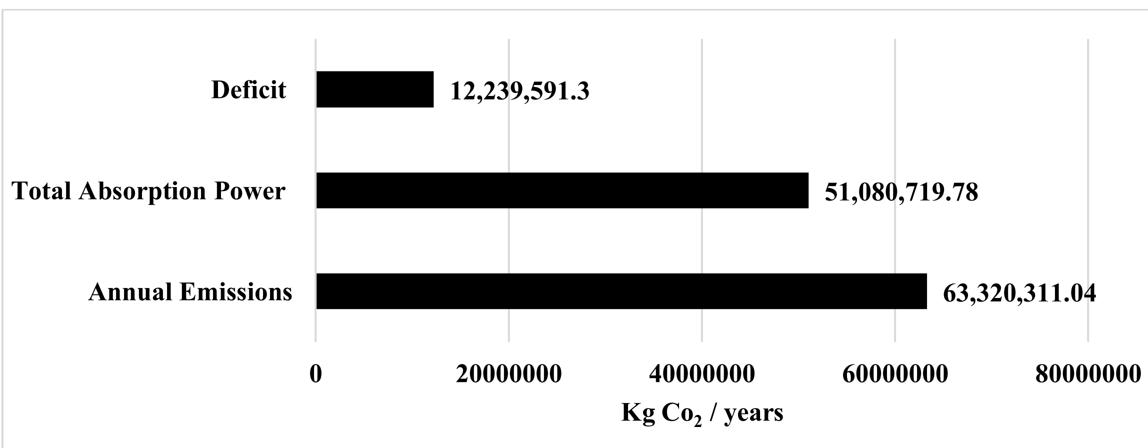

FIGURE 2. Comparison Chart of Emissions vs. Absorption Capacity

Several factors influence the 19.33% absorption deficit on the Pandaan-Malang Green Toll Road. One of the causes is the high volume of vehicles. This number generates substantial emissions that are not in proportion to the absorption capacity of the existing vegetation. Additionally, variations in length between toll road segments also contribute to the uneven distribution of vegetation. Shorter or space-limited segments tend to have less vegetation and a lower variety, resulting in a lower carbon absorption potential [55]. The low absorption capacity of the vegetation used exacerbates this unevenness. Some plant species, such as Bermudagrass, can only store around 699 kg of carbon per hectare, which is still far from sufficient to offset emissions in areas with high traffic [56]. Despite the contribution of green belts to absorption, emissions still dominate the annual carbon balance [57]. This phenomenon is evident in other transportation infrastructures that experience similar deficiencies on a large scale. This situation highlights the importance of restructuring greening strategies and integrating emission control policies with a systemic and data-driven approach.

Roadside vegetation provides ecosystem benefits, but its carbon sequestration capacity covers only a small fraction of total traffic emissions due to limitations in area and species diversity [58]. This suggests that quantity alone is insufficient, as the quality and type of plants also play a crucial role. The thousands of tons of carbon absorbed each year are not enough to offset the rate of emissions from heavy vehicles [59]. Even in areas with large reserves of vegetation carbon, an annual deficit still occurs [60]. Local vegetation species, such as Canary Island pine, have a good absorption capacity; overall, vegetation along roads cannot achieve carbon neutrality due to the continuous increase in vehicle activity [56].

This analysis and evaluation show that these challenges cannot be overcome simply by planting certain vegetation types, even with high absorption capacity. However, a comprehensive strategy is needed that includes the design of green toll roads based on actual emission calculations, the selection of layered plant species, and a time- and space-based vegetation monitoring system [61]. Maintaining the ecological function of highways requires collaboration among infrastructure planning, low-emission transportation policies, and the implementation of measurable and well-managed green landscape conservation. Through an ecosystem-based approach that considers traffic patterns, vegetation density, and seasonal changes, highway green belts can achieve maximum carbon mitigation effectiveness [62]. On the other hand, transportation infrastructure greening strategies need to be complemented by spatial data-based monitoring systems and cross-sector policy support to address long-term emission pressures [61]. This shows that the success of the ecological function of toll roads is determined by the synergy between technical, ecological, and adaptive environmental management aspects [63].

The policy implications of these findings emphasize the need for specific measures from the government or toll road operators. Jasa Marga must provide a replanting plan with various species that are pollution-resistant and highly resilient. The Ministry of Public Works and Public Housing can set toll road height standards with specific minimum carbon absorption targets. Thus, green corridors are aesthetically pleasing and are clear indicators of climate change in the transportation sector.

CONCLUSION

This study shows that the Pandaan–Malang Green Toll Road can only absorb 19.33% of total annual carbon emissions, resulting in a significant absorption deficit. This imbalance confirms that the function of green corridors is still far from optimal. Ecological risks are increasing due to the dominance of trembesi monoculture, which is vulnerable to pests and climate pressures, making diversifying adaptive species an urgent necessity. In terms of policy, a vegetation zoning strategy, IoT-based monitoring technology for real-time tracking of emissions and absorption, and multi-stakeholder involvement in vegetation management are needed to ensure the resilience of the toll road ecosystem. The limitations of this study include the use of secondary vegetation data, the exclusion of non-vehicle emission sources, and the neglect of secondary pollutants. Future research should focus on developing superior species that combine high carbon sequestration with resistance to pollutants and extreme climates, modeling sequestration dynamics using machine learning, and conducting field verification of vegetation physiological responses while integrating endemic species. In this way, the Green Toll Road can be transformed into climate-resilient carbon-balancing infrastructure.

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