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Original Article

Carbon sequestration potential of green corridor to reduce transportation greenhouse gas emissions: a case study in Malang City

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Abstract

The increasing rate of population growth and urbanization will lead to escalating greenhouse gas (GHG) emissions from the transportation sector, which brings various negative impacts of climate change to people's lives. This study aims to measure GHG emissions and estimate the potential for carbon sequestration in green corridors as an alternative solution to achieving carbon neutrality by 2030. An inventory and projection of GHG emissions in the transportation sector in Malang City for 10 years were carried out using the Intergovernmental Panel on Climate Change (IPCC) tier 1 method. It was estimated with the i-Tree canopy web version, along with determining the baseline GHG emission target to be reduced. The results showed that GHG emissions in the transportation sector in Malang City amounted to 511,011.24 tons CO_2-eq and are projected to reach 6,043,940 tons CO_2-eq in 2034. The highest potential is observed in the green corridor in Klojen District, totaling 12,816 trees and dominated by *Swietenia sp*. Street trees in Malang City's green corridors in the 2024-2034 interval potentially reduce GHG emissions by 8,770.40 tons CO_2-eq in Malang City. The green corridor is projected to contribute 1.45 % to Malang's regional target in GHG mitigation. The enhanced potential sequestration of green corridors needs to be considered as one of the effective efforts in achieving carbon neutrality in 2030.

Keywords: carbon sequestration, climate change, green corridor, greenhouse gas, street trees, transportation.

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Introduction

The relationship between income, urbanization, energy consumption, and CO_2 emissions from the transportation sector is complex and interconnected (Alataş, 2022). Rapid urbanization has significantly contributed to high greenhouse gas (GHG) emissions, with urban areas expected to accommodate an increasing percentage of the global population by 2050 (Xi et al., 2022). This urbanization trend exacerbates carbon emissions, primarily from fossil usage in power generation, construction, and transportation (Zhang et al., 2019). According to IPCC (2023), global GHG emissions in 2019 came from the sectors of energy, industry, transportation, and building by approximately 79% and 22% came from agriculture, forestry, and other land use (AFOLU).

Studies have shown that expansions of urban areas lead to the formation of urban heat islands (UHIs), which contribute to increased energy consumption, carbon emissions, air pollution, and negative impact on human health and well-being (Xi et al., 2023). Countries like Bangladesh and the Philippines exemplify how urbanization drives emissions primarily through increases in fossil fuel consumption for transportation and infrastructure development (Raihan, 2023).

Climate change impact, including rising temperature, sea-level rise, and extreme weather events, pose significant challenges, particularly for urban areas (Filho et al., 2019; Dano et al., 2023; Ridha et al., 2022; Ma et al., 2023; Jalali et al., 2024). Solutions to mitigate these impacts include Nature-Based Solutions (NBS), such as urban greening and carbon sequestration in vegetation (Ariluoma et al., 2023); Pereira et al., 2024). Effective urban planning and management strategies are essential to optimize carbon sequestration in urban green spaces (Behera et al., 2022; Yao et al., 2022). This involves selecting appropriate tree species, assessing ecosystem services, and employing innovative methodologies to estimate carbon sequestration potential accurately (Laux et al., 2022; Tao et al., 2023; Magazzino et al., 2023).

However, the high rate of land use change and limited green open space, especially in Malang City, and the high pressure of transportation GHG emissions, need efforts to increase the effectiveness of existing green open space. Green space in cities, although very narrow due to land conversion, has the potential to remove CO_2 in the atmosphere and increase carbon stocks in trees and soil through sequestration (Behera et al., 2022). The integration of high-resolution mapping, modeling approaches, and field surveys can help quantify carbon sequestration and guide urban greening initiatives. Additionally, promoting nature-based solutions in transportation planning can complement efforts to achieve carbon neutrality.

The purpose of this study is to determine the level of GHG emissions in the transportation sector in the business as usual (BAU) scenario in Malang City as well as its projection in the next 10 years and how much potential carbon sequestration in the green corridor in reducing it. This study can be used as a basis for designing green corridors that have greater sequestration capacity so that they provide an optimal contribution to achieving carbon neutrality by 2030.

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Methods

The primary data sources employed in this study are secondary data sets concerning tree vegetation inventory in green corridors and fuel oil consumption of motor vehicles in Malang City for the years 2021, 2022, and 2023. The secondary data comes from a tree inventory by the Malang City Environment Office in 2023. The study utilized purposive sampling. The selection of green corridor areas is based on the area of road space on roads that are crowded with vehicles, except toll roads and railways. These green corridors managed and surveyed by the Malang City Environmental Agency, were observed and documented to verify the condition of tree vegetation. Each tree was identified for its vegetation type and the number of individuals present at each site.

Description of the study area

This quantitative descriptive research was conducted in September-December 2023. The observation of tree vegetation inventory in the green corridor was carried out over five days in December 2023. The research location focused on green corridors along vehicular roads in 5 (five) districts of Malang City including Klojen, Blimbing, Lowokwaru, Sukun, and Kedungkandang districts as shown in the yellow lines in Figure 1. and described in Table 1.

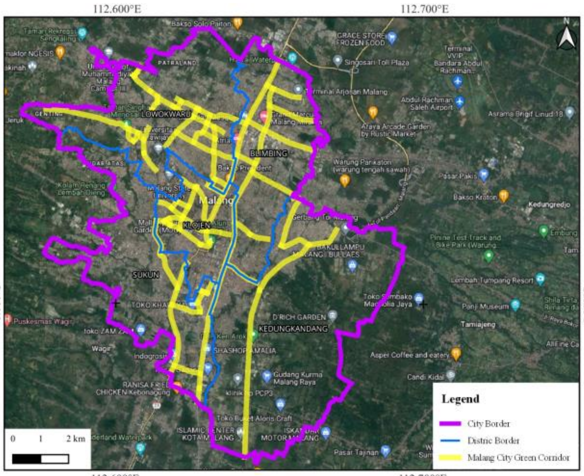

Figure 1. Study Area in Green Corridor of Malang City
Source: Modification from DPUPRPKP Kota Malang (2022)

Table 1. Description of Study Area

No.	District	Length of Road (m)	Area (m^2)
1	Blimbing	22,456.78	19,094.48
2	Klojen	15,052.40	10,666.40
3	Kedungkandang	12,865.28	12,388.75
4	Lowokwaru	27,360.39	19,924.25
5	Sukun	10,976.67	17,270.58
	Total	88,711.52	79,344.46
Length of Malang City's Road Existing (m)		1,851,662.42	
Area of Malang City's Green Corridor Existing (m^2)			138,506.41

Source: Modification from Pemkot Malang (2019); Pemkot Malang (2023).

Data analysis

GHG emissions in the transportation sector

Greenhouse gas (GHG) emissions in the transportation sector are assessed based on the combustion of fuel in various mobile sources, including private vehicles (such as cars, minivans, and SUVs) and commercial vehicles (like buses, minibuses, pickups, trucks, and motorcycles). GHG emissions are quantified in terms of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) based on fuel consumption, which varies by fuel type. The carbon content is determined according to the emission factors associated with each type of fuel. (IPCC, 2006). Estimation of GHG emissions from road transportation using the IPCC Tier-1 method, which is based on the total amount of CO_2, CH_4, and N_2O emissions and converted as CO_2 emissions. Based on Tier-1, emissions of CO_2, CH_4, and N_2O are calculated by the equation (IPCC, 2006):

$$Emission = \sum_{a} [Fuel\ a\ .\ EF\ a]$$

Where:
Emission : emissions of CO_2, CH_4, and N_2O (kg)
Fuel a : fuel sold (TJ)
Table 2. Road transport default CO_2 emission factor
EF a : emission factor (kg/TJ).
a : type of fuel (e.g. petrol, diesel, natural gas, LPG, etc.)

The IPCC's default emission factors for fuel combustion at mobile sources are shown in Table 2 and Table 3.

Table 2. Road Transport Default CO_2 Emission Factor

Fuel Type	Default (kg/TJ)	Lower (kg/TJ)	Upper (kg/TJ)
Motor Gasoline	69,300	67,500	73,000
Gas/ Diesel Oil	74,100	72,600	74,800

Source: IPCC (2006)

Table 3. N_2O and CH_4 Emission Factors Road Transport Default

Fuel Type	CH_4 (kg /TJ)			N_2O (kg /TJ		
	Default	Lower	Upper	Default	Lower	Upper
Motor Gasoline-Uncontrolled	33	9.6	110	3.2	0.96	11
Gas/Diesel Oil	3.9	1.6	9.5	3.9	1.3	12

Source: IPCC (2006)

The Global Warming Potential (GWP) value is used to convert non-CO_2 GHG emission data into carbon dioxide equivalent (CO_2-eq) by following the Second Assessment Report of the IPCC (2nd AR of IPCC). The GWP value is referred to as Table 4.

Table 4. GWP Value of GHG Inventory

No.	Gas	GWP (CO_2-eq)
1	CO_2	1
2	Methane (CH_4)	21
3	Nitrous Oxide (N_2O)	310

Source : Kementerian Lingkungan Hidup dan Kehutanan (2019)

The GHG emission data series for the transportation sector is projected until 2034 using the STELLA dynamic system. Fuel is categorized into two groups: motor gasoline (pertalite, pertamax, and pertamax turbo) and diesel oil (diesel, dexlite, and pertamina dex). GHG emissions are projected with a baseline rate of increase and rate of decline in fuel consumption from 2021 to 2023. The validity of dynamic system calculations follows the Absolute Mean Error (AME) Validation Test as a method to test the accuracy of forecasting models. The model is valid if the AME $\leq$ 30% (Rusiawan et al., 2015).

Carbon Sequestration Capacity in Green Corridor

Estimation of carbon sequestration capacity in green corridor areas using the web version of the i-Tree canopy program on the https://canopy.itreetools.org/ site which includes determining conservation locations, the application will display points in the observation area to determine the criteria onto Google Earth imagery. The land cover criteria used are tree (T) and non-tree (NT). The tree is a canopy cover of tree vegetation and besides that, it is a non-tree such as grass, road, structures, and impervious surfaces. The number of points is determined to be at least 1000 points to obtain a low standard error (SE) and 95% confidence. Amount sequestered is based on 11.220 tons of CO_2, per ha/yr and rounded (Nowak, 2021).

Transportation Sector GHG Reduction Target by 2034

The carbon sequestration capacity of each green corridor is projected by 2034 and compared to the projected GHG emissions of transportation that year. The GHG emission reduction target in 2034 to achieve carbon neutrality is a reduction in the sequestration capacity of green corridors with GHG emissions in the transportation sector of Malang City.

The carbon reduction to be achieved is formulated as follows (KLHK, 2023):

$$PEn = B - En$$

Where :

PEn : Carbon Reduction to be achieved (tons CO_2-eq/year)

B : Baseline, GHG Emissions in the Transportation sector (tons CO_2-eq/year)

En : Green corridor sequestration capacity (tons CO_2-eq/year)

Results

GHC Emissions in The Transportation Sector

The calculation of the GHG emission inventory of the transportation sector with IPCC Tier 1 in 2021, 2022, and 2023 shows that the emission trend tends to increase (Figure 2). Carbon emissions from vehicles that use gasoline motor-type fuel are much higher than vehicles with fuel from the diesel oil group. Transportation GHG emissions in 2021, 2022, and 2023 amounted to 409,782.810 tons of CO_2-eq., 506,905.317 tons of CO_2-eq., and 511,011.24 tons of CO_2-eq.

GHG emission projections are estimated with the STELLA dynamic system at intervals from 2024 to 2034 or for 10 years as a BAU scenario and 2021 as a baseline. The BAU scenario assumes that there will be no changes in population conditions, energy consumption patterns, and policies. The determining factor of emissions is the rate of increase in fuel needs and the rate of decrease. For 10 years, the rate of decline in fuel consumption has not had a significant effect. The GHG emission trend in the transportation sector will increase until 2034 to reach 6,043,940 tons of CO_2-eq. The validity of calculating transportation GHG emission projections in dynamic systems can be accepted with an AME percentage of 6.05% or less than 30%. Projections of GHG emissions in the transportation sector with the STELLA Dynamic System in the range of 2021 to 2034, are presented in Figure 3.

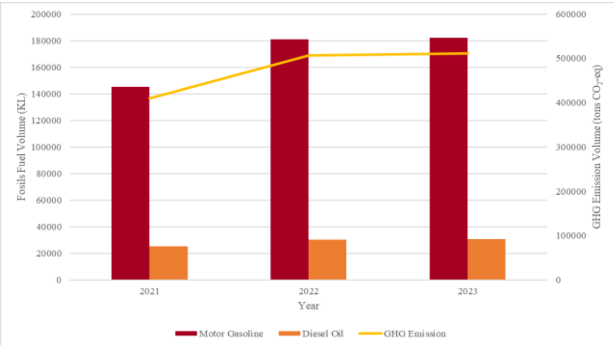

Figure 2. GHG Emission Inventory of Transportation Sector in Malang City

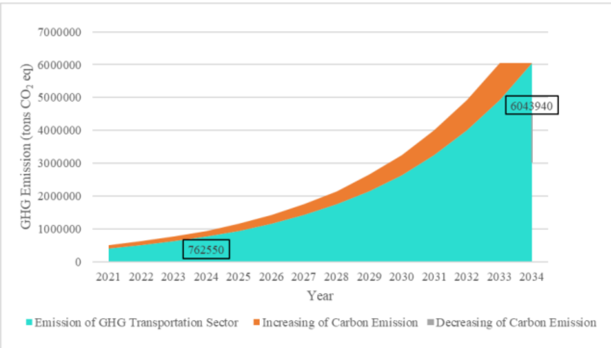

Figure 3. GHG emission projections in the Transportation Sector in Malang City

Carbon Sequestration Capacity in Green Corridor

Based on the results of observation and secondary data analysis, it is evident that the total number of trees identified across all research sites in the 5 districts of Malang City is 12,816 trees. Figure 4 illustrates the majority of tree vegetation in Malang City's green corridors which has a minimum number of individuals of 100 trees.

The sequestration capacity of the green corridor was assessed by randomly plotting at least 1000 area points across the five districts in Malang City, as presented in Table 5.

Transportation Sector GHG Reduction Target in 2034

The GHG emission reduction targets of the transportation sector are presented in Table 6. This data illustrates the disparity between the GHG emissions of the

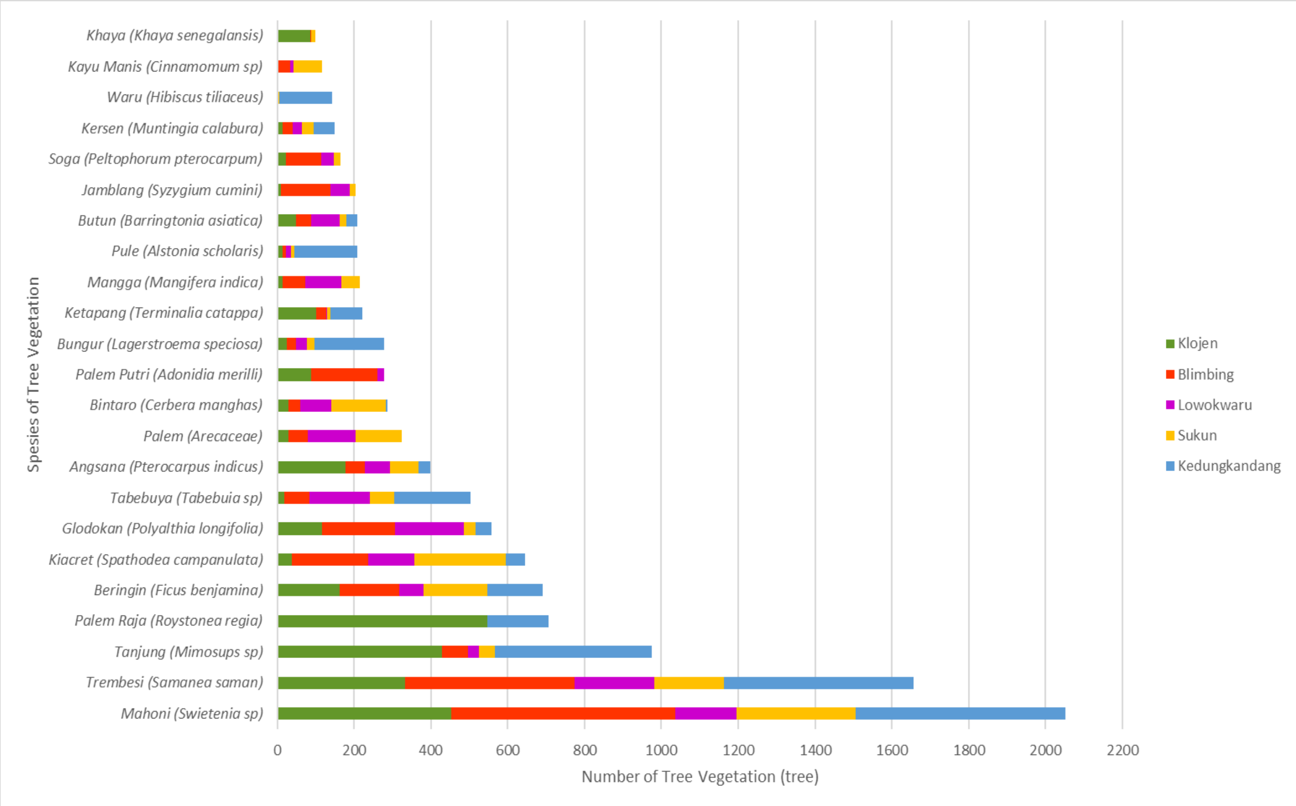

Figure 4. The majority of tree vegetation in Malang City's green corridors.

Table 5. Carbon sequestration capacity in Malang City in 2024

No.	District	Number of Existing Trees	Road Length (m)	% Canopy		Canopy Area (Ha)		Sequestration Capacity (tons CO_2-eq/y)
				NT ± SE	T ± SE	NT ± SE	T ± SE	
1	Klojen	2,995	15,052.4	58.50 ± 1.56	41.50 ± 1.56	58.50 ± 1.56	41.50 ± 1.56	316.09
2	Blimbing	2,903	22,456.8	60.80 ± 1.54	39.20 ± 1.54	28.08 ± 0.71	18.10 ± 0.71	203.13
3	Kedungkandang	2,843	12,865.3	48.00 ± 1.58	52.00 ± 1.58	12.35 ± 0.41	13.38 ± 0.41	150.13
4	Lowokwaru	2,050	27,360.4	61.91 ± 1.46	38.09 ± 1.46	20.75 ± 0.49	12.77 ± 0.49	143.23
5	Sukun	2,025	10,976.7	61.55 ± 1.47	38.45 ± 1.47	9.19 ± 0.22	5.74 ± 0.22	64.46
	Kota Malang	**12,816**	**88,711.5**					**877,04**

Tabe 6. Transportation sector GHC reduction target

No.	District	Number of Existing Trees	Sequestration Capacity (tons CO_2-eq)	
			2024 (Annual)	2024-2034 (**En**)
1	Blimbing	2,903	203.13	2,031.30
2	Klojen	2,995	316.09	3,160.90
3	Kedungkandang	2,843	150.13	1,501.30
4	Lowokwaru	2,050	143.23	1,432.30
5	Sukun	2,025	64.46	644.60
	Malang City	12,816	877.04	8,770.40
GHG Emissions in the Transportation Sector (tons CO_2-eq) (**B**)			762,550.00	6,043,940.00
Reduction Target in Transportation Sector (tons CO_2-eq) (**PEn**)			761,672.96	6,035,169.60
Contribution to Malang City's Total GHG Reduction (10.02% /y)			1.148%	1.45%
Contribution to NDC's Total GHG Reduction (31.89% in 2030)			0.361%	0.46%

transportation sector and the carbon sequestration capacity of the green corridor, representing the targeted reduction in free GHG emissions in the atmosphere.

Discussion

GHG emissions from the transportation sector are the second largest GHG contributor after the energy sector (Hu et al., 2023). Globally, activities in the transportation sector have produced 20% of GHG emissions in particular CO_2 (Jiang et al., 2024). The rise in GHG emissions within the transportation sector today correlates positively with economic and technological development. The continuous increase in CO_2 emissions results in numerous undisclosed consequences for the Earth's ecosystem and the human environment (Zhang et al., 2024). GHG emissions in Malang City show an increasing trend from 2016 until now. The main contributor to GHG emissions in Malang City is known to be the transportation sector (DLH Kota Malang, 2021).

In the GHG emission model of the Malang City transportation sector using a dynamic system, the trend in emission sharply increases over the next 10 (ten) years, specifically in 2034. However, the enhanced Nationally Determined Contributions (NDC) document sets a target of reducing GHG emissions in Indonesia by 31.89% with its efforts and 43.20% with adequate international support by 2030 (KLHK-RI, 2022) and 10.02% for the regional target of Malang City in 2025 (Bappeda, 2023). Various mitigation efforts are required to reduce GHG concentrations in the atmosphere, particularly in the transportation sector. Temperature anomalies and hydrological and climatological meteorological disasters resulting from climate change in Malang City exhibited an increase from 2020 to 2022. The occurrences of landslides, extreme weather events, and earthquakes rose significantly during this period (BPS Kota Malang, 2023).

The most common type of tree vegetation is *Swietenia sp*, which is as many as 2,052 trees or 16.01% of 12,816 identified trees. In Klojen District, it is identified as having the highest number of trees and the highest carbon sequestration capacity observed was 316.09 CO_2-eq tons/year with the most common species being *Roystonea regia*. This aligns with the canopy area, green corridor's area, the number of trees, and vegetation density compared to Blimbing and Lowokwaru districts which have longer roads but the amount of tree vegetation and sequestration capacity is smaller (Table 5.). In addition, sequestration capacity is specific to tree species. For example in Table 4, tree cover (%T) in Blimbing, Lowokwaru, and Sukun districts is almost the same but the sequestration capacity is very different. According to the study of Shadman et al. (2022) the annual sequestration potential of each species *Swietenia macrophylla* has 297.60 kg CO_2-eq/year, *Polyalthia longifolia* 55.27 kg CO_2-eq/year, and at the top are *Moringa oleifera* 368.72 kg CO_2-eq/year, *Mangifera indica* 333.11 kg CO_2-eq/year, *Ceiba pentandra* 233.36 kg CO_2-eq/year, *Delonix regia* 324.28 kg CO_2-eq/year, and *Ficus religiosa* 113.91 kg CO_2-eq/year.

Increasing the area of the GOS (Green Open Space) canopy with more complex landscape structures in street space can have better carbon sequestration (Tao et al., 2023). Urban GOS, especially in trees along roads or green corridors, has the potential to develop sequestration capacity. Research in Dhaka city parks shows that greening in the GOS can increase the potential for carbon sequestration (Shadman et al., 2022). Therefore, the presence of GOS in densely populated cities constitutes an important component of land use planning that must be evaluated for its capacity to reduce total GHG emissions.

Existing street trees in the green corridor in Malang City have the potential to absorb GHG emissions of 8,770.40 tons of CO_2-eq until 2034. However, the projected GHG emissions of the transportation sector in 2034 are much higher, totaling 6,043,940 tons of CO_2-eq. Consequently, the effectiveness of green corridors in reducing GHG emissions in the transportation sector is limited, leaving a substantial amount of free GHG emissions in the atmosphere, estimated at 6,035,169.60 tons of CO_2-eq as a target to get neutral carbon. The existence of trees in the existing green corridor in Malang City has the potential to contribute to reducing GHG emissions in the transportation sector by 1.45% from 10.02% of Malang City's regional target in reducing GHG emissions from all sectors. When compared with the NDC's GHG emission reduction target of 31.89%, the green corridor will contribute 0.46% in 2034.

The high concentration of greenhouse gases (GHGs) in the atmosphere highlights the need for efforts to reduce them as a proactive measure against climate change. In urban areas, a key strategy for adapting to climate change and mitigating its effects is to decrease carbon dioxide (CO_2) emissions and enhance carbon sequestration. (Wang et al., 2021). One of the GHG emission mitigation actions recommended in FOLU Net Sink 2030 is to build green open space to increase carbon sequestration capacity (KLHK, 2022).

The sequestration capacity of the green corridor appears very small compared to the high GHG emissions it seeks to reduce. However, the existence of green corridors needs to be maintained because proper vegetation management and selection can increase their contribution to carbon sequestration in addition to reducing micro temperatures and beauty. The results showed that proper felling of mature trees can increase annual sequestration by 32% compared to no logging (Liu et al., 2023). Studies conducted on street trees in Reykjavik have demonstrated that the identification of tree species, their diversity, and their impact on road infrastructure are crucial components in achieving the climate change mitigation goals outlined in the Reykjavik City Plan (Crosby et al., 2021).

Efforts in the management and selection of road tree species need to pay attention to the parameters of sequestration capacity. As in Figure 4., the majority of trees in all sub-districts in Malang City seem to be chosen on shade parameters, and wind barriers as in the Regulation of the Minister of Public Works Number: 05/PRT/M/2012 concerning Guidelines for Tree Planting in the Road Network System and pay little attention to the concept of sequestration capacity. The characteristics of leaves during carbon assimilation and the age of the tree significantly affect their sequestration capacity, underscoring the importance of careful consideration in the process of tree replacement and pruning (Fini et al., 2023). Carbon sequestration in urban trees is strongly influenced by the age and climate of their environment. Research by Vaughn et al., (2014), the conservation of older tree stands with proper tree maintenance can be a viable GHG mitigation strategy.

However, it is undeniable that tree planting is not a major contributor to GHG emission reduction, given the availability of urban land. This requires a combined effort to reduce GHG emissions through policy measures such as reducing fossil fuel consumption for various purposes in aspects of people's lives (Shadman et al., 2022). The observed length of city roads is only 88,712 m, while the total road length in Malang City spans 1,251.24 km, comprising 16.63 km of state roads, 13.32 km of provincial roads, and 1,221.29 city roads (BPS Kota Malang, 2023). Therefore, there are still very many highway areas that can be optimized to increase the potential for GHG emission reduction, by planting tree vegetation with high carbon sequestration capacity. In addition, public policies and the participation of the private sector and the community are needed in efforts to reduce GHG emissions from the source. Additionally, selecting tree species with high carbon-sequestration capabilities and providing proper care for green corridors by the vegetation characteristics and environmental characteristics can significantly enhance the contribution of green corridors to reducing GHG emissions, especially in the transportation sector.

Conclusion

Based on the findings of the study, GHG emissions in the transportation sector in Malang City amounted to 511,011.24 tons CO_2-eq and are projected to reach 6,043,940 tons CO_2-eq in 2034. Street trees in Malang City's green corridors in the 2024 - 2034 interval potentially reduce GHG emissions by 8,770.40 tons CO_2-eq in Malang City. The green corridor is projected to contribute 1.45 % to Malang's regional target in GHG mitigation. It is imperative to prioritize the planting and selection of vegetation types with high sequestration capacity for example *Moringa oleifera*, *Mangifera indica*, *Ceiba pentandra*, *Delonix regia*, *Ficus religiosa*, and *Swietenia macrophylla*, along with fulfilling other requirement, across all green corridors along the road and GOS in Malang City. Efforts to reduce GHG emissions in the transportation sector in achieving carbon neutrality in 2030 need to be strengthened by the formulation of public policies and other strategies related to mass transportation, the adoption of non-fuel power sources, and the integration of other mitigation technologies.

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