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Mitigation of CO_2 Emissions Based on Aboveground Biomass Assessment in Tropical Regions (Case Study: Gresik City, East Java, Indonesia)

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Indonesia is a tropical region experiencing rapid industrial growth. Gresik City is located in East Java Province, Indonesia, and is recognized as an industrial area with major activities including nickel and steel smelting, electronics, petrochemicals, and energy production. Sukorejo and Gulomantung villages in Gresik City are coastal areas with residential conditions surrounded by industries. Industrial and residential activities in Sukorejo and Gulomantung villages emit CO_2 emissions, which can enhance the greenhouse effect. One of the initial steps in controlling greenhouse gases is through the assessment of aboveground biomass and the calculation of carbon stocks. This study estimates carbon stocks from vegetation in Sukorejo and Gulomantung villages to absorb CO_2 emissions from industrial and residential activities in June to August 2023. Calculation of CO_2 emissions uses data on energy consumption and electricity usage from industrial and residential sources. CO_2 emissions are estimated absorbed by vegetation using allometric carbon calculation equations. Calculation of carbon stocks is based on aboveground biomass (AGB) of vegetation. The estimation of AGB is conducted using allometric equations based on wood density and diameter at breast height (DBH). The research findings indicate that the total CO_2 emissions from industrial and residential sources in the villages of Sukorejo and Gulomantung amount to 165 196.14 tons/year. The carbon stock in Sukorejo and Gulomantung total 2871.74 tons/ha with a CO_2 absorption capacity of 22 403.68 tons/year, resulting in 142 792.46 tons/year of unabsorbed CO_2. Increasing the planting of large shade trees in Gulomantung is necessary due to the availability of extensive vacant land. This study concludes with two optimal scenarios: scenario 1 involves adding one tree species, while scenario 2 consists of a combination of six large shade tree species.

Keywords: aboveground biomass, carbon stock, CO_2 emission.

Introduction

Climate change is the impact of increasing greenhouse gases (GHG) consisting of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Based on the Paris Agreement, countries have committed to limiting the rate of increase in global warming to just below 2°C from pre-Industrial Revolution levels and making efforts to limit temperature changes to at least 1.5°C (UNFCC, 2015). The energy sector and industrial processes contribute over 80% of the world's total global emissions (Climate watch data, 2020). In 2019, Indonesia's largest GHG emissions came from the forest and other land use (FOLU) sector by 50% and from the energy sector by 34% (Ministry of Environment and Forestry of Indonesia, 2020). Emissions from the industrial sector constitute direct GHG emissions, whereas emissions from land use mostly represent indirect emissions, referring to how specific land use practices result in GHG emissions into the atmosphere (Page et al., 2021).

Several studies have been conducted in various countries regarding the mitigation of climate change and GHG emissions (Abdelaty et al., 2023; Agbossou et al., 2022; Bezuidenhout, 2023; Sithole et al., 2023; Sparrevik and Utstøl, 2020). Forest ecosystems and mangroves are crucial in the global carbon cycle, as they store substantial amounts of carbon in both vegetation and soil, and exchange this carbon with the atmosphere through processes such as photosynthesis, respiration, decomposition, and degradation (Vergara-Díaz et al., 2021; Velázquez-Pérez et al., 2019). One way to mitigate GHG emissions is through the assessment of aboveground biomass (AGB). Several studies on AGB for various land uses have been conducted in Indonesia, including on the islands of Kalimantan, Sulawesi, and Java (Afentina et al., 2022; Analuddin et al., 2020; Winarso et al., 2015). The assessment of carbon stocks in the biomass of living plants in a land area can depict the amount of CO_2 absorbed from the atmosphere by plants (Birungi et al., 2023; Hairiah et al., 2011). It is crucial to further investigate this area to understand the significance of AGB assessment in mitigating CO_2 emissions. This research addresses environmental challenges by providing insights into effective strategies for CO_2 emission mitigation through AGB assessment and carbon stocks.

Urban areas generally exhibit higher CO_2 emissions compared with rural areas. This phenomenon can be attributed to heightened human activities and the scarcity of green open spaces. In accordance with the Republic of Indonesia Law No. 26 of the year 2007 concerning spatial planning, the minimum requirement for urban forest or green open space within a city is 30% of the city's total area. The Sukorejo and Gulomantung villages, Gresik City, possess a combined total area of 186 hectares, with a green open space covering 40.28 hectares. The villages of Sukorejo and Gulomantung are situated within the Kebomas sub-district, located in the coastal region of Gresik City, and are encompassed within an industrial zone. Many residents there have expressed concerns regarding the emission of black smoke from factories and the airborne wood dust generated from the industrial wood cutting activities. Individuals residing in close proximity to industrial zones are associated with an elevated risk of developing various neurological disorders, encompassing inflammatory conditions of the central nervous system (CNS), extrapyramidal movement disorders, as well as epilepsy (Choi et al., 2023). Poor air quality has significant implications for human health and can lead to various ailments, such as respiratory disorders, cardiovascular, mental, digestive, lung cancer, heart disease, cerebrovascular disease, and may worsen the condition of people with stroke (Kuntic et al., 2023; Szyszkowicz, 2022; Boucasse et al., 2022; Keller et al., 2023). Consequently, concerted efforts are required to mitigate these emissions.

This study undertakes carbon stock calculations of vegetation in the villages of Sukorejo and Gulomantung as a means to mitigate CO_2 emissions originating from industrial and residential sources. The concentration of industrial activities in specific regions significantly influences air pollution (Liu et al., 2022). A study conducted in Finland reveals that artificial surfaces have emerged as the land cover class with the most intensive emissions due to their inclusion of point source emissions from fuel combustion in energy production and industrial plants (Holmberg et al., 2021). The most significant CO_2 emissions stem from the production and utilization of energy (Sunaryo et al., 2023). Energy efficiency should be enhanced across all possible sectors, and regulations should specify the necessary energy standards that need to be adhered to (Fernandez-Antolin et al., 2023). In this study, industrial emissions stem from fuel combustion and electricity usage, similarly manifested in residential emissions, albeit with an additional component attributed to human breathing.

Vegetation plays a crucial role in sequestering air pollutants. The augmentation of green spaces can confer beneficial effects on lipid metabolism and afford protection against the adverse impacts of air pollution (Mei et al., 2023). Individuals residing in areas with a higher prevalence of green spaces are less likely to develop ischemic strokes compared with those living in regions with fewer vegetation (Avellaneda-Gómez et al., 2022). Green spaces contribute to enhancing atmospheric oxygen levels, which are vital for the health and well-being of urban populations (Abuhasel, 2023). Urban forests have a profound impact on carbon equilibrium both locally and globally (Zhuang et al., 2022).

The carbon balance sequestered by plants is a method employed for carbon calculation without the need to harm/fell trees, utilizing allometric computations. Allometric calculations can be applied to estimate the biomass of diverse plant forms (Middleton, 2020). Various methods of allometric calculation have been employed to estimate biomass and carbon stock assessments (Abebe et al., 2023). It is necessary to assess all phases in a biomass supply chain while considering the emissions they produce to achieve a reduction in GHG overall (Virbickas and Kliopova-Galickaja, 2017). This study aims to estimate the absorption of CO_2, carbon stock, and oxygen production in Sukorejo and Gulomantung village, Kebomas sub-district, Gresik City. Estimating carbon stocks based on AGB calculations. The research also involves climate change mitigation efforts by identifying emission sources and CO_2 absorption through plant biomass calculations. Efforts to mitigate climate change involve not only reducing carbon emissions but also necessitating a harmonious approach in preserving the carbon storage and carbon sequestration functions of mangrove ecosystems (Indrayani et al., 2021). This research is expected to provide information to the public regarding the role of plants in absorbing CO_2, enhancing oxygen production, and possessing biomass reserves that accumulate through CO_2 uptake. This is expected to enhance public awareness for environmental preservation and efforts towards Indonesia's low-emission, climate-resilient future in the 2020–2030 period.

Methods

This research was conducted in the villages of Sukorejo (7°11'32.57"S – 112°38'7.44"E) and Gulomantung (7°11'12.40"S – 112°37'50.83"E), both located within the same subdistrict of Kebomas, Gresik Regency. This research employs a quantitative descriptive method, which involves gathering fundamental data about factual situations or events in a numerical or numeric form. The research was conducted from May to July 2023. This study distinguishes between vegetation locations in green open spaces and green corridors. The field data collection for vegetation in green open space specifically involves tree stands by creating a 10 m x 10 m plot to determine the observation area's extent and measurements at the tree level (Ismaini et al., 2015). The green corridor employs plots measuring 40 m x 5 m (Utami and Putra, 2020; Hairiah et al., 2011). Sample areas are determined through purposive sampling or random selection, followed by the establishment of sample plots. The minimum sample plot size is 10% of the total research area. The determination of transect plots resulted in 5 plots for green corridors and 82 plots for green open spaces (*Table 1*).

The estimation of carbon stock can be carried out by calculating the total carbon content in a plant after determining its density, volume, and biomass (Utami and Putra, 2020; Liu et al., 2023). The calculation of plant biomass can employ both destructive and non-destructive methods. Destructive methods aim to develop allometric equations, while non-destructive methods are used when the allometric equation for the measured plant species is already known (Hairiah et al., 2011). This research calculates AGB using a non-destructive method based on the allometric equation developed by Chave (*Table 2*).

Table 1. *The total number of transect plots in this study*

Vegetation location	Total area (m^2)	Plot area (m^2)	Number of plots
Green corridor	10,321	1,032	5
Green open space	330,817	33,082	82

Table 2. *Allometric equations to estimate AGB based on their climatic zones (Chave et al., 2005)*

Rainfall (mm/year)	Allometric equation	
Dry (< 1500)	$AGB_{est} = 0.112 \times (\rho . D^2 . H)^{0.916}$	(1)
	$AGB_{est} = \rho \times \exp\left(-0.667 + 1.784\, LN\,(D) + 0.207\left(LN(D)\right)^2 - 0.0281\left(LN(D)\right)^3\right)$	(2)
Moist (1500–4000)	$AGB_{est} = 0.0509 \times \rho . D^2 . H$	(3)
	$AGB_{est} = \rho \times \exp\left(-1.499 + 2.148\, LN\,(D) + 0.207\left(LN(D)\right)^2 - 0.0281\left(LN(D)\right)^3\right)$	(4)
Wet (> 4000)	$AGB_{est} = 0.0776 \times (\rho . D^2 . H)^{0.94}$	(5)
	$AGB_{est} = \rho \times \exp\left(-1.239 + 1.980\, LN\,(D) + 0.207\left(LN(D)\right)^2 - 0.0281\left(LN(D)\right)^3\right)$	(6)

Description: ρ is wood density (g/cm^3); D is diameter at breast height (cm); H = tree height (m);

Based on data from the Indonesian Central Bureau of Statistics, Gresik Regency experiences moderate rainfall, ranging from 1500 to 4000 mm/year. Therefore, this research calculates AGB based on equation (4). The calculation of aboveground biomass is performed using wood density (ρ) from an online database (World Agroforestry, 2009). D is diameter at breast height (DBH) (cm). The calculation of carbon stock (Cn) is based on equation (7) following the Indonesian National Standard 7724:2011:

$$C_n = AGB \times 0.47 \tag{7}$$

The carbon reserve calculation aims to estimate the absorption of CO_2 from industrial and residential sources. Meanwhile, the estimation of CO_2 absorption is conducted using equation (8) as follows:

$$CO_2 = C_n \times \frac{44}{12} \tag{8}$$

The estimation of the oxygen released by plants takes into account the oxygen generated during photosynthesis minus the oxygen utilized in plant respiration. If throughout the year, the carbon dioxide absorbed during the photosynthesis process exceeds the carbon dioxide released, then carbon accumulation will occur within the trees and be converted into net carbon accumulation. The calculation of oxygen production utilizes equation (9).

$$O_2 = C_n \times \frac{32}{12} \tag{9}$$

In the industrial sector, the calculation of CO_2 emissions requires data on energy consumption (EC) and emission factor (EF) based on the following equation (10). In the residential sector, the calculation of CO_2 emissions originates from the use of LPG, electricity, and human breathing, using equations (11), (12), and (13) (*Table 3*).

Table 3. *CO_2 emission equation for industrial and residential source*

Source	CO_2 emission equation		References
Industrial	$CO_2 emission = EC \times EF$	(10)	Agus et al., 2013
Residential			
LPG usage	$CO_2 emission = {}^{a}LPG \times EF \times {}^{b}NCV$	(11)	Fitri et al., 2020
Electricity	$CO_2 emission = {}^{c}EP \times EF$	(12)	Fitri et al., 2020
Human breathing	$CO_2 emission = {}^{d}n \times EF$	(13)	Cai et al., 2018

[a]LPG is liquified petroleum gas usage (kg/month); [b]NCV is net calorific volume (0.0000473 Tj/Kg); [c]EP is electric power (Kwh); [d]n is total population (person).

Results and Discussion

Calculation of aboveground biomass and carbon stock

Estimation of carbon reserves in the villages of Sukorejo and Gulomantung is conducted based on CO_2 absorption capacity according to tree species. Tree measurements data are limited to trees with a diameter > 5 cm, as trees with a diameter < 5 cm fall into the category of understory vegetation with lower CO_2 absorption rates (Utami and Putra, 2020; Hairiah et al., 2011). The determination of plot locations is accomplished using Google Earth assistance by creating green open space polygons and green corridors with tree vegetation cover types.

The observations indicate that there are 25 vegetation species in the villages of Sukorejo and Gulomantung, with a total of 847 plants. The most dominant trees are the chawan tree with 188 individuals and the angsana tree with 107 individuals. The tree diameter ranges within 5–114 cm. *Table 4* shows the results of aboveground biomass calculations and carbon stock.

Table 4 shows that the Angsana tree (*Pterocarpus indicus*) has the highest biomass value, totaling 192 577.06 kg. The Sirsak tree (*Annona muricata*) has the lowest biomass and carbon reserves with a biomass value of 169.27 kg. The species density of a tree in a given area influences the CO_2 absorption capacity and O_2 production (Birungi et al., 2023). The plant biomass in a particular region is determined by tree density, the number and species composition of trees, tree diameter, moisture content, soil fertility, and temperature (Banjarnahor et al., 2018; Azizah et al., 2019). The total biomass is 6110.10 ton/ha, while the carbon stock generated by the green areas is 2871.74 ton/ha, the absorbed carbon dioxide is 22 403.68 ton/year, and the oxygen production is 7657.99 ton/year. The presence of tree species significantly influences carbon absorption, with a greater number of large-diameter trees resulting in a higher volume of absorbed carbon.

Industrial source

This research sampled 2 industries in the Sukorejo village and 3 industries in the Gulomantung village. These industries operate in the furniture and wood sectors. Furniture industry and wood industry A are located in Sukorejo village with coordinates

Table 4. *Aboveground biomass and carbon stock in the Sukorejo and Gulomantung villages*

No	Name of species	Density (g/cm^3)	Number of plants	Total biomass (kg/m^2)
1	*Pterocarpus indicus*	0.7426	107	192 577.06
2	*Muntingia calabura*	0.3	46	2945.01
3	*Mangifera indica*	0.5977	4	4377.87
4	*Psidium guajava*	0.6713	14	2911.63
5	*Syzygium aqueum*	0.73	6	9429.14
6	*Albizia chinensis*	0.4283	37	30 152.50
7	*Artocarpus heterophyllus*	0.5359	10	1413.16
8	*Albizia retusa*	0.4733	31	58 455.68
9	*Azadirachta indica*	0.5237	68	52 485.52
10	*Ceibata petandra*	0.3032	11	13 584.37
11	*Samanea saman*	0.5237	5	11 999.00
12	*Mallotus philippensis*	0.6836	41	31 790.52
13	*Hibiscus tiliaceus*	0.4836	79	7543.69
14	*Leucaena leucocephala*	0.6411	17	4930.84
15	*Annona muricata*	0.4	3	169.27
16	*Guazuma ulmifolia*	0.5273	15	12 951.58
17	*Tectona grandis*	0.6127	105	37 395.07
18	*Cerbera manghas*	0.5404	16	37 380.69
19	*Morinda citrifolia*	0.646	6	1933.24
20	*Melanolepis multiglandulosa*	0.385	188	66 445.49
21	*Swietenia mahagoni*	0.66	9	3759.60
22	*Broussonetia papyrifera*	0.47	4	836.21
23	*Plumeria rubra*	0.56	21	771.83
24	*Nephelium lappaceum*	0.7673	4	2431.45
25	*Ficus benjamina*	0.58	1	22 339.11
Total biomass (kg/m^2)				611 009.53
Total biomass (ton/ha)				6110.10

Table 5. *CO_2 emission from the industrial sector in Sukorejo and Gulomantung villages*

No	Industry	Fuel type	Consumption fuel	EF	CO_2 Emission (ton/year)
A	**Sukorejo village**				
1	Furniture industry	Diesel	[a]2800	[f]74.1	100.08
		Natural gas	[b]76 000	[f]56.1	149.84
		Electricity	[b]1 900 000	[g]0.725	16 530.00
2	Wood industry A	Diesel	[a]200	[f]74.1	7.15
Total					16 787.07
B	**Gulomantung village**				
3	Wood industry B	Wood/wood waste	[d]3600	[f]112	147 168.00
4	Wood industry C	Diesel	[a]5000	[f]74.1	178.72
		Electricity	[e]5530	[g]0.725	38.49
5	Wood industry D	Diesel	[a]100	[f]74.1	3.57
Total					147 388.78
Emission CO_2 Total (ton/year)					164 175.85

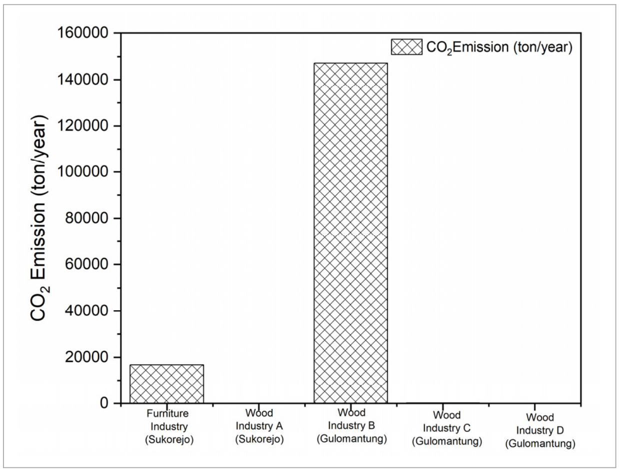
[a](L/month); [b](m^3/month); [c](kWh/month); [d](kg/day); [e](kVh/month); [f](ton CO_2/TJ); [g](kg/CO_2/kWh)

7°11’25.99”S – 112°38’4.84”E and 7°11’31.05”S – 112°38’11.52”E. While wood industry B with coordinates 7°10’53.31”S – 112°37’54.57”E, wood industry C (7°10’44.84”S – 112°37’52.31”E), and wood industry D (7°11’29.54”S – 112°37’40.64”E) are located in Gulomantung village. Wood industries A, B, C, D are undefined codes for industry names that cannot be published. Data collection in the industrial sector was carried out through interviews regarding fuel consumption and electricity usage. The interview results in Sukorejo village indicate that the furniture industry uses fuels such as diesel, natural gas, and electricity, while wood industry A uses diesel fuel for its operational needs. The interview results in Gulomantung village reveal that wood industry B utilizes wood as fuel, wood industry C uses a combination of solar and electricity as fuel sources, while wood industry D relies on diesel fuel. Wood industry C utilizes solar energy to power generators and forklifts, whereas industry D uses solar energy to power generators in case of electricity blackouts.

The calculation results indicate that CO_2 emissions from the industrial sector in Sukorejo amount to 16 787.07 tons/year, while in the village of Gulomantung, it is 147 389 tons/year (*Table 5*). The total CO_2 emissions in the villages of Sukorejo and Gulomantung amount to 164 175.85 tons/year. The largest energy consumption in the industrial sector in Sukorejo and Gulomantung is attributed to electricity usage.

Table 5 indicates that the highest CO_2 emissions in Sukorejo village originate from electricity usage in the furniture industry, totaling 16 530 tons per year. Meanwhile, the highest CO_2 emissions in Gulomantung village stem from the use of wood fuel in wood industry B, amounting to 147 168 tons per year (*Fig. 1*). Wood industry B emits more CO_2 because it uses wood fuel in its operations, which has the highest emission factor

Fig. 1. *CO_2 emission from industrial source in the Sukorejo and Gulomantung villages*



compared with other fuels. The extensive use of wood as a fuel source can exacerbate air quality (Jelonek et al., 2021). In the furniture sector, the use of wood as a fuel significantly contributes to CO_2 emissions (Peng et al., 2022). Emissions from wood have a notable impact on inflammatory effects or asthma (Junge et al., 2021).

Residential source

The calculation of total CO_2 emissions in the residential sector is obtained based on the respiration of the population, the monthly consumption of LPG, and the monthly consumption of electricity. Human respiration is an essential process in the terrestrial ecosystem carbon cycle (Cai et al., 2018). Human respiration can represent a significant source of CO_2 in urban areas depending on their population density (Cai et al., 2022). CO_2 emissions from human respiration are significantly influenced by air temperature (Li et al., 2022). The population of Sukorejo village is 1490 individuals with 436 households, while Gulomantung has a population of 3064 individuals with 853 households. Data collection for LPG and electricity usage was conducted using the random sampling method, with the determination of sampling respondents using the Slovin method (Hakim and Endangsih, 2020). The results of the Slovin calculation indicate that the sample size for the population in Sukorejo village is 81 households, and in Gulomantung, it is 90 households. *Table 6* presents the results of the CO_2 emissions calculation in Sukorejo and Gulomantung villages.

The total CO_2 emissions from residential sources in Sukorejo and Gulomantung villages amount to 1020.29 tons per year. Electricity usage contributes the most to CO_2 emissions, with 320.64 tons per year in Sukorejo and 218.72 tons per year in Gulomantung (*Fig. 2*). Research findings in the city of Pekanbaru also indicate that CO_2 emissions from electricity usage are greater when compared with LPG usage in the residential sector (Fitri et al., 2020). Emissions from electricity usage are higher compared with LPG because many people use electricity excessively on a daily basis. Therefore,

Fig. 2. *CO_2 emission from industrial source in the Sukorejo and Gulomantung villages*

Table 6. *CO_2 emission from residential source in the Sukorejo and Gulomantung villages*

No	Residential	Total	EF	CO_2 emission (ton/year)
A	**Sukorejo village**			
1	Human breathing	^{a}1490.00	^{d}68.99	102.80
2	LPG	^{b}3342.00	^{e}63 100	119.70
3	Electricity	^{b}33 652.25	^{f}0.794	320.64
		Total		543.13
B	**Gulomantung village**			
1	Human breathing	^{a}3064.00	^{d}68.99	211.39
2	LPG	^{b}1314.00	^{e}63 100	47.06
3	Electricity	^{c}22 955.00	^{f}0.794	218.72
		Total		477.16
		Total CO_2 emission (ton/year)		1020.29

^{a}(person); ^{b}(kg/month); ^{c}(kWh/month); ^{d}(kg CO_2/person.year); ^{e}(kg/Tj); ^{f}(kg/kWh) the communities of Sukorejo and Gulomantung villages need to consider implementing energy-saving technologies to reduce electricity consumption and generate fewer CO_2 emissions (Sandberg et al., 2021; Bataineh and Rabee, 2022; Gesteira et al., 2021).

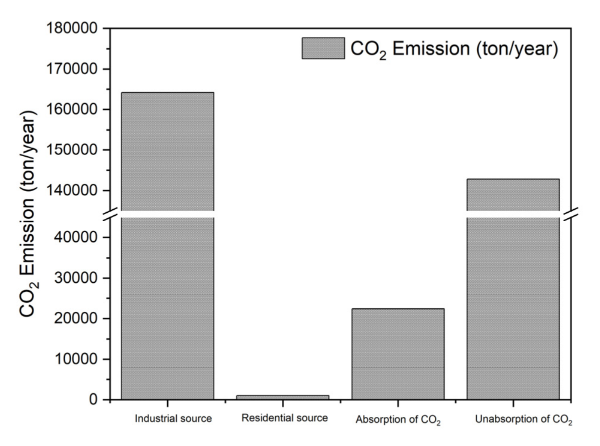
Estimation of CO_2 absorption

Essentially, plants undergo the process of photosynthesis to produce food and energy. In plants, carbohydrates derived from photosynthesis play a crucial role as primary energy sources, carbon frameworks for the synthesis of organic compounds, and energy storage materials (Trouvelot et al., 2014). Therefore, plants play a role in the absorption of carbon dioxide. As a result of this absorption, carbon dioxide is stored within the plant's body as carbon stock. The calculation results indicate that the vegetation in Sukorejo and Gulomantung villages have the capacity to absorb CO_2 emissions of 22 403.68 tons per year. The total CO_2 emissions from industrial and residential sources amount to 165 196.14 tons. Therefore, the unabsorbed CO_2 emissions by vegetation amount to 142 792.46 tons per year (*Table 7*) (*Fig. 3*). CO_2 emission absorption is low because the vegetation in Sukorejo and Gulomantung villages is limited, consisting mostly of shrubs.

Table 7. *Absorption of CO_2 emissions based on aboveground carbon stock*

Description	CO_2 emission (ton/year)
Sukorejo village	
Industrial source	16 787.07
Residential source	543.13
Gulomantung village	
Industrial source	147 388.78
Residential source	477.16
Total CO_2 emission	165 196.14
Absorption of CO_2	22 403.68
Unabsorbed CO_2 emissions	142 792.46

Fig. 3. *The balance of CO_2 absorption*



Hence, mitigation efforts are needed to reduce CO_2 emissions. The research findings of Kusuma et al. (2023) indicate that the addition of vegetation is not feasible in Sukorejo village due to land constraints. The recommendation in this research is to increase the planting of green spaces. Gulomantung village has a larger amount of vacant land compared with Sukorejo. Therefore, prioritizing additional plantations is emphasized in Gulomantung (red line on *Fig. 4*). The addition of vegetation to green open spaces is recommended with the aim of reducing unabsorbed CO_2. *Table 8* shows the ability of various plant species to absorb CO_2 emissions (Dahlan, 2007).

Fig. 4. *The plan for the location of additional plantings*

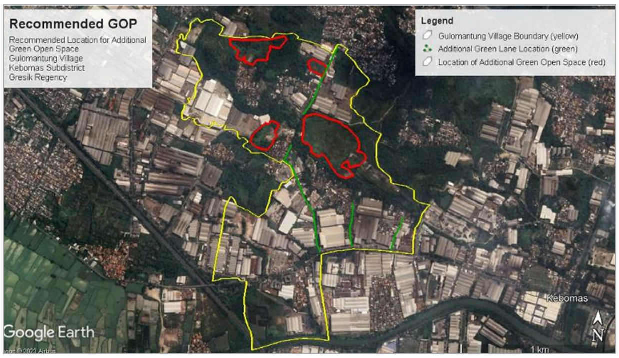


Table 8. *The ability of various plant species to absorb CO_2 emissions*

No	Name of species	CO_2 absorption (ton/plant/year)
1	*Samanea Saman*	28.49
2	*Cassia surattensis*	5.30
3	*Cananga odorata*	0.76
4	*Ficus benjamina*	0.54
5	*Filicium decipiens*	0.40
6	*Swietenia mahagoni*	0.30

The scenarios are developed by determining the minimum vegetation needed to absorb CO_2 emissions that

Table 9. *Scenario for vegetation requirements to reduce CO_2 emissions*

No	Species name	Scenario 1						Scenario 2
		(Only 1 type plant)						(A combination of 6 plants)
1	*Samanea Saman*	5012	-	-	-	-	-	835
2	*Cassia surattensis*	-	26 965	-	-	-	-	4494
3	*Cananga odorata*	-	-	188 732	-	-	-	31 455
4	*Ficus benjamina*	-	-	-	266 454	-	-	44 409
5	*Filicium decipiens*	-	-	-	-	352 722	-	58 787
6	*Swietenia mahagoni*	-	-	-	-	-	482 847	80 475

remain unabsorbed in Sukorejo and Gulomantung villages. This research recommends the addition of large shade trees. The study presents two scenarios for vegetation augmentation: Scenario 1 involves the addition of a single plant species, while Scenario 2 entails a combination of six plant species (*Table 9*). The calculation of the number of plants is based on the CO_2 absorption capacity of each plant species, multiplied by the unabsorbed CO_2 emissions as shown in *Table 7*.

The selection of plant species in each scenario is based on the prevailing climatic conditions in Indonesia. The results of Scenario 1 indicate that the minimal requirement for Trembesi (*Samanea Saman*) is the lowest compared with Mahoni (*Swietenia mahagoni*), with 5012 trees needed for Trembesi (*Samanea Saman*) and 482 847 trees required for Mahoni (*Swietenia mahagoni*). In Scenario 2, to reduce CO_2 emissions, a combination of Trembesi (*Samanea Saman*) requires 835 trees, Cassia (*Cassia surattensis*) requires 4 494 trees, Kenanga (*Cananga odorata*) requires 31 455 trees, Beringin (*Ficus benjamina*) requires 44 409 trees, Kiara Payung (*Filicium decipiens*) requires 58 787 trees, and Mahoni (*Swietenia mahagoni*) requires 80 475 trees. This study recommends scenario 2 more strongly due to the diversity of vegetation types and its aesthetic appeal. To enhance the green infrastructure in Gulomantung and take advantage of the available large vacant land, this research proposes the following actions to increase the planting of large shade trees: conduct a detailed land assessment, engage the community, and secure funding and resources.

The requirements for trees suitable for open green land potential include light exposure, water availability, soil conditions, and climatic conditions. Many trees have the ability to counteract air pollution through adaptive mechanisms. When plants are subjected to pollutants in urban settings, they exhibit various reactions in terms of respiration, photosynthesis, stomatal activity, enzymatic processes, or membrane integrity. Trees can enhance air quality by reducing pollutant concentrations through deposition effects, particularly in areas dominated by background concentrations (Grylls and Reeuwijk, 2022). A substantial increase in green open spaces significantly reduces urban air pollution levels (Afentina et al., 2022). The utilization of green spaces can lead to the establishment of green zones, offering aesthetic advantages by introducing diverse plant varieties. Nevertheless, further discussion in this study is needed regarding the considerations of adding various types of vegetation to enhance CO_2 absorption and its implications for spatial planning in Gresik City.

Conclusions

This study provides an important estimation of carbon stocks and an assessment of carbon emission sources in tropical regions, particularly in the context of industrial and residential areas. The findings reveal a significant imbalance between CO_2 emissions and absorption, with the region's aboveground biomass and carbon stocks absorbing 22 403.68 tons of CO_2 per year, while total emissions reach 165 196.14 tons/year. This discrepancy, with 142 792.46 tons/year of CO_2 remaining unabsorbed, underscores the critical role of vegetation in mitigating carbon emissions, especially in rapidly developing tropical urban areas. The results emphasize the importance of enhancing green spaces and increasing the diversity of large shade tree species to improve CO_2 absorption capacity. This is particularly relevant for tropical regions where industrial growth and urbanization are prevalent. Further research is needed to include woody necromass and litter biomass in carbon stock calculations to provide a more comprehensive understanding of carbon dynamics in similar tropical environments.

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