Analysis of Revegetation Plant Growth on Post-Mining Land as an Effort to Restore the Function of Absorbing Carbon Dioxide Emissions

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ABSTRAK

Kegiatan pertambangan dapat mengurangi sumber emisi karbondioksida melalui pembukaan lahan pertambangan, sehingga diperlukan upaya pemulihan fungsi lahan melalui reklamasi dengan revegetasi. Peningkatan lahan bervegetasi dapat membantu mitigasi perubahan iklim. Penelitian ini bertujuan untuk mengevaluasi pertumbuhan tanaman revegetasi guna mengetahui keberhasilan revegetasi. Penelitian dilaksanakan pada lahan pascatambang dengan mengamati beberapa jenis tanaman revegetasi. Parameter yang diamati meliputi tinggi, diameter batang, jumlah tanaman, tingkat kelangsungan hidup tanaman serta serapan karbon. Data dianalisis menggunakan pendekatan deskriptif. Hasil penelitian menunjukkan bahwa tingkat keberhasilan revegetasi pada lahan bekas tambang di PT X mencapai 93% dimana persentase dari pertumbuhan tanaman mencapai 93,7%, kesehatan tanaman 92,3% dan jumlah tanaman/ha sebanyak 590 tanaman. Serapan karbon yang dihasilkan adalah sebesar 10,12 ton. Keberhasilan revegetasi yang tinggi dapat meningkatkan sumber produksi oksigen dan penyerapan emisi karbondioksida sehingga dapat mengembalikan fungsi lingkungan lahan bervegetasi. Selain itu, perubahan tutupan lahan berdampak langsung pada perubahan simpanan karbon.

Kata kunci: reklamasi, revegetasi, emisi, CO_2

ABSTRACT

Mining activities can reduce carbon dioxide emissions by opening mining areas, so efforts are needed to restore land function through reclamation and revegetation. Increasing vegetated land can help mitigate climate change. This study aims to evaluate the growth of revegetation plants to determine the success of revegetation. The study was conducted on post-mining land by observing several types of revegetation plants. Observed parameters included height, stem diameter, number of plants, plant survival rate and carbon absorption. Data were analyzed using a descriptive approach. The results showed that the revegetation success rate on ex-mining land at PT X reached 93%, with plant growth at 93.7%, plant health at 92.3%, and a plant density of 590 plants/ha. The resulting carbon absorption was 10.12 tons. High revegetation success can increase oxygen production and carbon dioxide absorption, thereby restoring the environmental functions of vegetated land. In addition, changes in land cover directly affect carbon storage.

Keywords: reclamation, revegetation, emissions, CO_2

1. INTRODUCTION

Global warming occurs because too many greenhouse gases are released into the atmosphere, especially carbon dioxide (CO_2), produced from burning fossil fuels such as coal, oil, and natural gas. These greenhouse gases capture heat from the sun and raise the Earth's surface temperature, leading to significant global climate change (Dahlan, 2017).

Indonesia's rapid population and economic growth pose significant challenges to climate change mitigation (Adiputra, 2018). Population-driven anthropogenic activities have intensified land-use changes, resulting in deforestation, urban expansion, and ecosystem degradation (Al-sharif & Pradhan, 2014).

The conversion of vegetated areas into built-up land reduces green cover and emphasizes the need for monitoring strategies to maintain vegetation as a CO_2 sink (Pratiwi, 2022). Land-use change is strongly associated with climate change through carbon stock

depletion and land-cover reduction over time (Sumarlin et al., 2021). The main greenhouse gases produced by the coal industry are methane and carbon dioxide. According to experts, 40% of global CO_2 emissions are generated by the coal industry (Alyabyev et al., 2020).

Mining activities degrade land quality and accelerate land degradation. The decline in land quality on ex-mining land is related to soil fertility and chemical properties, soil texture, dryness, and waterlogging, making the land challenging to plant (Mansur, 2011). Revegetation activities are one part that determines reclamation activities. Revegetation is the replanting of ex-mining land to improve biodiversity, restore landscape aesthetics, and sustainably restore native plant communities to control erosion and surface runoff (Setiadi, 2005).

On reclaimed land, nutrient levels are low, pH is very low, and there is significant metal contamination. Therefore, revegetation activities must be carried out by selecting plants based on their survival ability. Usually, revegetation begins by selecting drought-resistant or fast-growing plants and considering land conditions (Setyowati et al., 2017). Post-mining reclamation activities must be carried out on land cleared by mining to protect the environment and address land damage (Kamarullah et al., 2025).

Post-mining reclamation activities must be carried out on land cleared by mining to protect the environment and address land damage. The implementation of mining activities must be well planned and consistently carried out to achieve the intended outcomes, given the importance of reclamation and revegetation in these activities. (Ahdyannor et al., 2021). Monitoring and evaluating the results of reclamation activities are needed to see whether a reclamation and revegetation activity method is successful (Harsono et al., 2024).

Most existing studies focus on ecological restoration outcomes without explicitly linking revegetation performance to carbon sequestration capacity. Therefore, this study addresses this gap by analysing revegetation plant growth as an initial indicator of carbon dioxide absorption potential on post-mining land, thereby providing a complementary perspective in evaluating the effectiveness of mine reclamation efforts.

According to the Minister of Forestry Regulation number P. 4/Menhut-II/2011 concerning Forest Reclamation Guidelines, evaluations must be conducted at least once a year to assess the success of reclamation activities carried out by mining companies. The activity that determines the success of reclamation is revegetation activities. Therefore, the study aims to evaluate the growth of revegetation plants to determine the success of revegetation.

2. RESEARCH METHODOLOGY
2.1. Research site
The research was conducate at PT X, South Sumatera. This research is located in a reclamation area with a planting year 2022 total area of 5.3 Ha.
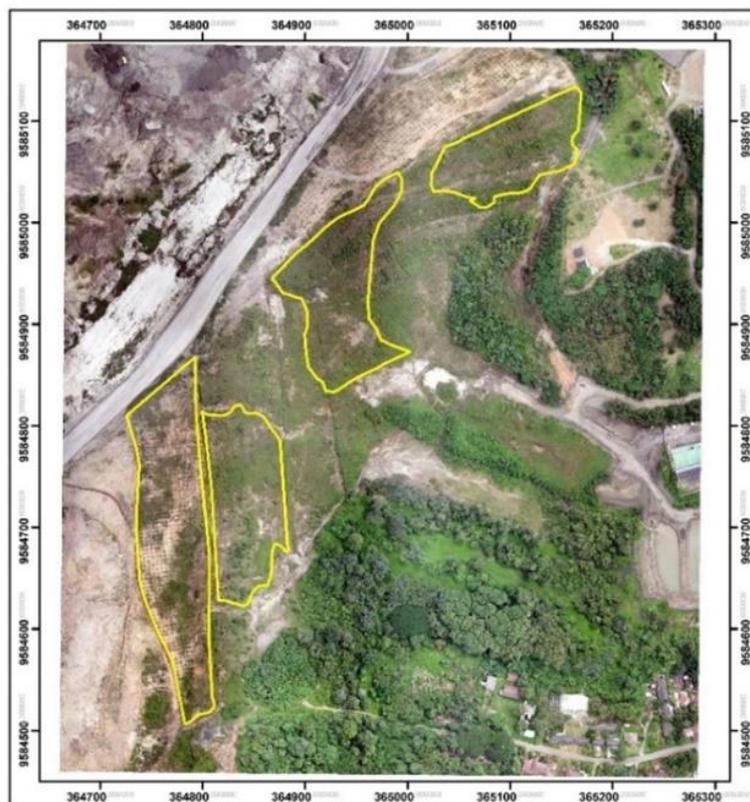

Figure 1. Map of Research

2.2. Method of Collecting Data

Before collecting data, field observations must be conducted; the aim is to obtain an overview of the research site, the plants to be measured, the land condition, and so on. In this research, data was collected through sampling. Sampling used the plot method. Sample plots were determined using the Systematic Sampling with Random Start (SSRS) method with a sampling intensity of 5% (Minister of Forestry of the Republic of Indonesia, 2009), and plots were measured at 40 x 25 m (0,1 ha). According to the regulations, Systematic Sampling with a Random Start is a method in which the first sample is selected randomly. A measuring plot measuring 40 x 25 m uses a plastic rope. The sampling method resulted in 4 plots from the total revegetation area at the 2022 planting year location (5,3 Ha), each assigned a unique ID.

2.3. Data Analysis

Data analysis for plant growth on reclaimed land includes plant type, height and diameter, number of plants, and plant health. This data will be analyzed statistically descriptively using the following formula (Rusdiana & Setiadi 2019). This study uses a descriptive approach because it does not use inferential statistical tests.

2.3.1. Stem Diameter and Plant Height

The equation for calculating the average diameter and height of a plant is as follows:

$$d = \sum_{i}^{n} \frac{di}{n}$$

$$t = \sum_{i}^{n} \frac{ti}{n}$$

d = average stem diameter (cm)
t = average height (cm)
di = diameter of the ith tree
ti = height of the ith tree
n = number of trees measured

2.3.2. Plant Growth Percentage

$$T = \frac{\sum hi}{\sum Ni} \times 100\%$$

T : percent plant growth (%)
ni : number of plants living in plot i
Ni : the number of plants that should be in the i plot

The average percentage of plant growth is calculated using the formula below:

$$R = \sum_{i=1}^{n} \frac{Ti}{n}$$

R : average percentage of plant growth
Ti : percentage of plant growth in plot i
n : number of plots

2.3.3. Number of Plants Per Hectare

The number of plants per hectare is calculated using the formula below:

Number of plants per hectare =
    (Land area)/(planting distance)

Number of plants per measuring plot =
    (Area of measuring plot)/(planting distance)

2.3.4. Plant Health

The percentage of plant health will be calculated using the formula below:

$$K = \frac{ns}{nh} \times 100\%$$

K : Percentage of Plant Health (%)
ns : Number of healthy plants
nh : Number of living plants

2.3.5. Recapitulation of Assessment Results

Recapitulation of assessment results is calculated using the formula below:

$$TN = \frac{TS1+TS2+TS3}{SM1+SM2+SM3}$$

TN : Total Value
TS1 : Total score for the criteria for plant growth percentage
TS2 : Total score for the assessment criteria for the number of plants per hectare
TS3 : Total score for assessing plant health criteria
SM1 : Maximum value of plant growth percentage criteria
SM2 : Maximum value of the criteria for the number of plants per hectare
SM3 : Maximum value of plant health criteria

Standardization of the Success of Revegetation Activities. Guidelines for successful revegetation are listed in the Minister of Forestry Regulation No. P60 of 2009, where the criteria for revegetation or tree planting are listed in Pasal 4, paragraph (2) letter c, namely as follows:

1. Size of planting area
   The planting area for reclamation activities was obtained from the team's measurement results report, then mapped and compared with the planting plan..

2. Percentage of plant growth
   The percentage of plant growth in each measuring plot is calculated by comparing the number of existing plants with the planned number for that plot.

Table 1. Realized Value of Planting Area and Percentage of Plant Growth

Realization	Value
≥ 90%	5
80 % - 89 %	4
70 % - 79 %	3
60 % - 69 %	2
< 60 %	1

Source: Permenhut No. P 60 tahun 2009

3. Number of plants per hectare
   The number of plants per hectare is determined with a maximum planting distance of 4 x 4 m, so that the number of trees per hectare is at least 625.

Table 2. Realized Value of Number of Plant Per Hectare

Realization	Value
≥ 625	5
551 – 624	4
476 – 550	3
400 – 475	2
< 400	1

Source: Permenhut No. P 60 tahun 2009

4. Composition of plant species
Usually, revegetation activities are carried out first with fast-growing species, but then enrichment is needed with local long-cycle species.

Table 3. Value Composition of Long-Cycle Plant Species

Composition	Value
≥ 40 %	5
30 % - 39 %	4
20 % - 29 %	3
10 % - 19 %	2
< 10 %	1

5. Plant health
When calculating plant growth, attention to their growth or health conditions is also necessary. Observations on plant growth are divided into 3 (three categories: healthy plants, plants that grow fresh and have relatively straight stems, dense crowns with a minimum height according to standards, and are free from pests and diseases/weeds. Unhealthy plants are plants that grow abnormally or are attacked by pests, with yellow or abnormally colored leaves and bent stems; miserable plants are plants that grow abnormally or are attacked by pests and diseases, so that, if they are maintained, there is little chance they will grow well.

Table 4. Percentage Value of Plant Health

Realization	Value
≥ 90%	5
80 % - 89 %	4
70 % - 79 %	3
60 % - 69 %	2
< 60 %	1

In Pasal 15, based on the criteria and indicators for the level of success of forest reclamation as intended in Pasal 14, the total evaluation value is calculated using the following formula:

$$TN = \sum_{i=1} [TS_i/SM_i \times B_i]$$

TN : Total value
TS i : Total score for assessment criteria i
SM i : Maximum value of criterion i
n : Number of criteria
B i : Weight for criterion i (The maximum total score is 100)

Based on the calculation of the total value as intended in Pasal 23, the following criteria and conclusions will be obtained:

1. Total score > 80: Good (reclamation implementation results are acceptable).
2. Total score 60 – 80: Medium (the results of the reclamation implementation are accepted with a note that improvements need to be made until it reaches a value > 80).
3. Total score < 60: Bad (reclamation results are unacceptable, and intensive maintenance is required).

2.3.6. Carbon dioxide Absorption
1) Carbon Stock Estimation
a. Biomass calculation
The allometric equation used is (Kettrings et al., 2001):

$$Y = 0{,}11 \times \rho \times DBH^{2.62}$$

info:
Y : Total biomass (kg)
P : Wood density (gr/cm3)
dbh : Diameter/height data (cm)

b. Carbon stock
The amount of carbon stored is calculated assuming that the carbon content is half of the biomass according to the IPCC (2001) as follows:

$$C = 0.5 \times W$$

info:
C : Carbon stock (tons)
0.5 : Carbon content
W : Total biomass (kg)

2) Carbon dioxide Absorption Calculation
Carbon dioxide absorption analysis is calculated using carbon stock data.

$$CO_2 = C \times 3.67$$

info:
CO_2 : CO_2 uptake (tCO_2)
C : Carbon stock (tons)
3.67 : Atomic ratio of carbon dioxide to carbon = 44/12 (tCO_2/ton C)

3. RESULT AND DISCUSSION
Based on the Minister of Forestry Regulation No. P60 of 2009, The success of plant life is determined by five aspects: the planting area's size, the percentage of plant growth, the number of plants per hectare, the composition of plant types, and plant health. This research used three criteria for successful plant growth: plant growth percentage, number of plants per hectare, and plant health.

3.1. Plant Growth
The plant growth observed in this research measured plant height and diameter in the revegetation area of PT X for planting year 2022. The results of observations conducted at the research site were divided into four plots (Figure 2).
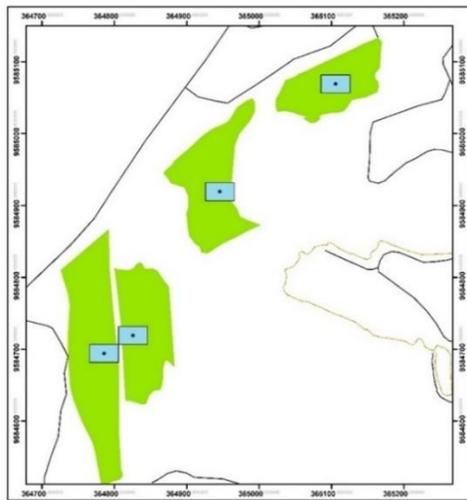
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Figure 2. Scatter Plot Measure

The research results showed that the plants in the revegetation area of PT X, consisting of Angsana (Pterocarpus indicius), Sengon Buto (*Entorolobium cyclocarpum*), and Johar (*Cassia siamea*), where the ones with the best growth are the plants in the fourth plot, namely Angsana plants with an average plant height of 224 cm. In comparison, the average diameter is 5 cm. This research found that plot 1 contained four plant types: Angsana, Sengon Buto, and Johar. In plots 2 and 3, 1 plant type, namely Angsana, was found. Meanwhile, in plot 4, there are two plant types: Angsana and Sengon Buto. To see the plant types per plot, see Table 5.

Table 5. Plant Types Per Plot

Measuring plot	Local Names of Plants	Plant Scientific Name	Number of Plants Planted
1	Angsana	*Pterocarpus indicius*	29
	Sengon Buto	*Entorolobium cyclocarpum*	22
	Johar	*Cassia siamea*	12
2	Angsana	*Pterocarpus indicius*	63
3	Angsana	*Pterocarpus indicius*	63
4	Angsana	*Pterocarpus indicius*	32
	Sengon Buto	*Entorolobium cyclocarpum*	31

Angsana plants can be planted at the start of planting activities because they grow quickly. Plants that overgrow on mine-revegetation land play an essential role in accelerating the formation of a microclimate and improving soil conditions, enabling revegetation to proceed smoothly. The effect is on the speed of the vegetation succession process because it creates conditions that can cause plants or other vegetation types to enter and grow (Badan for Standardization of Environmental and Forestry Instruments, 2022). Tree trunk diameter is the factor that makes the greatest contribution to the amount of carbon reserves in a stand, compared with the tree density factor (Irsyadi & Novemnbrianto, 2025).

Table 6. Average Growth Identification of Plant Height, Diameter, And Crown

Plot	Type of plant	Diameter (cm)	High (cm)	Crown (cm)
1	Angsana	4	131	105
	Sengon Buto	4	139	128
	Johar	3	113	98
2	Angsana	3	141	120
3	Angsana	4	198	160
4	Angsana	5	224	151
	Sengon Buto	4	155	95

It is thought that the growth of each plot differs due to differences in environmental conditions. According to Sopandie (2013), plant growth can be influenced by several factors, including environmental factors (biotic and abiotic) and climate (such as weather); some plants are susceptible to humidity and temperature.

Table 7 shows that the highest plant growth percentage is in plot 3 (98,4%) and the lowest in plot 4 (85,7%). The low plant growth is due to plant deaths, but no replanting or replacements are carried out, resulting in a low overall growth rate.

Table 7. Average Percentage of Plant Growth in the PT X Mine Revegetation Area Planting 2022

Plot	Plot area	Plant Spacing	Trees Planted	Trees grow	Growth Percentage (%)
1	1000 m	4 x 4 m	63	59	93,7 %
2	1000 m	4 x 4 m	63	61	96,8 %
3	1000 m	4 x 4 m	63	62	98,4 %
4	1000 m	4 x 4 m	63	54	85,7 %
Average					93,7 %
Value					5

The company planted the primary plants to revegetate the mine reclamation area, aiming to create a sustainable ecosystem. The main plant types are usually annual plants from the fast-growing species group and/or pioneer trees that can generally grow in open areas. Mining area reclamation activities by mining companies can be carried out by planting pioneer trees to restore the ecosystem and its structure (Aipassa & Hasan, 2020; Ge et al., 2010).

3.2. Number of Plants Per Hectare
The number of plants per hectare is 625, with a maximum planting distance of 4 x 4 m, as per Minister of Forestry Regulation No. 60/Menhut-II/2009. The research shows a minimum of 63 plants per measuring plot, with an area of 0,1 ha (40 x 25 m) and a 4 x 4 m spacing. To get the number of plants per hectare, the number of plants per plot obtained in the field is converted to hectares by multiplying it by 10.

Table 8. Number of Plants Per Plot

Planting Year	Plot	Plant type	Number of plants planted	Number of living plants	Total	Total (number/ha)
2022	1	Angsana	29	27	59	590
		Sengon Buto	22	20		
		Johar	12	12		
	2	Angsana	63	61	61	610
	3	Angsana	63	62	62	620
	4	Angsana	32	27	54	540
		Sengon Buto	31	27		
Average						590
Value						4

The table above shows that the number of plants per hectare in ID 1 is 590, ID 2 is 610, ID 3 is 620, and ID 4 is 540. The average number of plants per hectare is 590 plants. The number of plants per hectare obtained has not yet reached 625, so it is still categorized as good but not perfect, according to the Minister of Forestry Regulation No. P60/2009. The number of plants per hectare did not meet the target because many died, and no replanting or replacement of dead plants was carried out.

3.3. Plant Health

Field observations showed that the health percentage in plot 1 was 86,4%. In Plot 2, the health percentage is 93,4%. In Plot 3, the plant health percentage was 96,8%. In plot 4, the plant health percentage was 92,6%. The average health percentage across the four plots was obtained by dividing the total percentage across all plots by the total number of plots. In this observation, the average plant health percentage was 92,3%. With plant health at 92.3%, it can be categorized as in the PT X mine revegetation area. The planting year 2022 has good plant health.

Based on Table 9, of the total number of plants, 218 were healthy, 17 were less healthy, and 1 was miserable. The causes of unhealthy plants include abnormal growth, disease or pest attacks, and yellow or abnormally colored, bent leaves (Figure 3). Meanwhile, miserable plants grow abnormally, are attacked by disease pests, are stunted, have no leaves, and have no stems. Typically, if maintained, it will have little chance of growing well.

Table 9. Average Percentage of Plant Health in the Revegetation Area of PT X Area Planting 2022

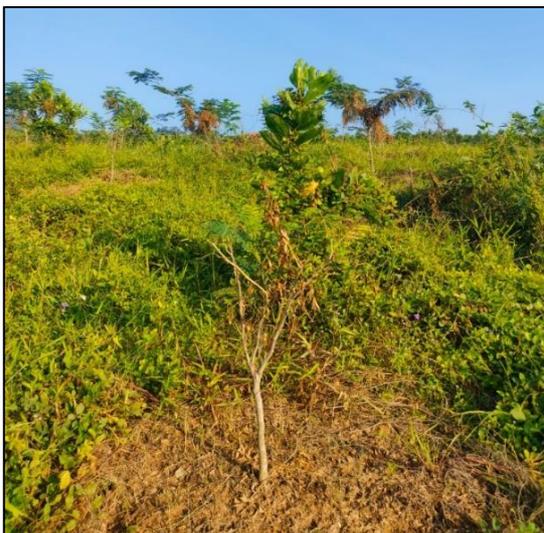| Plot	Type of Plant	Number of Live Plants	Number of Health Plants	Percentage of Plant Health (%)
1	Angsana Sengon Buto Johar	59	51	86,4 %
2	Angsana	61	57	93,4 %
3	Angsana	62	60	96,8 %
4	Angsana Sengon Buto	54	50	92,6 %
	Avareage			92,3 %
	Value			5

Figure 3A. Unhealthy Plants

Figure 3B. Plants Languish

3.4. Plant Survival Rate

The final assessment was conducted to determine the plants' survival rate in the revegetation area of PT X, Planting year 2022. Based on the Minister of Forestry Regulation No. P60/Menhut-II/2009 is based on the percentage of plant growth, number of plants per hectare, and percentage of plant health. The assessment is carried out by clustering the measuring plots used in the revegetation area for the 2022 planting year, so that the evaluation of the measuring plot units reflects the actual condition of the revegetation plants on the reclaimed land.

Table 10. Recapitulation of Plant Life Success Rates

Planting year 2022			
Category	Value	Score	Level of success (%)
Plant growth (%)	93,7 %	5	
Number of plants per hectare	590	4	**93 %**
Plant health (%)	92,3%	5	

The revegetation plant growth success rate on ex-mining land at the PT X in 2022 reached 93%. The successful growth of these plants can return the former mining land to its productive function, producing oxygen and absorbing carbon dioxide. During mining activities, vegetated land has been removed, so CO_2 is not absorbed by plants and is released directly into the atmosphere, potentially increasing greenhouse gas levels and exacerbating global warming. Therefore, urgent efforts are needed to restore land function through revegetation or reforestation.

3.5. Absorption of CO_2 Emissions

The resulting carbon uptake was 10,12 tons. This absorption is relatively low due to the trees' small diameter (Table 11).

Table 11. Absorption Emissions

Plot	Type of plant	Ø (Cm)	Biomass (kg)	Kg to Ton	Carbon (Ton)	Carbon Absorb (ton)
1	Angsana	4	72,96	0,73	0,36	1,34
	Sengon Buto	4	36,58	0,37	0,18	0,67
2	Johar	3	16,43	0,16	0,08	0,30
3	Angsana	3	77,57	0,78	0,39	1,42
	Angsana	4	167,53	1,68	0,84	3,07
4	Angsana	5	130,91	1,31	0,65	2,40
	Sengon Buto	4	49,39	0,49	0,25	0,91
Total						10,12

The amount of carbon reserves is influenced by several variables, including biodiversity and vegetation density (KD et al., 2024). Of all these factors, tree trunk diameter contributes most significantly to increasing carbon reserves compared to density (Irsyadi & Novembrianto, 2025). Plant age and diameter influence the amount of carbon reserves, so the success of revegetation in the reclamation area dramatically affects environmental restoration, which functions as an oxygen producer and a CO_2 absorber. Research by Ahirwal & Maiti (2017) states that post-mining land reclamation with revegetation increases total carbon stock and CO_2 sequestration potential as revegetation ages. Misebo et al., (2022) stated that vegetation growth contributes to carbon accumulation in both biomass and soil.

Post-mining land tends to have an acidic pH and is nutrient-poor. Successful revegetation can restore and even improve soil chemistry and increase biodiversity. With revegetation, carbon reserves can be increased and land fertility restored. Syaufina & Ikhsan (2013) indicate that mining companies indirectly increase carbon reserves through post-mining land reclamation activities. Post-mining reclamation, including land revegetation, can improve the condition of land damaged by mining activities. The quality of plant growth is an indicator of the success of reclamation. The higher the success of revegetation, the greater the potential for the presence of carbon dioxide emission absorbers on the post-mining land.

The role of revegetating ex-mining land is very important because it can create a microclimate, provide oxygen, and serve as a CO_2 absorber. The presence of mining land eliminates vegetated land, resulting in the loss of sources of emission absorption. According to Hanoe (2022), in addition to emissions from burning, mining also produces emissions from clearing land for mining, due to the loss of vegetated land cover. Vegetated land functions to absorb carbon dioxide emissions, produce oxygen, and maintain water quality. So revegetation is needed on ex-mining land to restore land function.

Post-mining land reclamation and revegetation activities play an important role in restoring vegetation, degraded land, and controlling climate change, as CO_2 is removed from the atmosphere due to the impact of mining activities (Farosandi et al., 2024). Successful mine reclamation and the advancement of green and climate-friendly mining practices are key to this (Chen et al., 2023).

Coal mining activities regularly disturb the ecosystem and significantly affect the regional carbon pool and carbon storage function (Wang et al., 2026). Land reclamation is an important step to reduce the environmental impact of coal mining, can restore land use functions, improve the ecological environment, and increase carbon storage capacity (Zhanjun et al., 2012; Hodačová & Prach, 2003).

4. CONCLUSION

Successful revegetation is crucial for the environment because mining activities remove vegetated land that absorbs carbon dioxide and produces oxygen. The higher the success rate, the greater the likelihood of restoring its function to its original state. PT X's revegetation success rate of 93% resulted in 10,12 tons of carbon sequestration and is expected to restore its function.

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