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Land reclamation strategy of former coal mine in kutai kartanegara regency, East Kalimantan Province

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Abstract This study analyzes reclamation strategies for former coal mine land in Kutai Kartanegara Regency, East Kalimantan, Indonesia, using a comprehensive approach that integrates the analysis of post-mining soil physical and chemical characteristics with stakeholder assessments. The study was conducted in two sub-districts with the largest coal mining activities, namely Loa Janan and Loa Kulu, covering a total mining area of 2,117 hectares. The results show significant environmental degradation, with soil fertility status in the former mining area categorized as low to very low, characterized by low Cation Exchange Capacity (CEC), Base Saturation (BS), P_2O_5, and C-Organic. Water quality analysis showed parameters such as Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) exceeded quality standards, indicating serious water pollution. The study uses the Interpretive Structural Modeling (ISM) method to identify main barriers to reclamation and the Analytical Hierarchy Process (AHP) method to prioritize strategies for addressing these barriers. The ISM analysis revealed that land degradation and weak law enforcement were the main drivers of reclamation problems with high driving power and low dependence. The AHP analysis identified achieving reclamation targets (0.172), using organic fertilizers (0.114), and implementing monitoring and evaluation (0.106) as the top three priority strategies, followed by law enforcement (0.096) and planting endemic plants (0.095). This study concludes that an integrated approach combining technical, financial, regulatory, and social aspects is essential for the successful reclamation of former mining land in Kutai Kartanegara, emphasizing clear reclamation targets, soil quality improvement, an effective monitoring system, supported by comprehensive law enforcement and local community engagement.

Keywords: reclamation, land, strategy, ISM, AHP

1. Introduction

Coal mining in East Kalimantan, Indonesia, plays a complex dual role in national development. On the one hand, the sector contributes significantly to regional GDP and national income, particularly through coal exports, which account for a significant portion of Indonesia's GDP and non-tax state revenue (Astuty & Trilaksana, 2024). On the other hand, the environmental impacts caused by coal mining are substantial, affecting soil, water, and air quality, and causing public health issues (Handono et al., 2024; Mahroini & Chien, 2024). This situation, as noted by several researchers (Indrayati, 2023; Kirsanov et al., 2023), requires a balanced approach to harness economic potential while minimizing its environmental impact.

Recent studies indicate that mining activities have contributed significantly to land degradation, ecosystem disruption, and environmental damage on both local and regional scales (Ojonimi et al., 2021; Efendi et al., 2023; Rahman et al., 2022). The environmental impact of coal mining in East Kalimantan is substantial and widespread, especially in the immediate mining locations, affecting soil quality, water resources, and biodiversity (Woodbury et al., 2020). Mining activities cause significant water pollution, mainly through runoff containing hazardous chemicals, which damages aquatic ecosystems and poses health risks to local communities (Hasii & Gasii, 2024).

In terms of soil and biodiversity impacts, mining activities have disrupted soil quality, caused erosion, and led to the loss of vegetation, which in turn affects local biodiversity. The reduction in vegetation cover in wetland areas is linked to increased human activity from mining, and habitat destruction threatens protected species while reducing ecological balance in the region (As et al., 2025). Furthermore, environmental pollution from mining has been associated with increased morbidity and mortality rates in surrounding communities, highlighting the urgent need for improved environmental management and public health policies (Handono et al., 2024).

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Studies show that mining activities cause long-term changes in soil structure, hydrological patterns, and ecosystem functions (Fugiel et al., 2017). Mining disturbances alter the structure of microbial communities, with significant differences between reclaimed grassland areas and surrounding environments (Ma et al., 2023). Mining residues can accumulate, changing soil biochemistry and hindering microbial activity, which is crucial for nutrient cycling (Martínez-Toledo et al., 2023). Despite the clear negative impacts of coal mining, some argue that mining operations contribute significantly to the local economy by providing jobs and infrastructure development, but these economic benefits must be weighed against the long-term environmental and health costs associated with mining activities (Nasir, 2023).

Post-mining land reclamation in Indonesia has undergone significant evolution, shifting from simple revegetation to a comprehensive and integrated ecosystem restoration approach, emphasizing the integration of biophysical and socio-economic factors (Woźniak & Jurczyk, 2020). In the context of integrated ecosystem restoration, contemporary research advocates for reclamation that combines ecological and local social contexts, ensuring that restoration efforts are tailored to specific environmental conditions (Gusman et al., 2024). Biodiversity aspects are a primary focus, as indicated by the need for ecological justice in reclamation policies, which currently lack an adequate framework (Wicaksono & Rahmawati, 2024). In terms of technological innovation, the adoption of green mining practices has shown positive impacts on ecosystem stability and mining productivity, highlighting the benefits of sustainable approaches (Hisyam et al., 2024).

The regulatory framework for mining in Indonesia, specifically Law No. 4 of 2009 on Mineral and Coal Mining, has established the legal foundation requiring mining companies to develop detailed reclamation plans to reduce environmental impacts (Haryadi et al., 2023). As an enforcement measure, the Ministry of Energy and Mineral Resources has established regulations that include criminal sanctions for companies failing to comply with reclamation obligations (Wartiningsih & Nuswardani, 2023). At the regional level, East Kalimantan has developed regulations that specifically advocate for the integration of local wisdom into reclamation efforts, promoting community involvement and sustainable practices (Gastramat et al., 2024). Recent studies emphasize the importance of balancing ecological justice with reclamation practices, suggesting that regulations must consider non-human entities in their framework to achieve truly sustainable outcomes (Wicaksono & Rahmawati, 2024).

Recent environmental assessments in Kutai Kartanegara have highlighted the limitations of conventional reclamation methods in addressing the complexity of post-mining tropical ecosystems. In the context of ecological challenges, post-mining areas often face serious issues such as low pH, high metal concentrations, and reduced organic matter, which significantly complicate reclamation efforts (Asnawi et al., 2023). Social aspects are also a crucial consideration, given that communities in East Kalimantan heavily rely on environmental services, making their involvement vital for the success of sustainable reclamation (Kristanti et al., 2019). Given the complexity of reclamation challenges in Kutai Kartanegara and the urgent need for effective strategies, this study aims to develop a comprehensive and sustainable reclamation strategy for former coal mining land by integrating post-mining soil physical and chemical characteristics analysis with stakeholder assessments using the Analytical Hierarchy Process (AHP).

2. Materials and Methods

2.1. Characteristics and Selection of Study Area

This study was conducted in Kutai Kartanegara Regency, East Kalimantan Province. The research area includes two sub-districts, Loa Janan and Loa Kulu, which are home to the largest coal mining operations. In Loa Kulu, coal mining is carried out in Bakungan Village, while in Loa Janan, mining activities take place in Jembayang Village and Sungai Payang Village. The total coal mining area in both locations is 2,117 hectares. The topography of the study area is mostly undulating to hilly, with slopes varying from gentle to steep. The USDA Soil Taxonomy classifies soils into five groups: Ultisol, Entisol, Histosol, Inceptisol, and Mollisol. The Bogor Soil Research Institute further categorizes the soils in the study area into four types: Podzol, Alluvial, Andosol, and Regosol. This region experiences annual rainfall ranging from 2,000 to 4,000 mm and an average temperature of 26°C. Demographically, the population growth rate is high, at 3.92% per year, with a population density of 25 people/km^2. The mining sector contributes significantly to the Gross Regional Domestic Product (GRDP), accounting for 83.84% of the total economic output of the region. The location of the study area can be seen in Figure 1.

2.2. Data Analysis Technique

The Data Analysis technique used to determine the physical and chemical characteristics of post-coal mining soil was through laboratory testing. The analysis steps began with the selection of sample points, which were deliberately chosen at four observation points. Sample collection was carried out at each observation point, where soil samples were collected from a depth of 0 to 30 cm using the composite method. Specifically, the team collected soil samples from four directions (north, south, east, and west) with an interval of approximately 1 meter. The samples were then thoroughly mixed to form a composite, and about 1 kg of composite sample was stored. The final step involved laboratory analysis, where five composite soil samples were analyzed to determine their physical and chemical properties.

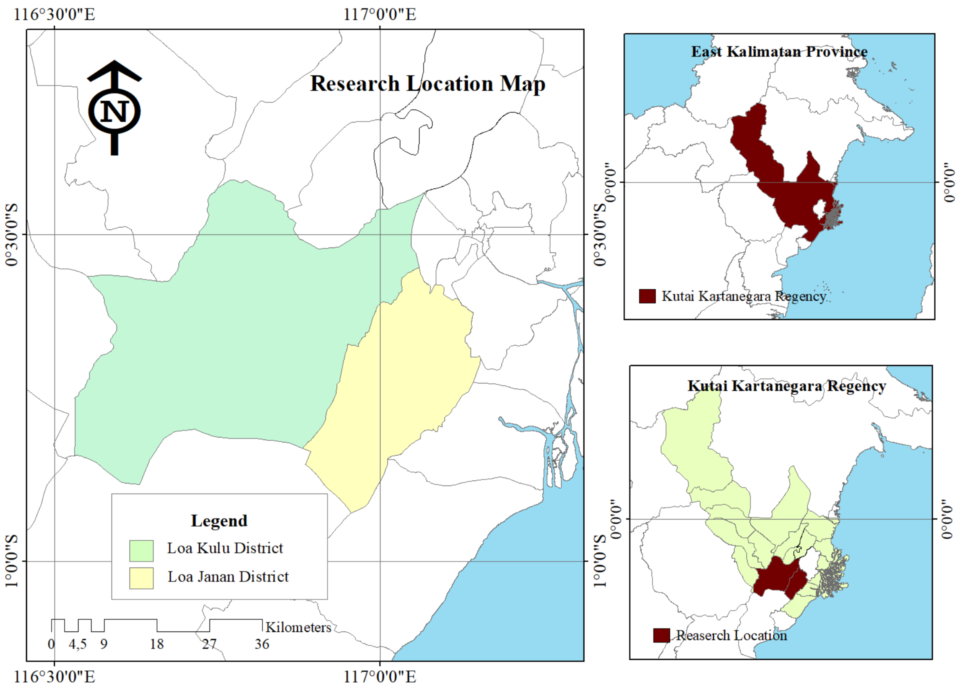

Figure 1 Research Location Map.

Soil physical properties were evaluated using laboratory data and compared with the USDA (United States Department of Agriculture) soil texture classification criteria. We assessed chemical properties and compared them with the soil fertility evaluation criteria established by the Soil Research Center, Bogor, in 1983. The team analyzed the physical characteristics of post-mining land based on the percentage of soil texture. Soil texture classification was determined using the hydrometer method. The procedure involved the following steps.

Next, to determine the reclamation strategy for post-mining land in the study area based on expert opinions, this study uses the Analytical Hierarchy Process (AHP) method. The assessment criteria in AHP can be seen in Table 2 and the Coal Mine Reclamation Strategy Hierarchy can be seen in Figure 3. The experts will provide assessments based on pairwise comparisons using a scale of 1 to 9. The experts' opinions are presented on a scale of 1 to 9 (Saaty Scale, 2013), as shown in Table 1.

The experts involved come from various fields, including the Environmental Agency of Kutai Kartanegara Regency, higher education institutions, community leaders, Non-Governmental Organizations (NGOs), religious leaders, and the Regional Development Planning Agency (Bappeda) of Kutai Kartanegara Regency. The total number of experts is 15. The analysis was carried out using Expert Choice 2011 software. The acceptable consistency ratio (CR) value is less than 0.1 (Umar et al., 2017). The hierarchy of coal mine reclamation strategies is presented in Figure 2.

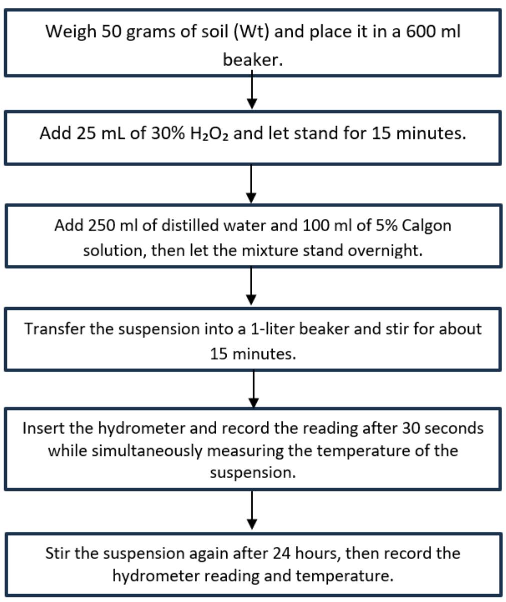

Figure 2 Steps for analyzing soil texture using the hydrometer method.

Table 1 Criteria for soil fertility based on physical and chemical soil propertiesh.

Test Parameters	Units	Index				
		Very Low	Low	Medium	High	Very High
Physical Properties						
Solum / Effective Depth	cm	<15	15-20	20 - 25	25 - 35	>35
Permeability (cm/hour)	cm/hour	< 0.5	0.5 - 2.0	2.0 - 6.25	6.25-12.5	>12.5
Aggregate Stability (%)	%	<0.5	0.5-1.5	1.5-2.5	2.5-3.5	>3.5
Soil Drainage		Poor	Slightly Poor	Moderate	Fair	Good
Texture		P	PL	LP	Lib, LiP, L, D, LD, LLiP	Li, LliD, Lli, LiD
Chemical Properties						
pH		< 4.0	4.0 - 5.0	5.1 -5.9 & 8.0 - 8.5	6.0 - 6.5 & 7.5 - 8.0	6.6 - 7.5
Cation Exchange Capacity (CEC)	me 100 g^{1}	< 5	5 - 16	17 - 24	25 - 40	>40
Organic Carbon	%	< 1	1 - 2	2 - 3	3 - 5	>5
N-total	%	< 0.10	0.1 - 0.2	0.21-0.5	0.51-0.75	>0.75
P-total	ppm	<4	5 - 7	8 - 10	11 - 15	>15
K-total	me 100 g^{1}	< 0.1	0.1 - 0.2	0.3 - 0.5	0.6 - 1.0	>1.0
Base Saturation	%	< 20	20 - 35	36 - 50	51 - 70	>70

Source: LPPT Bogor (1983). Notes: Li (Clay), Lib (Heavy Clay), D (Dust), P (Sand), L (Loam), LiD (Dusty Clay), LiP (Sandy Clay), LLi (Clay Loam), LD (Dusty Loam), LP (Sandy Loam), LliD (Clay-Dusty Loam), LliP (Sandy-Clay Loam), PL (Sandy Loam-Sand)

Table 2 Assessment criteria in AHP.

Value	Description
1	A is as important as B
3	A is slightly more important than B
5	A is much more important than B
7	A is much more important than B
9	A is clearly more important than B
2,4,6,8	When unsure between two closely related values

Source: Saaty (1983); Marimin and Maghfiroh (2010).

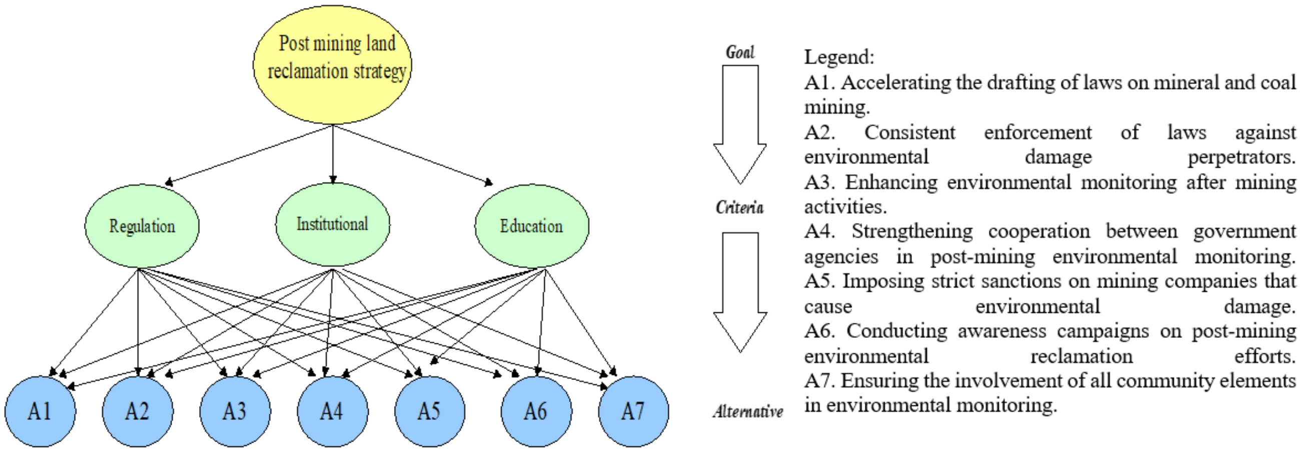

Figure 3 Coal Mine Reclamation Strategy Hierarchy.

3. Results and Discussion

3.1. Condition of Former Mine Land

The research results show that the land of PT. BKS's former mining area has experienced a significant decline in quality. Based on the analysis, the soil in the former mining area has Cation Exchange Capacity (CEC), Base Saturation (BS), P_2O_5, K_2O, and C-Organic that are categorized as low to very low. For example, CEC ranges from 14.51-15.49 me/100g, and C-Organic only reaches 1.49%. For a more detailed view of the soil fertility status in the research area, please refer to Table 3 below.

Based on the data in Table 3, it can be seen that the soil fertility status in the research area is categorized as low, particularly for the parameters of CEC, BS, and nutrient content such as P_2O_5 and K_2O. The soil fertility status in the former mining land of PT. BKS indicates a concerning condition, with the majority of fertility parameters falling into the low to very low categories. In highly degraded soils, potassium (K) availability is often low, affecting cation balance and crop yields (Firmano et al., 2020). The low CEC values (14.51-15.49 me/100g) in the mining PIT area indicate the soil's limited ability to retain and exchange essential nutrients for plant growth (Rodríguez-Vila et al., 2017; Arifin et al., 2018). The low to very low Base

Saturation (BS) values (16.20-21.29%) indicate limited exchangeable bases and the low availability of exchangeable bases in the soil, which are crucial for plant nutrition (Rosenstock et al., 2019). This situation is further worsened by the very low P_2O_5 content (2.48-4.82 ppm) in the mining PIT area, indicating phosphorus deficiency that can inhibit plant growth.

Table 3 Soil fertility status in the study area.

No.	Location	CEC (me/100g)	KB (%)	P_2O_5 (ppm)	K_2O (ppm)	C-Organic (%)	Status
1	Mine PIT Area	14,51-15,49 (R)	21,29-16,20 (R-SR)	4,82-2,48 (SR)	48,50-27,19 (T-S)	1,49-0,95 (R-SR)	Low
2	Mine Road outside the Mine PIT	10,44-9,61 (R)	18,01-14,78 (R)	6,73-5,88 (R)	30,37-30,37 (S)	1,45-0,83 (R-SR)	Low
3	Stock pile 1	46,50-35,34 (ST-T)	11,29-6,25 (R)	2,63-4,18 (SR)	61,84-46,24 (ST-T)	2,76-0,86 (S-SR)	Low
4	Stock pile 2	32,55-26,04 (T)	15,24-20,31 (SR-R)	4,95-12,69 (SR-S)	42,93-50,67 (T)	1,80-0,83 (R-SR)	Low

The exchangeable base cation pool is crucial for maintaining plant growth, and neglecting non-exchangeable nutrient pools can lead to misinterpretation of soil fertility (Rosenstock et al., 2019). Interestingly, the K_2O content shows variation from moderate to high (27.19-48.50 ppm) in different observation locations, particularly in the stockpile area, which reaches a very high status (61.84 ppm). The low to very low C-organic content (0.95-1.49%) indicates a lack of organic matter in the soil. The phenomenon of higher CEC values (35.34-46.50 me/100g) observed in the stockpile area, despite low base saturation (BS), suggests a complex interaction between soil nutrient retention and availability. This situation indicates that although the soil has better nutrient retention capacity, the availability of exchangeable bases remains low, reflecting the challenges in soil management, especially in reclaimed mining areas. Higher CEC values indicate an improved nutrient retention capacity in stockpiled soils (Ledesma et al., 2025).

Low base cations indicate that although nutrients are present, they are unavailable for plant absorption, which can hinder vegetation establishment (Gupta et al., 2019). Long-term stockpiling can lead to anaerobic conditions, affecting soil health and nutrient dynamics (Abdul-Kareem & McRae, 1984). Studies show that stockpiling alters the biological, chemical, and physical properties of the soil, often resulting in decreased nutrient availability despite higher retention capacity (Ledesma et al., 2025; Abdul-Kareem & McRae, 1984). Research on post-coal mining land in South Sumatra supports these findings, revealing similar nutrient retention patterns with inadequate availability (Ledesma et al., 2025). The addition of organic matter has been shown to enhance nutrient bioavailability in stockpiled soils, indicating a potential management strategy (Gupta et al., 2019).

3.2. Water Quality

The results of surface and groundwater quality measurements around the research area show a significant decline in quality due to mining activities. Based on the analysis, parameters such as Total Suspended Solids (TSS), turbidity, and pH were found to not meet environmental quality standards. For example, TSS values at several sampling points exceeded 50 mg/L, indicating that further management of mining wastewater (Acid Mine Drainage, AMD) is necessary. For more detailed information regarding the water quality data, please refer to Table 4 below.

The results of water quality analysis around the PT. BKS mining area show significant degradation in quality across several key parameters. The physical parameters show very high TSS values, ranging from 54 to 120 mg/L, far exceeding the environmental quality standard of 50 mg/L for classes 1 and 2. TSS values in the Coal Mining Area show significant variation based on several studies. Sujiman (2024) found TSS concentrations in settling ponds ranging from 76 mg/L to 801 mg/L, indicating significant variability and potential pollution risks (Sujiman, 2024). Meanwhile, Darma et al. (2022) reported TSS levels at PT. Baramega Citra Mulia Persada ranging from 101 mg/L to 150 mg/L, showing that mining activities contribute to increased TSS levels (Darma et al., 2024). Another study by Azhari et al. (2022) recorded TSS levels exceeding 200 mg/L at PT. Antang Gunung Meratus, highlighting challenges in effectively managing wastewater (Azhari et al., 2023). The high TSS levels can have detrimental effects on aquatic ecosystems, including reduced light penetration and increased sedimentation, which can harm aquatic life (Adyatma et al., 2024).

Kintap River is categorized as lightly polluted due to TSS levels not meeting quality standards, emphasizing the need for effective monitoring and management strategies (Adyatma et al., 2024). On the other hand, while high TSS values are concerning, some studies indicate that effective wastewater treatment systems can reduce these impacts, showing potential pathways to improve water quality in mining-affected areas. Water turbidity also shows very high values (70-484 NTU), indicating high suspended particle content that can disrupt aquatic ecosystems. The chemical parameters show significant deviations from quality standards. The pH values range from 6.41 to 7.25, still within the quality standard range (6-9), but tend to be acidic at some sampling points. This condition is better than findings by Nasir et al. (2021), who reported pH values of 3.5 to 5.8 in acid mine drainage in East Kalimantan. However, the BOD (12.140-65.658 mg/L) and COD (85.059-918.640 mg/L) values are significantly high compared to the quality standards (BOD: 2-3 mg/L; COD: 10-25 mg/L), indicating a high organic content that could degrade water quality.

Table 4 Water Quality Data in the Study Area.

No.	Parameters	Unit	Sampling Location							Quality Standard *)	
			1	2	3	4	5	6	7	Class 1	Class 2
A.	Physics										
1	Temperature	˚C	27,0	27,6	27,6	28,2	29,3	26,6	28,4	- Deviation 3	Deviation 3
2	TDS	mg/L	40,4	22,0	23,5	20,5	30,0	40,3	55,5	100	1000
3	TSS	mg/L	112	76	72	70	120	114	54	50	50
4	Conductivity	µS/cm	85,3	47,0	50,1	44,0	63,6	85,1	116,8	-	-
5	Salinity	%	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-	-
6	Turbidity	NTU	147	202	268	215	484	70	220	-	-
7	Color	Pt-Co	8,52	12,3	7,01	12,7	7,76	69,7	23,1	-	-
B.	Chemistry										
1	pH	-	6,50	6,41	6,80	7,25	6,61	6,42	6,81	6 - 9.	6 - 9.
2	Dissolved Oxygen (DO)	Mg/L	58,645	52,920	73,674	58,109	76,155	10,879	17,802	6	4
3	Biological Oxygen Demand (BOD)	Mg/L	12,408	12,140	17,848	12,631	65,658	55,691	35,238	2	3
4	Chemical Oxygen Demand (COD)	Mg/L	87,690	85,059	113,997	96,459	88,047	918,640	136,095	10	25
5	Sodium (Na)	Mg/L	4,783	2,764	2,78	2,592	6,459	5,565	9,214	-	-
6	Phosphate (P)	Mg/L	ttd	ttd	ttd	ttd	ttd	ttd	ttd	0,2	0,2
7	Potassium (K)	Mg/L	0,823	0,563	0,516	0,48	0,658	1,745	1,261	-	-
8	Manganese (Mn)	Mg/L	0,0489	0,0489	0,0479	0,0489	0,0484	15,032	0,1743	0,1	-
9	Zinc (Zn)	Mg/L	0,037	0,032	0,371	0,046	0,054	0,042	0,075	0,05	0,05
10	Copper (Cu)	Mg/L	ttd	ttd	ttd	0,04	ttd	0,04	ttd	0,02	0,02
C.	Microbiology										
1	Total Coli	jml/100ml	150	150	93	>2,400	1,100	1,100	1,100	1000	Jml/100 ml
2	E. Coli	-	Positive	Negative	Negative	Negative	Positive	Positive	Negative	-	-

Source: PT. BKS, 2023.

Description:
1. Saka Kanan Bentuhung River S: 00˚43′08.8" E: 116˚56′17.5".
2. Mahakam River (Close to the Residential Area of Jembayan Village) S: 00˚33′27.3" E : 117˚01′02.9".
3. Mahakam River (1) S : 00˚33′56.5" E : 117˚00′50.7".
4. Mahakam River (2) S : 00˚34′46.0" E : 117˚01′09.2".
5. Margasari Village Residents' Well (Mr. Ruslan's Well) S: 00˚35′18.0" E: 116˚59′48.9".
6. Perigi Hulu River Ds. Jembayan S : 00˚34′53.8" E : 117˚00′55.3".
7. Bakungan River (Near Dsn.Tepian Manggis) S : 00˚35′50.1" E : 117˚01′38.0".
8. *) Quality standards based on PP No. 22 of 2021.

Several heavy metals show concentrations exceeding the threshold, such as Manganese (Mn) reaching 15.032 mg/L at sampling point 6, far above the quality standard of 0.1 mg/L. This is similar to findings by Widodo et al. (2020), who found Mn concentrations reaching 12.5 mg/L in coal mining areas. Zinc (Zn) and Copper (Cu) also show some points exceeding the quality standards, indicating potential heavy metal contamination. From a microbiological perspective, the Total Coliform parameter shows values ranging from 93 to >2,400 CFU/100ml, with some points exceeding the class 1 standard (1,000 CFU/100ml). The presence of E. coli in some sampling points (1, 5, and 6) indicates fecal contamination, which poses health risks to humans. Rahman et al. (2018) also reported high bacterial contamination in water around coal mining areas.

The dissolved oxygen (DO) levels observed in the mining area, ranging from 10.879 to 76.155 mg/L, are atypical and require further investigation. These values are far above the quality standard (4-6 mg/L), which is unusual and contrasts sharply with previous studies, which typically report lower DO values in the same environment, suggesting a potential anomaly in the water quality assessment. The unusually high DO levels may indicate the influx of oxygen-rich water, possibly due to aeration from mining activities, as noted in the Progo River study (Trisnaning et al., 2022). Meanwhile, mining operations often increase TSS and turbidity, which significantly degrade water quality (Risgiyanto et al., 2023; Yasmin et al., 2022). The increase in BOD and COD levels indicates organic pollution, which can deplete oxygen levels over time, affecting aquatic life (Zenati et al., 2023).

Mining activities also frequently introduce heavy metals into the water system, with research showing contamination from lead, zinc, and iron (Fekrache & Boudeffa, 2023; Yasmin et al., 2022), which poses risks to environmental and public health. Although some studies indicate that mining activities may not always cause significant water quality decline, showing that local factors and management practices can reduce the impact (Risgiyanto et al., 2023), the overall trend indicates the urgent need to improve wastewater treatment systems. Based on this comprehensive analysis, it can be concluded that the water quality around the mining area has significantly declined, particularly in terms of TSS, turbidity, BOD, COD, and some heavy metals. This condition requires serious attention through more effective mining wastewater treatment systems to prevent further environmental and public health impacts.

3.3. Analysis of Barriers and Strategies for Reclamation of Ex-Mine Land Using ISM and Methods

The ISM method is used to determine the main factors influencing the effectiveness of post-mining land reclamation. Based on expert observations and analysis, several main obstacles have been identified which can be seen in table 5, namely:

Table 5 List of Ex-Mine Land Reclamation Strategy Elements.

No.	Elements
1	Land Degradation
2	Limited funding
3	Availability of technology
4	Lack of law enforcement
5	Land use change
6	Floods and landslides

After analyzing the Structural Self-Interaction Matrix (SSIM) and Reachability Matrix (RM), the following is the Driver Power-Dependence (DPD) which can be seen in Figure 4 below.

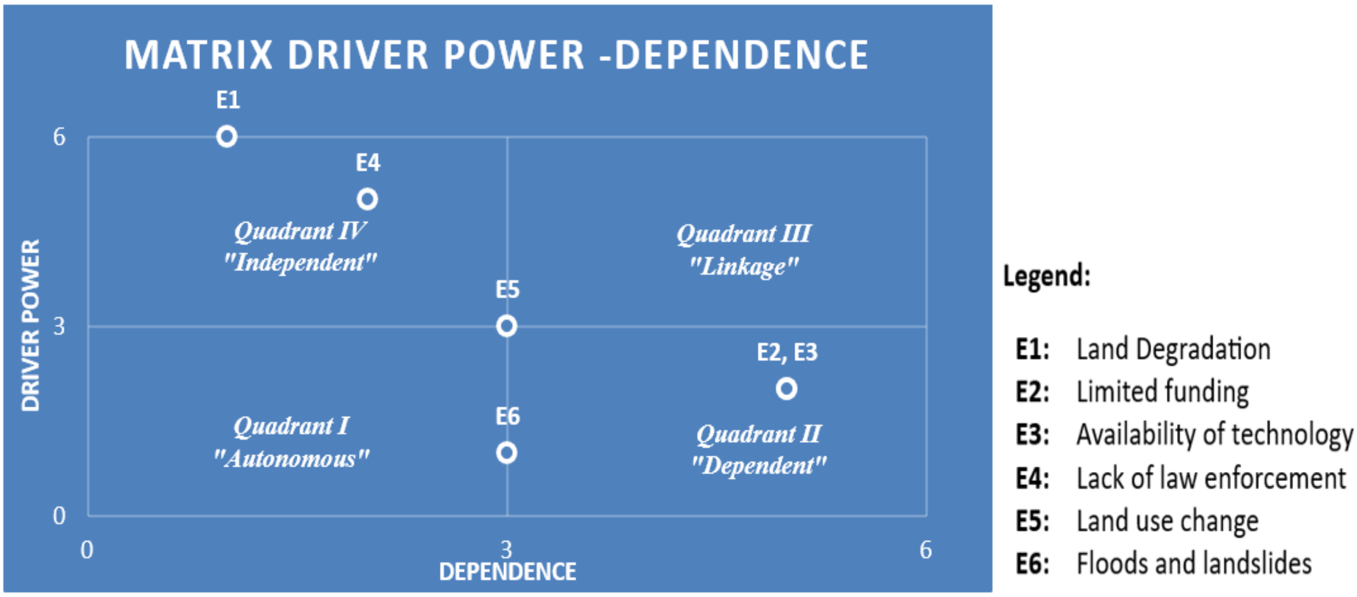

Figure 4 Power-Dependence Driver Matrix for Ex-Mine Land Reclamation Strategy.

Based on the analysis using the Matrix Driver Power-Dependence (DPD), a clear hierarchical pattern emerges in the interrelationship between environmental issues and disasters. The mapping results show that the elements of degraded land condition (E1) and lack of law enforcement (E4) are positioned in Quadrant IV as independent elements. This position indicates their role as key drivers in the system, with high driving power but low dependence on other elements. This suggests that land degradation and weak law enforcement are root causes that will influence the emergence of other issues in the system. This finding aligns with Tibbet's (2024) observation that post-mining land physical conditions and the regulatory framework are key drivers in the complexity of land rehabilitation management, where the presence of toxic substances and soil chemical changes complicate rehabilitation, requiring careful management of waste materials.

Meanwhile, land use change (E5) is placed in Quadrant III as a linkage element. The characteristics of this element show complex dynamics because it has moderate driving power and relatively high dependence. Any change in land use patterns will have a cascading effect and feedback within the system, requiring careful monitoring and management in spatial planning. Warfield (1974), one of the developers of the ISM method, emphasized that linkage elements require careful management because of their instability and potential to trigger both positive and negative feedback in the system. The application of ISM in environmental management shows that the linkage element acts as a mediator that connects driving factors (e.g., government policies, economic incentives) with affected factors (e.g., reclamation outcomes), confirming the strategic position of land use change in the mine reclamation system structure (Zhu & Wang, 2010).

Next, limited funds (E2) and technology availability (E3) are located in Quadrant II as dependent elements, indicating high dependence but relatively low driving power. Limited funds in land reclamation projects are often a major barrier as they affect the ability to implement effective reclamation strategies, especially those requiring investment in expensive technologies and infrastructure. This financial aspect is crucial, with high costs often associated with physical reclamation, which can contribute 60-90% of total expenditure (Maiti, 2013). On the other hand, the availability of adequate technology also plays a major role in determining the success of land reclamation. Limitations in appropriate technology can hinder efforts to restore and rehabilitate damaged ecosystems. This indicates that both factors, limited funds and technology availability, are highly influenced by other elements in the system, which can affect the overall success of the reclamation project. Additionally, economic risks, such as the quality of materials used (e.g., sand and soil), delayed payments, and contractor reliability, also significantly impact project success (Perera et al., 2021).

The absence of elements in Quadrant I (autonomous) indicates that all elements play a significant role in the system, with interconnections that cannot be ignored. This pattern reinforces the importance of a comprehensive approach in addressing environmental issues, prioritizing the improvement of land conditions and strengthening law enforcement as key drivers, while still paying attention to effective coordination in land use management. The absence of autonomous elements in the environmental system highlights the complex interconnection between issues that are interdependent, requiring systematic and integrated intervention. Environmental issues, being an evolving complex system, require a multifaceted approach that considers environmental, economic, and social factors (Miljanovic, 2007), as well as integrated management strategies to address interconnected issues such as deforestation, biodiversity loss, and climate change (Sivaramanan & Kotagama, 2022). After the matrix is obtained, a hierarchical structure of the elements in the Former Mining Land Reclamation Strategy is compiled, which can be seen in Figure 5 below.

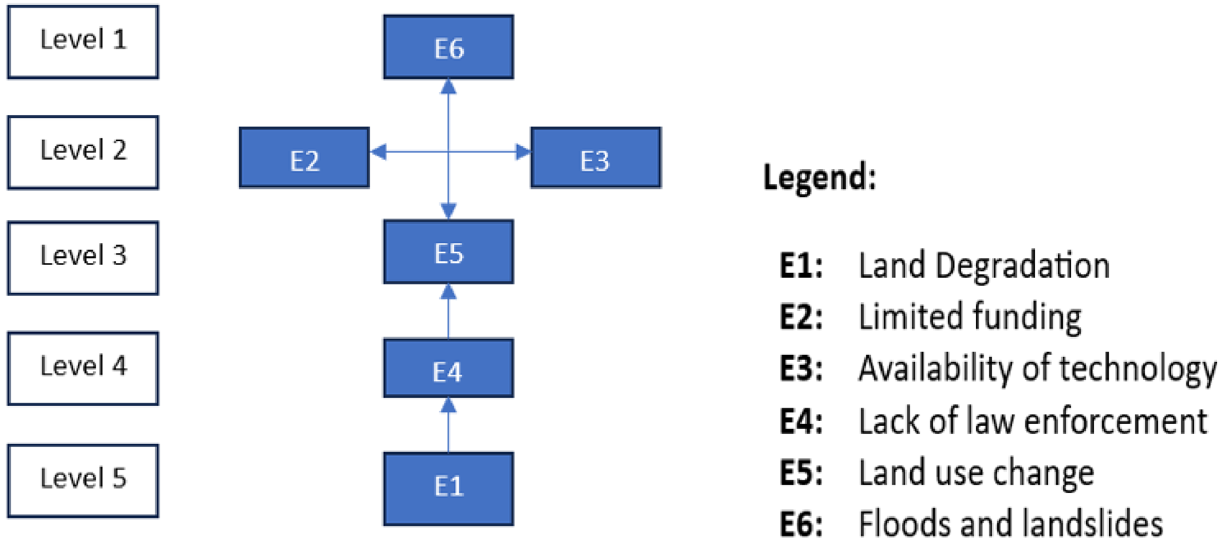

Figure 5 Hierarchical structure of elements in the Ex-Mine Land Reclamation Strategy.

From the figure above, it can be seen that element 1 (Degraded land condition) and element 4 (Lack of law enforcement) have the highest driving power, meaning these factors have the greatest influence on other barriers in post-mining land reclamation and therefore should be given top priority. This finding aligns with Sahoo and Kumar (2020), who identified six main barriers in green construction, including regulatory and management issues, which are hierarchically structured to show their interdependence, as well as with the ISM model, which emphasizes that root barriers significantly influence other barriers.

According to Attri et al. (2013), the position of elements at the lower levels of the ISM hierarchy structure indicates their fundamental role as root causes that influence the entire system dynamics. Singh and Kant (2008) added that interventions focused on elements at the lower levels of the hierarchy will have more significant leverage effects compared to efforts directed at elements at the higher levels. In the context of this research, the implication is that post-mining land reclamation strategies should prioritize improving physical land conditions and strengthening regulatory aspects through more effective law enforcement.

3.4. Reclamation Strategy with AHP

After the main obstacles are identified, the next step is to develop optimal strategies to overcome these obstacles using the Analytical Hierarchy Process (AHP) method, where the obstacles and strategies can be seen in Figure 6 below:

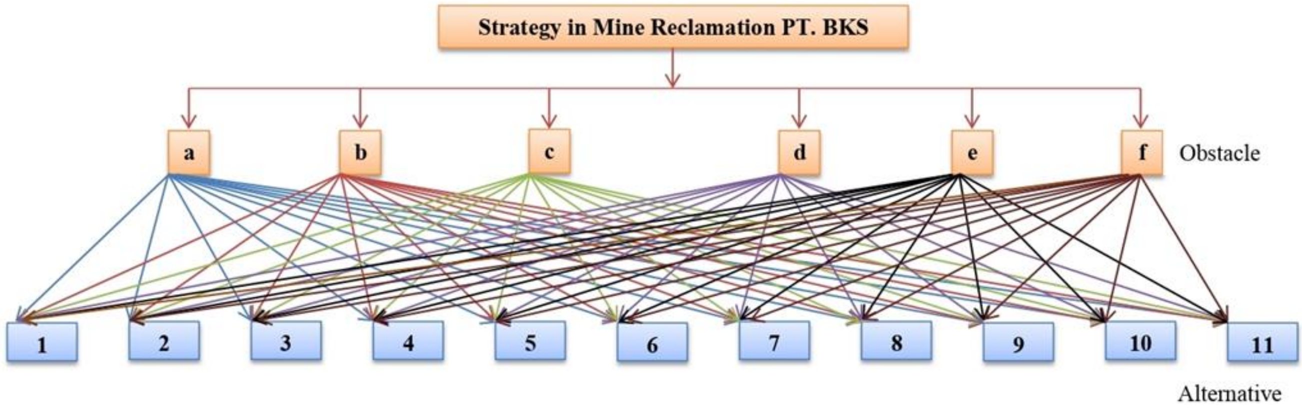

Figure 6 Diagram of Barriers and Strategies for Ex-Mine Land Reclamation.

Based on the results of the Focus Group Discussion (FGD) with experts in their respective fields, several key barriers to post-mining land reclamation in the research area have been identified. These barriers include: a) significantly degraded land conditions; b) limited funds for implementing reclamation programs; c) insufficient availability of adequate technology; d) weak law enforcement on reclamation obligations; e) uncontrolled land use changes; and f) high risks of flooding and landslides in the former mining area. The identification of these barriers through FGD aligns with the approach used by Macdonald et al. (2015) in their study on mine reclamation in developing countries, emphasizing the importance of involving multidisciplinary experts to gain a comprehensive understanding of the complexities of reclamation challenges. Mendoza and Prabhu (2006) also highlighted that the use of participatory methods like FGDs in decision-making related to natural resource management can enhance the quality and legitimacy of the strategies developed.

To address these barriers, a comprehensive strategy is needed, covering technical, financial, regulatory, and social aspects. The proposed strategies include: 1) continuous use of natural organic fertilizers by adopting nano technology; 2) planting endemic species to maintain local biodiversity; 3) rationalizing reclamation cost standards; 4) optimizing the use of reclamation guarantee funds; 5) developing a systematic monitoring and evaluation system; 6) implementing innovative technologies; 7) applying environmentally friendly technologies; 8) comprehensive law enforcement; 9) setting reclamation targets with a maximum deadline of 30 calendar days after mining activities; 10) enhancing community participation; and 11) managing natural resources sustainably.

These strategies reflect the conceptual framework developed by Zipper et al. (2021) on an integrative approach to post-mining land reclamation, which includes biophysical, socio-economic, and institutional aspects. According to Wang et al. (2016), integrating various aspects into reclamation strategies is crucial to addressing the complexities of challenges faced in post-mining land rehabilitation.

These strategies are expected to accelerate the land recovery process while maintaining environmental sustainability. This integrated approach combines technical, financial, regulatory, and social aspects to ensure the success of post-mining land reclamation programs. In terms of financial aspects, rationalizing reclamation cost standards and optimizing the use of guarantee funds are priorities to overcome limited funds. This needs to be supported by a rigorous monitoring and evaluation system to ensure the effectiveness of fund usage. Setting clear reclamation time targets, with a maximum of 30 calendar days after mining activities, provides a measurable time frame for implementing the reclamation program.

The integrated approach in post-mining land reclamation aligns with the concept proposed by Alday et al. (2014) on the importance of integrating ecological, economic, and social aspects in post-extractive land restoration. Skousen et al. (2019) also emphasized that the success of mining land reclamation programs highly depends on the integration of various aspects, including technical, financial, regulatory, and social, implemented within a framework of long-term sustainability.

Regulatory and social aspects also receive special attention through comprehensive law enforcement and increased community participation. Local community involvement in the reclamation process not only helps in monitoring but also supports the creation of sustainable natural resource management. This integrated approach is expected to address existing barriers and produce effective and sustainable reclamation programs. According to Lima et al. (2016), community participation in post-mining land reclamation not only improves program effectiveness but also ensures the long-term sustainability of reclamation results through a stronger sense of ownership and responsibility from the local community.

To ensure the success and effectiveness of reclamation strategies, a comprehensive assessment of various factors influencing implementation is required. Therefore, in this study, analysis using the Analytical Hierarchy Process (AHP) method was conducted to identify the priority strategies that should be adopted. The results of the AHP analysis can be seen in Figure 7 below.

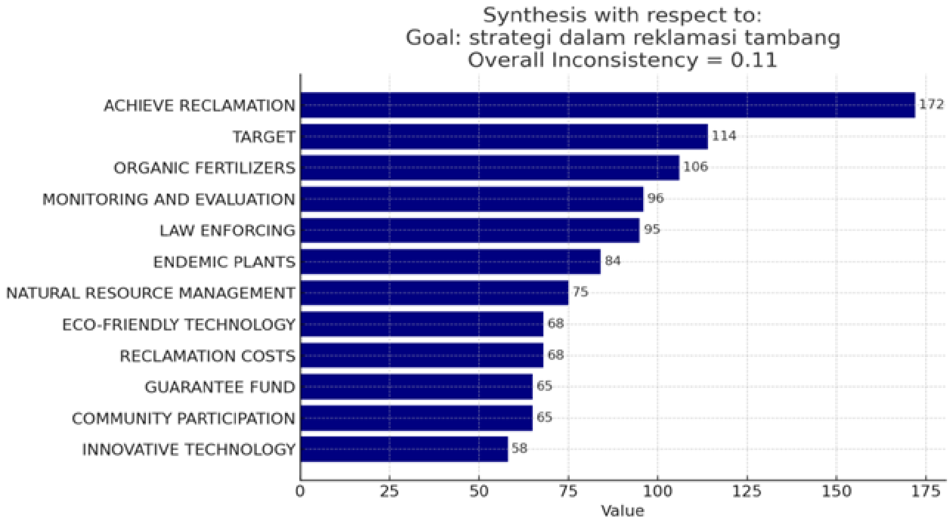

Figure 7 AHP Analysis of Former Mine Land Reclamation.

The results of the analysis show the prioritization of reclamation strategies with an inconsistency ratio value of 0.11. Achieving reclamation targets is the highest priority with a weight of 0.172, followed by the use of organic fertilizers (0.114) and the implementation of monitoring and evaluation (0.106). This supports the opinion of Kusuma and Hermawan (2021) on the importance of optimizing the use of funds and strict monitoring. Law enforcement and the planting of endemic plants, with weights of 0.096 and 0.095, also support the findings of Rahmawati and Pribadi (2021) regarding the importance of regulatory aspects and biodiversity in the reclamation process.

The strategic priorities identified through this AHP analysis reflect the principles proposed by Saaty (2008), the developer of the AHP method, about the importance of determining priorities based on relative assessments of various criteria and alternatives. The inconsistency ratio of 0.11, although slightly exceeding the ideal threshold of 0.10 recommended by Saaty, is still acceptable in the context of research involving subjective expert assessments (Goepel, 2018).

The finding that achieving reclamation targets is the highest priority (0.172) aligns with Yao et al. (2018), who identified that setting clear targets and deadlines is a key factor in the success of post-mining land rehabilitation programs. According to Hilson (2002), setting specific and measurable targets with a clear time frame allows for more effective monitoring and evaluation, which in turn can improve accountability and efficiency in implementing reclamation programs.

The second and third priorities, organic fertilizer use (0.114) and the implementation of monitoring and evaluation (0.106), reflect the approach recommended by Sheoran et al. (2010) regarding the importance of soil quality improvement and monitoring mechanisms in post-mining land rehabilitation. A study by Mensah et al. (2020) also shows that the use of organic fertilizers in mine reclamation not only improves soil structure and fertility but also supports the formation of soil microbiota that is crucial for ecosystem sustainability.

The technological aspects, which include environmentally friendly technology (0.075) and innovative technology (0.058), occupy a medium priority, in line with Li et al. (2017), who highlighted the role of technology in accelerating the mining land recovery process, but noting that technology should be adapted to the specific conditions of the location and not be the sole solution.

Meanwhile, community participation, with a weight of 0.065, remains an important component in the reclamation strategy, although it does not occupy the highest priority. This finding aligns with the perspective of Whitmore et al. (2018), who emphasized that although community participation is important, technical and regulatory aspects are still the main foundation in post-mining land reclamation. However, Burton et al. (2012) cautioned that neglecting community participation could hinder the long-term sustainability of reclamation programs, even though the program might be successful in the short term.

The results of this AHP analysis provide a quantitative foundation for implementing reclamation strategies identified through FGD and previous literature studies. The AHP-based prioritization approach allows decision-makers to allocate resources and efforts more efficiently within the context of resource limitations (Kurttila et al., 2000). Furthermore, the hierarchical structure in AHP provides a more comprehensive understanding of the relationships between various criteria and alternatives in the strategic decision-making process (Ishizaka and Labib, 2011).

Moreover, the integration of the ISM and AHP results in this study provides a more comprehensive and robust analytical framework. According to Kannan et al. (2009), the combination of ISM and AHP methods in complex system analysis, such as environmental management, can provide a deeper understanding of the hierarchical structure of the system and the prioritization of strategic interventions. Li et al. (2014) added that such multi-methodological approaches enable triangulation of results and cross-validation, which enhances the reliability of the recommendations produced.

The findings of this study also have significant practical implications for policymakers and land reclamation practitioners. The strategic priorities identified through AHP analysis can serve as a guide in resource allocation and reclamation program planning (Bhushan and Rai, 2004). Meanwhile, understanding the hierarchical structure of barriers through ISM analysis can help in developing a systematic approach to address the root problems in mine reclamation (Sushil, 2012).

In a broader context, the findings of this study enrich the literature on methodological approaches in post-extractive environmental management in developing countries and still require further empirical studies to improve the effectiveness of policies and practices in the field.

5. Conclusions

This study shows that law enforcement and improving land conditions are the main priorities in post-mining land reclamation in Kutai Kartanegara. In addition, the implementation of innovative technologies and community participation are also crucial for the success of reclamation. Strategies involving the use of organic fertilizers, planting endemic plants, and strict monitoring are expected to accelerate land recovery and support sustainable development.

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Ethical considerations

There is no ethics in this research.

Conflict of Interest

There is no conflict of interest for any of the authors.

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