

## Ecological Analysis of Post-Mining Bauxite Void Waters in Bintan Regency Based on Water Quality Parameters

Reza Muzzamil Jufri\*, Maryono, Fuad Muhammad

Universitas Diponegoro, Indonesia

Email: muzzamil.jufri@gmail.com\*

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### ABSTRACT

*Bauxite mining that has been ongoing for decades in Bintan Regency, Riau Islands Province, has left several voids or former excavated ponds. The existence of these post-mining voids has the potential to affect environmental quality, especially regarding water quality components and the suitability of land use in the surrounding area. This study aims to analyze the current condition of bauxite void water quality after mining in Bintan Regency as a basis for assessing the ecological aspects of the post-mining area. The analysis was conducted descriptively and comparatively by comparing the physico-chemical water parameters against class II water quality standards, in accordance with Government Regulation Number 22 of 2021. Data were obtained from the Bintan Regency Environment Agency (DLH) in 2023, including parameters such as pH, DO, BOD, COD, TSS, TDS, Total Phosphate, and Fecal Coliform. The results showed that most of the water quality parameters were within the class II standard range, except for pH, which varied between 0.24 and 7.75, indicating that some locations were highly acidic. The pH value is the main limiting parameter in determining the ecological conditions of the post-mining voids. Based on the calculation of the compliance score, about 68.8% of voids are classified as "Appropriate," and 31.2% as "Fairly Appropriate." These findings indicate that most voids have undergone natural stabilization processes, although some still require advanced ecological rehabilitation to normalize water quality and support post-mining environmental functions.*

**KEYWORDS** *Bintan Regency, bauxite, ecological, pH, void, water quality*

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## INTRODUCTION

Bauxite mining has become a critical component of the global mineral industry, with worldwide production reaching approximately 380 million metric tons annually, primarily concentrated in tropical and subtropical regions (United States Geological Survey, 2024). Indonesia, as one of the world's significant bauxite producers, contributes approximately 5–7% of global output, with mining activities concentrated in the Riau Islands Province, particularly in Bintan Regency (Ministry of Energy and Mineral Resources, 2023). These mining operations, while economically beneficial, have generated substantial environmental concerns, particularly regarding post-mining land degradation and water quality deterioration in abandoned mine sites (Ahirwal & Pandey, 2021).

Bintan Regency is one of the areas in the Riau Islands Province that has a long history of bauxite mining activities since the 1970s (Azizah et al., 2021). These activities have made a significant economic contribution to the region, but on the other hand, they also cause quite serious environmental problems, especially in the form of land damage and the formation of voids or ponds used for mining excavations. As mining permits expire, most of the ex-mining areas are now abandoned and are experiencing ecological degradation that requires special

treatment (Wicaksono & Rahmawati, 2024). Bauxite mining is one of the important economic activities that play a significant role in the growth of the mineral industry in Indonesia (Shinta & Wikarya, 2024). However, these activities also leave significant environmental impacts, especially when done openly without adequate reclamation planning (Duan et al., 2016). One form of this impact is the formation of voids or former mining ponds, which are large water-filled basins formed by the excavation of large amounts of soil and rock layers (Neto et al., 2021; Hendrychová et al., 2020). The existence of voids not only changes the morphology of the land and natural drainage systems but also has the potential to affect the quality of surface water and surrounding soils, especially through the process of leaching heavy metals and increasing levels of organic matter (Gupta et al., 2022).

In tropical regions such as Indonesia, intensive weathering processes and high rainfall can accelerate the formation of acid mine drainage, which reduces water quality around mining areas (Pradhan & Lee, 2019). This is of particular concern in Bintan Regency, Riau Islands Province, which has become one of the largest bauxite mining centers in Indonesia since the 1970s (Shinta & Wikarya, 2024). Large-scale mining activities in this region have left hundreds of hectares of open land with a large number of voids, especially in the Teluk Bintan, East Bintan, and Kijang sub-districts (Marganingrum et al., 2020).

While existing literature has extensively documented the geochemical characteristics of post-mining waters and revegetation impacts on water quality recovery (Putra et al., 2017; Syahrir et al., 2020), significant research gaps remain in understanding the comprehensive ecological status of post-mining voids in tropical bauxite mining contexts (Tibbett, 2024). Previous studies have primarily focused on isolated water quality parameters or short-term monitoring periods, lacking integrated assessments that combine multiple physicochemical parameters with ecological suitability classifications for post-mining land management (Simpson et al., 2025). Furthermore, while international studies have examined post-mining void rehabilitation in temperate climates (Hendrychová et al., 2020), the unique characteristics of tropical weathering processes, monsoon rainfall patterns, and lateritic bauxite geology in Indonesian contexts require region-specific ecological assessments (Neto et al., 2021). Various previous studies have shown that the water characteristics in the post-mining voids are strongly influenced by the geochemical factors of the parent rock and the level of revegetation around it (Putra et al., 2017; Syahrir et al., 2020). However, in Bintan Regency, studies that integrate void ecological conditions with regional spatial planning are still very limited (Cahayadi, Sidabutar, & Amelia, 2024). In fact, understanding the ecological and spatial suitability of post-mining land is very important to determine the direction of sustainable space utilization, both for conservation, recreation, and limited cultivation (Kivinen, 2017). The water quality in the post-mining voids is greatly influenced by the geochemical processes of the rocks, the rate of revegetation, and the time of water stagnation (Putra et al., 2017; Syahrir et al., 2020).

Parameters such as pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), and total phosphate (T-P) play critical roles in determining the ecological stability and biological productivity of aquatic ecosystems (Gupta et al., 2022). Specifically, pH levels influence metal solubility and bioavailability, thereby affecting aquatic organism survival and metal mobilization potential (Suhendrayatna et al., 2020). Dissolved oxygen concentrations determine whether aerobic or anaerobic conditions prevail, which fundamentally affects

decomposition processes and habitat suitability for aquatic fauna (Pradhan & Lee, 2019). The BOD and COD values reflect organic pollution loads and oxidizable matter content, serving as indicators of ecosystem metabolic capacity (Adekola et al., 2019). Meanwhile, suspended and dissolved solids impact light penetration and primary productivity, while phosphate concentrations regulate nutrient availability and eutrophication potential (Hendrychová et al., 2020). The interactive effects of these parameters collectively determine whether post-mining voids can support ecological functions or require intensive rehabilitation interventions (Cao & Tang, 2025).

Parameters such as pH, DO, BOD, COD, TSS, TDS, and Total Phosphate play an important role in determining the level of ecological stabilization of voids (Ameh, Machido, Tijjani, & Sow, 2023). However, this study addresses these gaps by providing a comprehensive, multi-parameter ecological assessment of bauxite post-mining void waters in Bintan Regency, integrating water quality analysis with ecological suitability classification based on Indonesian water quality standards (Government Regulation No. 22 of 2021). The novelty of this research lies in its holistic approach to evaluating post-mining void ecological conditions through compliance scoring methodology, which enables systematic categorization of void rehabilitation needs and informs evidence-based spatial planning decisions for sustainable post-mining land management in tropical contexts (Marelli, 2017). Scientific studies that focus on the ecological analysis of the quality of void water after bauxite mining in Bintan Regency are still limited, even though this information is important to assess the potential for environmental recovery and sustainability of the post-mining area (Azizah et al., 2023).

The primary objective of this study is to comprehensively analyze the existing water quality conditions in bauxite post-mining voids in Bintan Regency through systematic evaluation of physicochemical parameters, thereby establishing a scientific foundation for assessing the ecological condition and rehabilitation requirements of post-mining areas. Specifically, this research aims to: (1) characterize the physicochemical properties of void waters by measuring pH, DO, BOD, COD, TSS, TDS, total phosphate, and fecal coliform concentrations; (2) evaluate water quality status by comparing measured parameters against Class II water quality standards as stipulated in Government Regulation Number 22 of 2021; (3) determine the ecological suitability classification of post-mining voids through compliance score calculations; and (4) identify critical limiting factors that constrain ecological stabilization and recovery processes.

The significance of this research extends beyond academic contributions to inform practical environmental management applications. Theoretically, this study advances scientific understanding of post-mining aquatic ecosystem dynamics in tropical lateritic bauxite contexts, contributing empirical data to the limited body of knowledge on Southeast Asian mining rehabilitation ecology. Practically, the findings provide essential information for environmental management agencies, particularly the Bintan Regency Environment Agency (DLH), to prioritize rehabilitation interventions based on objective ecological assessments. Furthermore, the compliance scoring methodology developed in this study offers a replicable framework for evaluating post-mining void conditions in similar geological and climatic contexts throughout Indonesia and other tropical bauxite mining regions. From a policy perspective, this research supports evidence-based spatial planning decisions by identifying

which abandoned mining areas possess adequate ecological stability for alternative beneficial uses (such as aquaculture, recreation, or conservation) versus those requiring intensive remediation before repurposing. Ultimately, these findings contribute to Indonesia's commitment to sustainable mining practices and post-mining land rehabilitation as mandated by Law Number 3 of 2020 concerning Amendments to Law Number 4 of 2009 on Mineral and Coal Mining, thereby promoting environmental sustainability while supporting regional economic development objectives.

## METHOD

This research was carried out in the Bintan Regency area, Riau Islands Province, which is one of the areas with the highest bauxite mining intensity in Indonesia. Administratively, the research area includes several sub-districts with the highest concentration of void mines, namely Teluk Bintan, Kijang, East Bintan, and its surroundings. The location was chosen because it has a variety of post-mining land conditions that represent the ecological and spatial characteristics of Bintan Island in general. The research was conducted in the period from January to May 2024, focusing on the analysis of secondary data from the results of water quality monitoring in 2023 conducted by the Bintan Regency Environment Agency (DLH). This analysis is focused on evaluating the ecological condition of void waters through the comparison of measurement results against class II water quality standards and the calculation of compliance scores to describe the level of ecological suitability of post-mining areas.

### Water Quality Analysis

The value of each parameter is compared to the class II water quality standard as stated in Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management.

**Table 1. Table of class II water quality standards in accordance with Government Regulation Number 22 of 2021**

| Parameter                       | Unit | Class II Quality Standards | Information                      |
|---------------------------------|------|----------------------------|----------------------------------|
| pH                              | –    | 6–9                        | Ideal range for freshwater biota |
| DO (Dissolved Oxygen)           | mg/L | $\geq 4$                   | Minimum dissolved oxygen         |
| BOD (Biochemical Oxygen Demand) | mg/L | $\leq 3$                   | Dissolved organic matter levels  |
| COD (Chemical Oxygen Demand)    | mg/L | $\leq 25$                  | Indicators of organic pollution  |
| TSS (Total Suspended Solids)    | mg/L | $\leq 50$                  | Maximum suspended particles      |
| TDS (Total Dissolved Solids)    | mg/L | $\leq 1000$                | Maximum dissolved solids         |
| T-P (Total Phosphate)           | mg/L | $\leq 0.2$                 | Algae growth limiting nutrients  |

| Parameter      | Unit       | Class II Quality Standards | Information                        |
|----------------|------------|----------------------------|------------------------------------|
| Fecal Coliform | MPN/100 mL | ≤ 1000                     | Indicators of biological pollution |

The measurement results are classified into two categories, namely meeting and not meeting quality standards. The average value of each parameter is calculated to represent the general conditions of the post-mining void, taking into account variations between sampling locations.

$$\bar{x} = \frac{\sum_{i=1}^n X_i}{n}$$

Remarks:

$\bar{x}$ = average value of parameters,

$x_i$ = measurement value i,

$n$ = number of sampling locations.

#### Calculation of Compliance Score (R)

$$R = \frac{\text{Number of Parameters Meeting Quality Standards}}{\text{Number of Parameters}}$$

The score results are categorized into:

- Compliant (≥75%)
- Fairly Appropriate (50–74%)
- Not Suitable (<50%)

The R-value is then used to assess the level of ecological suitability based on the following categories:

**Table 2. Categorization of Ecological Conformity Levels**

| Compliance Score (R) | Category Ecology  | Interpretasi                                                               |
|----------------------|-------------------|----------------------------------------------------------------------------|
| ≥ 75%                | Appropriate       | The water conditions are relatively stable and close to natural conditions |
| 50–74%               | Quite Appropriate | Water conditions have mild disturbances (still recoverable naturally)      |
| < 50%                | Inappropriate     | Severe water conditions are disturbed, requiring ecological rehabilitation |

Furthermore, an interpretive analysis of the physical-chemical parameters of the water was carried out to determine the ecological characteristics of the post-mining void. Each parameter was compared with the quality standard threshold and its role was analyzed on the stability of aquatic ecosystems based on ecological references (Gupta et al., 2022; Pradhan & Lee, 2019).

### Ecological Interpretation Analysis

This analysis aims to assess the ecological significance of the water quality results in each parameter. Each parameter has a specific ecological function:

1. pH, an indicator of acidity level; a value below 6 indicates an acidic condition due to oxidation of mineral sulfide.
2. DO, indicates the availability of dissolved oxygen; low values indicate anaerobic waters.
3. BOD and COD, describe the organic load of water; the higher the value, the lower the ability of the waters to support biota life.
4. TSS and TDS, reflect turbidity levels and dissolved solids; high values indicate potential runoff or sedimentation.
5. Total Phosphate (T-P), reflecting nutrient content; high values can trigger eutrophication.

Fecal Coliform, an indicator of biological contamination from human or animal activities around the void. Interpretation was carried out descriptively with reference to supporting literature such as Gupta et al. (2022), Pradhan & Lee (2019), and Syahrir et al. (2020), to assess the level of natural stabilization of post-mining void waters.

### RESULTS AND DISCUSSION

Bintan Regency has a land area of about 87,700 hectares, with part of the area being former bauxite mining areas spread across East Bintan, Toapaya, Teluk Sebong, and Mantang Districts. Intensive mining activities since the 1970s have left dozens of voids or pools of former mine excavations of varying sizes and depths. These voids were formed from open excavations that reached the shallow aquifer layer and are now filled with rainwater and groundwater seepage. Most of the void area is on a flat to undulating topography with soil conditions that are poor in nutrients and have a reddish color typical of laterite. The natural vegetation around the void is generally shrubs, grasses, and acacia trees that grow naturally on reclaimed land. This condition indicates an early ecological succession process that began to form a semi-stable aquatic system.

The results of the analysis of water physics-chemical parameters from the 2023 Bintan Regency DLH data show significant variations between void locations. The average value of each parameter is compared to the class II water quality standard (PP No. 22 of 2021) as shown in Table 3 below.

**Table 3. Average Value of Bauxite Post-Bauxite Void Water Quality Parameters in Bintan Regency**

| Parameter  | Average | Minimum | Maximum | Quality Standard (Class II*) | General Description                                                                                            |
|------------|---------|---------|---------|------------------------------|----------------------------------------------------------------------------------------------------------------|
| pH         | 5,63    | 0,24    | 7,75    | 6,0–9,0                      | Water is acidic due to the weathering of bauxite laterites                                                     |
| TDS (mg/L) | 15,81   | 14      | 148,00  | ≤ 1000                       | The content of dissolved solids is still below the threshold, indicating that the water is classified as fresh |

| Parameter                     | Average | Minimum | Maximum | Quality Standard (Class II*) | General Description                                                                                                   |
|-------------------------------|---------|---------|---------|------------------------------|-----------------------------------------------------------------------------------------------------------------------|
|                               |         |         |         |                              | and has not experienced intrusion or high mineralization.                                                             |
| TSS (mg/L)                    | 2,59    | 1       | 8,00    | 50                           | Height in open void areas and erosion channels                                                                        |
| DO (mg/L)                     | 6,01    | 4,78    | 7,17    | $\geq 4$                     | Low in a flooded pool                                                                                                 |
| BOD (mg/L)                    | 2,42    | 1,05    | 6,79    | $\leq 3$                     | Shows high biological activity                                                                                        |
| COD (mg/L)                    | 15,23   | 8,32    | 26,74   | $\leq 25$                    | A few points above the threshold                                                                                      |
| T-P (mg/L)                    | 0,01    | 0,00    | 0,09    | $\leq 0,02$                  | Phosphate levels exceed the threshold at some points, potentially triggering eutrophication in enclosed water bodies. |
| Fecal Coliform (total/100 ml) | 62,68   | 7,80    | 490,00  | $\leq 1000$                  | High values in densely populated areas, indicating potential contamination of domestic waste.                         |

Source: Secondary Data Processing Results, DLH Bintan Regency (2023)

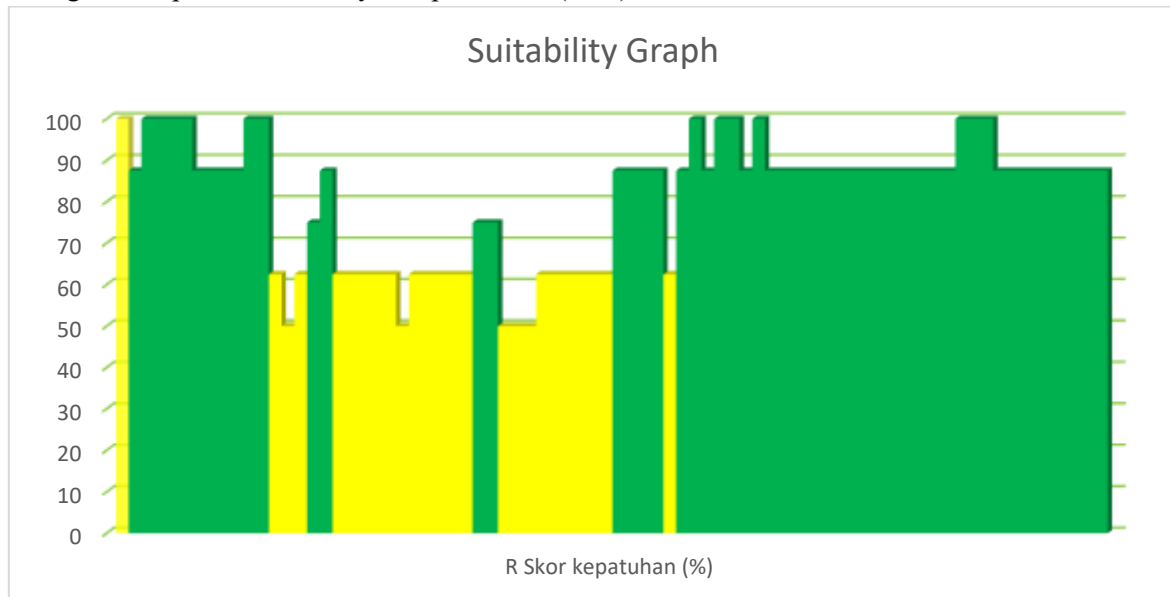
Based on the results of the analysis in Table 3, almost all water quality parameters meet the class II water quality standard, except for the pH which is slightly below the threshold of 6.0. The lowest pH value was recorded at 0.24 and the highest was 7.75, with an average of 5.63. This shows that some voids experience acidic water conditions due to the oxidation of sulfide minerals such as pyrite ( $\text{FeS}_2$ ) which is common in bauxite lateritic rocks. The value of Dissolved Oxygen (DO) is in the range of 6.01 mg/L, indicating that void waters still have sufficient dissolved oxygen levels to support aerobic biota activities. The BOD and COD parameters had values of 2.3 mg/L and 23.5 mg/L, respectively, still within normal limits, indicating that the organic load in the waters was relatively low and the decomposition activity was stable. Physical parameters such as TSS (2.59 mg/L) and TDS (15.81 mg/L) also show values below thresholds, which means that turbidity levels and dissolved solids are still relatively safe. The total content of Phosphate (0.01 mg/L) and Fecal Coliform (62.68 Jml/100 mL) showed that the post-mining void did not experience excess nutrients (eutrophication) and was minimally exposed to direct anthropogenic activities. This value indicates that the input of organic matter from the surrounding environment is very limited, so that the water conditions are relatively natural and biologically stable.

Of the eight parameters analyzed, seven met the quality standards, so the average compliance score achieved:

$$R = \frac{7}{8} \times 100 = 87,5\%$$

This value falls into the "Suitable" category ( $\geq 75\%$ ).

The general distribution of ecological categories shows that about 68.8% of void locations are classified as "Appropriate," while 31.2% are classified as "Moderate." No locations are categorized as Unsuitable, although some points show very low pH values ( $\leq 3.0$ ).



**Figure 2. Percentage of Void Ecological Suitability Category After Bauxite Mining in Bintan Regency**

■ Compliant: 68.8% ■ Compliant: 31.2%

Source: Results of Secondary Data Processing, DLH Bintan Regency (2023).

In general, the results of the analysis show that most of the post-bauxite voids in Bintan Regency are in fairly stable ecological conditions. Only a few points with extremely low pH indicate the potential for the formation of mine acid water. These findings are in line with the studies of Pradhan & Lee (2019) and Gupta et al. (2022), which stated that mine voids with long stagnation time tend to undergo natural neutralization processes due to metal precipitation and aerobic microorganism activity. Thus, most voids in Bintan can be categorized as semi-stable waters with low levels of disturbance, although they still require periodic monitoring and limited ecological rehabilitation.

## CONCLUSION

Analysis of water quality in bauxite post-mining voids in Bintan Regency reveals generally stable ecological conditions, with most parameters—DO, BOD, COD, TSS, TDS, Total Phosphate, and Fecal Coliform—falling within Class II water quality standards. However, pH remains a key limiting factor, averaging 5.63, which is slightly below the standard range of 6–9, reflecting acidic tendencies influenced by bauxite lateritic rock geochemistry. Compliance scores indicate that 68.8% of voids are classified as "Compliant" and 31.2% as "Moderate," with none considered non-conforming, suggesting ongoing natural stabilization and limited but meaningful ecological function, such as buffering rainwater and supporting aquatic life. Future research should focus on long-term monitoring of pH dynamics and the effectiveness of targeted acidity mitigation measures to enhance rehabilitation outcomes and support sustainable post-mining land use.

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