



Effectiveness of Ecological Management to Support Reclamation on Tails Land at the Milepost 21 Reclamation and Biodiversity Research Center Based on Environmental Policy

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Abstract

This study investigates the effectiveness of ecological management in supporting reclamation of tailings land at the Mile Post 21 Reclamation and Biodiversity Research Center, PT Freeport Indonesia. Using a qualitative descriptive approach, the research employs primary data obtained through interviews, documentation, and direct observation, complemented by secondary data from archives, reports, and company records. The analysis is guided by ISO 14001 environmental management principles, using a checklist method adapted from the Global Environmental Management Initiative (GEMI) to evaluate ecological, technical, socio-economic, and regulatory aspects of reclamation practices. Findings reveal that ecological management at Mile Post 21 has been highly effective, achieving more than 80% compliance with ISO 14001 indicators. Vegetation cover increased from less than 10% to over 75%, with more than 160 planted species complemented by natural succession involving over 500 species. Soil quality improved significantly, with organic carbon rising from <math><0.5\%</math> to 2.5%, pH levels increasing toward neutrality, and cation exchange capacity reaching medium-high levels. These changes facilitated the restoration of ecological functions and supported biodiversity recovery. Moreover, reclaimed land has been transformed into productive agricultural areas integrating crops, livestock, and aquaculture, providing socio-economic benefits for local communities and involving indigenous landowners in sustainable management. Despite technical challenges related to poor soil properties and managerial constraints such as long-term funding, the program demonstrates that ecological management, when implemented systematically under ISO 14001, can effectively restore degraded post-mining land into ecologically resilient and socially beneficial systems.

Introduction

Indonesia, as one of the countries with the largest mining activity in the world, faces major challenges in post-mining environmental management. The main problem that frequently arises is land degradation, leading to reduced soil fertility, water pollution, and damage to local ecosystems (Möller et al., 2024; Amanah & Yunanto, 2019). The solution to the impacts of open-pit mining activities requires planning from the initial to post-mining stages before mining begins, as an effort to maintain environmental sustainability. Appropriate post-mining planning is land reclamation.

Mine reclamation aims to restore ecosystem function and environmental quality after mining operations (Ahirwal & Pandey, 2021; Tibbett, 2024; Venkateswarlu et al., 2016). One of the

main challenges in recovery is meeting sustainability standards, such as soil fertility and restoring damaged ecosystems (Amanah & Yunanto, 2019; Bhaduri et al., 2022; TH, 2016; Miller et al., 2017). Reclamation is an activity carried out throughout the mining business to organize, restore, and improve the quality of the environment and ecosystems so that they can function again according to their intended purpose (Minister of Energy and Mineral Resources Regulation Number 7 of 2014). Based on Minister of Energy and Mineral Resources Regulation No. 7 of 2014 and Government Regulation No. 78 of 2010, reclamation activities are required in former mining areas to restore the land to its original condition.

This aligns with PT Freeport Indonesia's (PTFI) commitment to reclaim disturbed land no longer used for operational activities (Firdaus, 2016). This commitment is demonstrated by PTFI's receipt of the International Organization for Standardization 14001 (ISO 14001) certification, obtained in 2001.

ISO 14001 is an Environmental Management System that controls all aspects of environmental impacts by referring to established quality standards (Zimon et al., 2022; Battersby, 2022; Zebek, 2021). This is achieved through continuous, monitored, and measurable improvements involving all internal and external stakeholders. PTFI has conducted various studies and programs over the years to obtain reliable and scientific data that can serve as guidelines for optimal planting techniques and plant species (Tafes Desta et al., 2022). It also documents, implements, maintains, and continuously improves the environmental management system to maximize the success of these programs. PTFI is a mineral mining company affiliated with Freeport-McMoRan (FCX) and Mining Industry Indonesia (MIND ID). PTFI mines and processes ore to produce concentrate containing copper, gold, and silver, then markets the concentrate worldwide and primarily to the domestic copper smelter, PT Smelting. Freeport Indonesia has conducted exploration at two sites in Papua: the Erstberg mine (since 1967) and the Grasberg mine (since 1988), in the Tembagapura area, Mimika Regency, Papua Province (Sari, 2008).

In its operations to obtain gold and copper concentrate, PTFI produces tailings, or residual mining sand (SIRSAT), which generally have unfavorable physical and chemical properties (Sari, 2008; Morrison, 2022). Tailings is the material remaining after the concentrate is extracted from the crushed ore. Ore processing is a physical process in which the ore is ground to a fine powder and the minerals containing copper and gold are separated from the uneconomical rock particles. PT Freeport Indonesia uses a controlled tailings disposal management system that transports tailings to a designated area in the lowlands and coastal areas, called the Modified Ajkwa Deposition Area.

This deposition area is part of a riverbank engineered and managed for tailings deposition and control. PT Freeport Indonesia's mining operations have altered the ecological system around the Akjwa and Otomona rivers. This has resulted in changes in soil shape and conditions, vegetation and fauna patterns, and changes in the social and economic values of communities living in the tailings area, whose livelihoods are derived from farming and gathering (PT Freeport, 2009; Magidi & Hlungwani, 2023).

PT Freeport Indonesia has been disposing of mine waste in the upper reaches of the Ajkwa River since 1995. With a production capacity of 300,000 tons, according to calculations by the Supreme Audit Agency, an average of 230,000 tons of waste is produced daily. Of all the soil dredged and processed by the mining company, only 3 percent contains minerals. The remainder is largely disposed of. The tailings, or mining waste sand produced by PTFI, are deposited in a lowland area located between two embankments (the West Embankment and the East Embankment).

The MilePost 21 Reclamation and Biodiversity Research Center is a research site for tailings reclamation in lowland areas, demonstrating that native plant species successfully colonize and thrive on tailings. Tailings land is also suitable for growing various agricultural crops if the tailings are provided with sufficient organic carbon input (Yong et al., 2022; Yu et al., 2023).

The MilePost 21 Reclamation and Biodiversity Research Center is a research facility belonging to PTFI's Environmental Division, established to minimize the impact of mining activities on the environment. This division manages all environmental activities, from the highlands to the lowlands, within PTFI's Contract of Work area (Cahyadi, 2013; Bangun et al., 2021).

The objective of PT Freeport Indonesia's reclamation program at the MilePost 21 Reclamation and Biodiversity Research Center is to demonstrate sustainable methods for converting tailings deposits in depositional areas into productively usable land or returning the land to native vegetation after mining operations are completed (PT Freeport Indonesia, 2009). The natural succession process, which has occurred over 10-15 years, has resulted in changes in the composition of plant species (Puradyatmika et al., 2012) and microbes (Djuuna et al., 2013).

PT Freeport Indonesia, through its Environmental Division, has implemented conservation principles and environmental protection values within its good mining practices. Freeport Indonesia has complied with all environmental regulations issued by the Indonesian government and other relevant environmental requirements. Compliance with Indonesian environmental regulations has been evaluated through audits conducted by FCX-CTI and ISO 14001 audits, resulting in 100% compliance.

This is evidenced by the cumulative success of planting more than 160 plant species on land containing tailings. Some of the well-tested crop types include cover crops for animal feed such as legumes; native trees such as casuarina and matoa; fruit crops such as pineapple, melon, and banana; and vegetables and grains such as chili peppers, cucumbers, tomatoes, rice, beans, and pumpkins.

In addition to commercial crop production, another pathway to reforestation of tailings is natural succession. Natural succession occurs rapidly in most deposition areas, preceded by Phragmites grass karkat. Phragmites grass produces detrital biomass that increases the nutrient content of the tailings and improves its water-holding capacity, allowing the growth of other species as well. An independent research project on natural succession of plants growing on tailings found that within just a few years, more than 500 plant species had colonized and thrived (PTFI, 2009; Munford et al., 2022; Munford, 2024).

The Reclamation and Biodiversity Research Center strives to realize a sustainable farming system. Sustainable agriculture is a crop and animal production system that balances environmental, social, and economic aspects. This aligns with existing agricultural systems, where legumes are grown alongside king grass. These crops are harvested as livestock feed, and the manure is used to enrich the soil and disperse seeds. This approach involves customary rights holders in environmental management programs, prioritizing employment opportunities for customary rights holders, specifically to become partners in the environmental sector (Qomariyah Nurul, Habel Taime, et al., 2023).

Several previous studies have discussed the effectiveness of post-tin mining reclamation programs in several mining areas in Indonesia. For example, Dian Permata Sari and Imam Buchori (2015) examined the effectiveness of post-tin mining reclamation programs in Merawang District, Bangka Regency, a state-owned mining company. In this study, the authors used quantitative descriptive analysis techniques, which found the effectiveness to be very

ineffective. Both external and internal factors contribute to the far-reaching effectiveness of the reclamation program.

In a previous study by I Gede Eka Budiana, Jumani, and Maya Preva Biantary (2017), they evaluated the success rate of revegetation of former coal mine land at PT Kitadin's Embalut site in Kutai Kartanegara, East Kalimantan. They used descriptive methods. Data collection was conducted through observation and documentation. Based on indicators of success rate in growth, both diameter and height, it can be concluded that the reclamation and revegetation activities at PT Kitadin's Embalut site are considered good. Furthermore, comprehensive monitoring of plant growth is needed to ensure the company has a database of all plant growth levels within the PT Kitadin Embalut site.

Therefore, in this study, the researcher aims to evaluate the effectiveness of ecological management to support reclamation on tailings land in the PTFI mining area which is expected to meet the indicators of the level of reclamation activities that meet sustainability standards and restore damaged ecosystems to support the return of biodiversity comparable to the level of biodiversity observed in adjacent natural locations. However, nature is naturally able to recover itself through the process of primary natural succession.

Methods

Research Design

This study on the effectiveness of ecological management in supporting reclamation on SIRSAT land at the Reclamation and Biodiversity Research Center, Mile Post 21, employs a qualitative descriptive method. The research utilizes both primary and secondary data. Primary data are obtained through case studies on ecological management of plants using in-depth interviews, documentation, and direct observation with the aid of a checklist. The interview questions are carefully designed to ensure objectivity and clarity of purpose. Secondary data are collected from indirect sources such as archives, documents, files, and company records, and are used to provide a general description of the company and other related aspects.

Time and Location

The research is conducted in April 2025 at the Reclamation and Biodiversity Research Center, Mile Post 21, PT Freeport Indonesia. Geographically, the site is located between 136°55'–136°58' E and 4°32'–4°40' S, while administratively it falls under Mimika Baru District, Timika City, Central Papua Province. The site includes both the research center and reclaimed land areas that serve as the primary focus of observation.

Implementation of Research

The implementation of the research consists of several stages. First, the research objectives are formulated, including the identification of baseline ecological conditions prior to reclamation, the evaluation of applied ecological management techniques, the assessment of reclamation impacts on soil fertility and ecosystem sustainability, the measurement of reclamation success in restoring a stable and productive ecosystem, and the provision of strategic recommendations for future ecological management. Second, the preparation stage involves identifying the research site, selecting appropriate methods, developing a research plan with schedules and resources, and preparing research instruments such as interview guides and recording devices. Third, the fieldwork stage includes conducting observations, documentation, and interviews with research subjects, either face-to-face or through telecommunications. Fourth, data management is carried out through systematic collection, verification, and analysis of field data, with the application of triangulation to ensure accuracy and validity. Finally, the

concluding stage consists of evaluating data and drawing conclusions that reflect the contributions of the research to ecological management and reclamation practices.

Research Materials

The research materials consist of both primary and secondary data collected through surveys. Primary data are derived from case studies on ecological plant management using in-depth interviews, documentation, and direct observations supported by a checklist. Secondary data are obtained from archives, documents, files, and company records. Observational data are collected using a checklist developed based on the Environmental Management System framework, namely the Plan–Do–Check–Act (PDCA) cycle, linked with ISO 14001 elements. The checklist is adapted from the Global Environmental Management Initiative (GEMI) and covers five principles with 17 elements, generating a total of 31 questions. These questions address policy and commitment, planning, implementation and operation, checking and corrective action, as well as management review.

Data Analysis

Data collected from interviews and observations through the checklist are analyzed qualitatively by means of tabulation, scoring, percentage calculation, and narrative description. Each question in the checklist is assigned a score to reflect the actual condition, with the results further analyzed to determine the level of compliance with ISO 14001 standards. The assessment consists of 31 questions distributed across the five principles of ISO 14001, with a maximum total score of 62. A higher score indicates a stronger alignment with ISO 14001 requirements, reflecting the effectiveness of ecological management practices in supporting reclamation at the research site.

Results and Discussion

Ecological Management Effectiveness in Supporting Tailings Land Reclamation

A study examined the effectiveness of ecological management to support tailings land reclamation at the Mile Post 21 Research Center, located within the PT Freeport Indonesia Reclamation and Biodiversity Research Center, Mimika Baru District, Timika City, Central Papua Province. Based on data analysis from several ecological plant management studies, the results of observation, documentation, and in-depth interviews showed that the ecological management implemented on the tailings land at the Mile Post 21 Reclamation and Biodiversity Research Center has demonstrated a high level of effectiveness in supporting the reclamation process.

The success criteria for PT Freeport Indonesia's tailings land reclamation refer to the technical, ecological, and social standards established by the company in accordance with national regulations, specifically the 2020 Mineral and Coal Mining Law. The success criteria for PT Freeport Indonesia's tailings land reclamation were developed to assess the effectiveness of the reclamation program. These criteria cover several key assessment aspects: technical, ecological, socio-economic, and administrative, or regulatory compliance. Each aspect is assessed using clear indicators and then categorized into four levels of effectiveness: very effective, moderately effective, less effective, and ineffective. This classification allows for a more objective evaluation process while also providing direction for improvements in areas of weakness. The following table presents the criteria for successful reclamation of PTFI's tailings land.

Based on observations with the Environmental Central System & Project Manager, "Mr. Roberth Sarwom," regarding the success of PT Freeport Indonesia's tailings reclamation, 10

statements with a total score of 36 out of 40 were assessed, resulting in a classification of 3.5–4.0, categorizing the overall reclamation activity as "Very Effective." This assessment encompasses technical, ecological, socio-economic, and regulatory compliance aspects. With this achievement, PT Freeport Indonesia's reclamation program can be said to have met most of the success indicators. However, improvements in soil fertility and ecological function are still needed so that future reclamation is not only administratively effective but also able to build a more sustainable ecosystem and provide long-term benefits for the environment and community.

Based on field observations, the table above shows the evaluation of the effectiveness of ecological management at the Milepost 21 Reclamation and Biodiversity Research Center, based on the main indicators referenced in ISO 14001. Overall, these indicators indicate that the level of ecological management effectiveness at Milepost 21 is highly effective (>80% target achievement), reflecting the successful integration of ecological, social, and economic aspects in post-mining reclamation activities.

Vegetation cover increased significantly from an initial level of <10% to >75%, with the planting of more than 160 plant species, plus natural colonization of more than 500 species. This demonstrates the success of the revegetation and natural succession program; Biodiversity experienced a significant increase, with various species of flora and fauna returning to inhabit the reclamation area. This increase indicates that ecological functions are beginning to return to near-natural conditions. Soil quality has shown improvement, with organic carbon increasing from <0.5% to 1.2–2.5%, pH from 4.5 to 5.8–6.2, and CEC increasing from low to medium–high. These changes are a direct impact of the addition of organic matter, sustainable agricultural systems, and vegetation activity.

Productive utilization has grown rapidly with the development of integrated agriculture (rice, vegetables, cattle, chickens, and fish) utilizing tailings land. This indicates that reclamation not only restores ecological function but also provides economic value. Local community involvement has increased, with a partnership between PT Freeport Indonesia and customary landowners in managing the reclaimed land, providing socio-economic benefits. Compliance with ISO 14001 is demonstrated by internal and external audits showing 100% compliance annually, indicating environmental management in accordance with international standards and the principles of continuous improvement.



Figure 1. a) Tailings land in MP 21 before planting, b) Tailings land in MP 21 after planting

Effectiveness of Ecological Management for Environmental, Social, and Cultural Goals Based on ISO 14001 Commitments

Ecological management in tailings land reclamation has been proven to support the achievement of environmental, social, and cultural goals. Ecological management at the Milepost 21 Reclamation and Biodiversity Research Center is carried out in accordance with the principles of ISO 14001, namely the Environmental Management System, which emphasizes continuous improvement, regulatory compliance, and the integration of environmental, social, and cultural aspects. ISO 14001 serves as a guideline that ensures that each stage of reclamation prioritizes not only ecosystem restoration but also considers the interests of local communities and the preservation of local culture. This ecological management program is implemented through three main pillars: environmental objectives (ecosystem restoration and sustainable waste management), social objectives (economic empowerment and community involvement), and cultural objectives (preservation of Papuan traditional values and local wisdom).

Ecological management at Milepost 21 primarily aims to restore post-mining environmental functions through a series of strategic steps: The reclamation process involved planting more than 160 plant species selected based on their adaptability to tailings. This success was supported by natural succession, which added over 500 additional plant species over a period of 10–15 years. The result was increased vegetation cover that not only serves as land cover but also creates new habitats for local fauna. According to (Puradyatmika & Prewitt, 2012), approximately 160 plant species have successfully grown in the former tailing's deposition area, consisting of both native and non-native species. These species include pioneer plants, trees, shrubs, and grasses. Over time, primary natural succession has been observed to successfully establish pioneer plants such as *Phragmites karka*, *Acacia auriculiformis*, and *Casuarina equisetifolia*. These species play an important role in stabilizing the tailings surface, increasing soil organic matter, and facilitating the growth of more diverse vegetation.



Figure 2. a) Watermelon plants (*Citrullus lanatus*) on SIRSAT MP Land, b) Banana Plants (*Musa Paradisiaca*) in MP Tailings Land

Soil quality has significantly improved. The soil pH increased from 4.5 (acidic) to 6.2 (near neutral), organic carbon increased from <0.5% to >2%, and the cation exchange capacity (CEC) increased from 10–15 me/100g to 20–30 me/100g. These improvements support long-term vegetation growth and maintain the stability of the reclamation ecosystem. Tails waste is not left as post-mining waste but is utilized as a reclamation medium. The controlled deposition process at ModADA is followed by the planting of cover vegetation that can prevent erosion

and improve soil fertility. The conservation program is intensively implemented, including the release of endemic species such as the double-wattled cassowary (*Casuarius unappendiculatus*), the pig-nosed softshell turtle (*Carettochelys insculpta*), and the copper-tailed cuscus (*Phalanger alexandrae*). In addition, the MP21 facility is used to protect endangered species and support biodiversity research.

Social Objectives

ISO 14001 also emphasizes the importance of involving local stakeholders in all environmental management activities. Empowering Indigenous Land Owners, indigenous communities are actively involved as partners in reclamation, conservation, and agricultural management activities. This participation not only provides economic benefits but also enhances their sense of ownership of the reclaimed land.

Local Economic Development: Utilizing reclaimed land for integrated agriculture (rice, tomatoes, vegetables) and livestock (cattle, chickens, and fish) provides new sources of income for local communities. Harvests that are safe from heavy metal contamination, according to BPOM (National Agency of Drug and Food Control) tests, opens up opportunities for developing businesses based on reclaimed land. **Education and Training:** The MP21 Biodiversity Center serves as an environmental education platform for schoolchildren, university students, and the general public. This program equips the community with knowledge of reclamation, conservation, and sustainable agriculture, in line with the principle of long-term empowerment.

One of PT Freeport Indonesia's social commitments is to involve indigenous land owners in various environmental impact management programs. This involvement is realized through the provision of employment opportunities to local Papuan contractors, particularly in environmental projects centered at the Reclamation and Biodiversity Research Center at Mile Post 21. Previous research by Qomariyah Nurul, Habel Taime, et al. (2023) covered various contractor tasks, such as planting and maintaining reclamation vegetation, maintaining the MP21 area, managing agriculture, plantations, fisheries, cattle ranching, collecting water hyacinth from the river for compost, monitoring biodiversity, and planting mangroves in the Ajkwa estuary area.

The participation of customary rights holders in PT Freeport Indonesia's operational area is realized through mentoring in the micro, small, and medium enterprise (MSME) development program implemented by PT Freeport Indonesia. This program fosters local contractors who employ native Papuan and non-Papuan workers from various regional backgrounds, ethnicities, and educational levels. Each contractor is responsible for providing labor to carry out various activities in the reclamation program in the MP21 area. The recruited workforce is expected to have a high level of productivity to achieve the work targets set by the service provider. The achievement of these targets will be an indicator for assessing contractor performance by the Environmental Division as the service user.

Utilizing Mining Waste Sand (SIRSAT) to Become Productive Land

Land formerly used for tailings deposition is being engineered into a sustainable agricultural area that integrates food crops and animal feed. Cultivated crops include vegetables (eggplant, chili), grains (sorghum), and forage (king grass). Agricultural products are used to meet food and animal feed needs under the Cattle Project program. This management involves local labor, particularly from communities with customary rights, thus providing socio-economic benefits while maintaining ecosystem sustainability. The production cycle also utilizes livestock waste

as organic fertilizer to improve soil fertility, creating an environmentally friendly, closed-loop system that aligns with ISO 14001 commitments.

SIRSAT land is utilized to cultivate various types of crops, both food and animal feed, such as sorghum, eggplant, chili, and king grass. The planting system uses an intercropping method (intercropping) between forage crops such as king grass and food crops, maximizing land productivity. Plantation production is used for internal consumption and a portion is distributed to local communities as a form of empowerment.

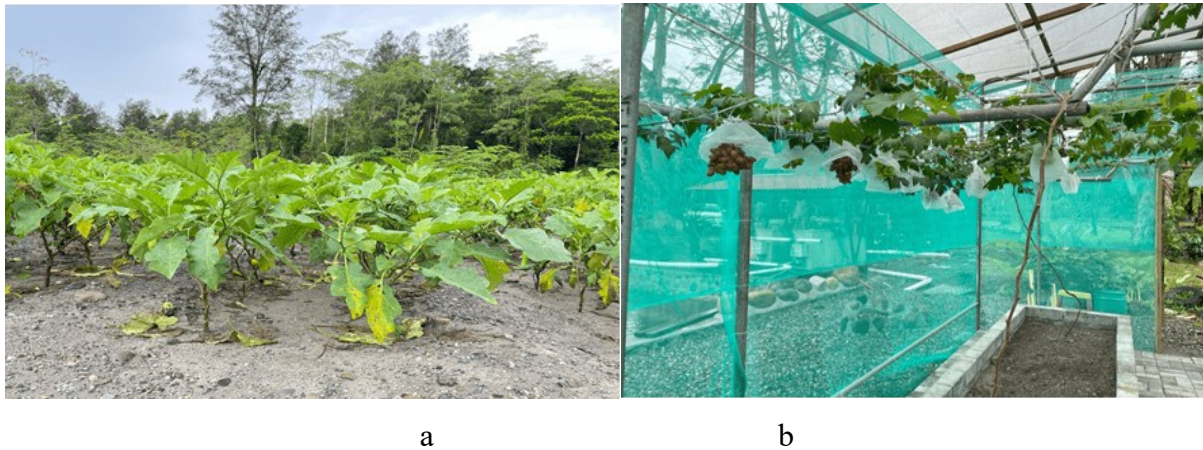


Figure 3. a) Eggplant (*Solanum melongena*) plants in the tailings land of MP 21, b) Trans, Ninel and Jupiter grape varieties in MP 21



Figure 4. Chopping King Grass (*Pennisetum purpuphoides*) for Cattle Feed at MP 21

Barriers to Ecological Management in Supporting Tailings Reclamation at the Mile Post 21 Biodiversity Reclamation Research Center

Ecological management at Milepost 21 demonstrates high effectiveness, and many indicators of reclamation success have been achieved. However, this process is not without challenges. The obstacles encountered are grouped into four main categories: technical, environmental, social, and managerial. Technical barriers relate to the physical properties and natural characteristics of the tailings media used for reclamation. Physical Characteristics of Tailings: Tailings media is predominantly sandy with very low organic matter content. This condition results in nutrient-poor soil and low water-holding capacity. To support plant growth, special treatment is required, including liming to neutralize soil acidity, as well as the addition of organic fertilizers and ameliorants to improve soil structure and fertility. Limitations of

Adaptive Plant Species: Not all plant species are able to adapt to tailings media. Plant species must be selected through strict selection based on their adaptability, tolerance to nutrient deficiencies, and ability to improve soil quality. This limits plant diversity in the early stages of reclamation. **Slow Natural Succession Process in Some Areas:** In areas with sediment depths exceeding 7 meters, soil conditions become increasingly poor in nutrients and moisture. This slows natural succession, necessitating additional interventions such as planting pioneer plants or providing special soil treatments to accelerate vegetation recovery.

Employees with adequate education are expected to increase their work productivity. Academic achievement during school is one of the company's considerations. By considering academic achievement, employees can be placed based on their academic achievements (Budi Rismayadi, 2016). This is in line with research by I Fitriandkk. The results showed that compensation, education level, and the physical work environment have a positive and significant impact on work productivity. Work ethic is a set of positive work behaviors based on a strong awareness, core beliefs, and total commitment to the integrated Sinamo paradigm (Saleh & Hardi, 2018). This is evidenced by Azalia Nabila Putri's research, which found that partial analysis showed that work ethic has a significant influence on employee productivity at PT Wangsa Jatra Lestari Surakarta.

Rismayadi (2016:5) states that internal and external factors play a role in workforce productivity in a business sector. Several factors, such as education level, wage rate, motivation, age, fatigue, and other individual factors, are important factors in workforce productivity. Meanwhile, external factors such as culture, work environment, safety, regulations, leadership, and others also impact workforce productivity in a business sector. Work discipline behaviors, such as attendance at work and inappropriate use of working hours, lead to decreased individual work performance, which impacts the overall team's achievement in completing work. Attendance levels contribute significantly because when work must be completed by several employees, the absence of one person can hinder completion. Similarly, absenteeism or inappropriate use of working hours at work. Some people working while one or two others are absent or doing other work outside of their job will impact the overall team's performance. Another contributing factor is a lack of responsibility for their work. Employees prefer to help with other tasks requested by their employer rather than complete their own responsibilities.

Managerial constraints relate to resource availability and management sustainability. **Sustainable Budget Limitations:** Maintaining reclamation areas requires significant costs, especially for research, experiments, and the development of new technologies. Unstable budget allocations can impact the consistency of maintenance activities. **Long-Term Monitoring Consistency:** Monitoring vegetation, soil quality, biodiversity, and environmental safety requires trained human resources and adequate equipment. Maintaining consistent monitoring over the long term is often challenging, especially when program priorities change or there are logistical limitations in the field.

Conclusion

Ecological management to support reclamation on the MP21 tailings land scored 3.6, falling within the 3.5-4.0 range, indicating overall "Very Effective." This assessment encompasses technical, ecological, socio-economic, and regulatory compliance aspects. However, improvements in soil fertility are still needed, and more active community involvement is expected so that the reclamation program is not only administratively effective but also able to build a more sustainable ecosystem and provide long-term benefits for the environment and the community. Ecological management of tailings land reclamation at the Mile Post 21

Reclamation and Biodiversity Research Center has proven highly effective in supporting environmental, social, and cultural sustainability. This success was achieved through the implementation of ISO 14001. PTFI has demonstrated through its Environmental Division that the principles of conservation and environmental protection within good mining practices have been implemented, empowering indigenous communities and preserving local wisdom, with a 100% compliance rate annually. 3. Ecological management of PTFI's tailings area faces technical challenges related to the nutrient-poor condition of the tailing's media, limited adaptive plant species, and slow natural succession. Social challenges stem from workforce factors such as education, work ethic, discipline, and responsibility, which impact productivity. Managerial challenges include budget constraints and the challenge of maintaining consistent long-term monitoring. The success of reclamation at Milepost 21 is determined not only by technical interventions but also requires solid social support and consistent managerial governance. Integration of technological innovation, human resource capacity building, and sustainable funding are key to ensuring reclamation can support sustainable environmental recovery.

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