

Bauxite Residue Deposit Reclamation – a Pathway to Reintegration

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Abstract

The remediation of areas impacted by industrial operations has been challenging for the bauxite processing industry, particularly regarding the residue storage facility areas. Understanding the social and environmental impacts are some of the most relevant stages for closure planning. Hydro Alunorte, the Norsk Hydro refinery plant in the north of Brazil, has operated since the '90s with Solid Residue Deposits 1 (DRS1). The deposit is a dry stacking bauxite residue storage facility, constructed with multi-staged expansions, with a total area of approximately 270 ha, operated for over 20 years based on drum filter disposal. In line with Hydro's ambition, Alunorte set the goal to progressively close the oldest deposit and promote the disposal area rehabilitation. The uncertainties regarding the success of all facets of a cover system associated with the lack of natural resources are undoubtedly some of the challenges to closure designs of bauxite residue deposits. This paper presents the different concepts tested on experimental areas focusing on the DRS1 closure design in terms of elimination of contact run-off, control of fugitive dust, improved visual aspect, and reintegration with native and adjacent bush areas. The tests assessed geotechnical, physic-chemical, and biological progress regarding soil regeneration, surface and subsurface drainage water quality, vegetation growth and mortality, displacements, constructive pore water pressure, and micro and mesofauna restoration. The monitoring data collected from experimental areas provided the layout with more excellent results based on the key performance indicators and determined the design of the progressively closed stripes. Furthermore, the paper will discuss the large-scale progressive closure performance. The author intends to provide guidelines and general practices for the reclamation of bauxite residue facilities.

Keywords: Filtered bauxite residue deposit, Bauxite residue disposal area reclamation.

1. Introduction

The closure and rehabilitation of a tailings facility is of great importance for mining companies. Implementing a successful disposal area reclamation depends on aspects such as the local environment, climate conditions, chemical nature of the tailings, and the post-closure land use and its integration with local communities.

DRS1, the bauxite residue disposal area of Hydro Alunorte, started its operation in 1995 and comprehends an area of approximately 270 ha in its current configuration. The refinery generates annually over 4.2 Mt of bauxite residue, deposited in the two bauxite residue areas, DRS1 and DRS2. The press filter plant, in operation since 2016, and the progressive deposit rehabilitation, which started in 2018, are some of the practices Hydro Alunorte has implemented to ensure safer and more sustainable operation. Hydro Alunorte intends to reduce operational impacts by

controlling fugitive dust, eliminating wastewater generation, improving the visual impact on the local community, and reintegrating the disposal area with adjacent vegetated areas.

The progressive rehabilitation is expected to be implemented within 15 years and will be done in stripes. It includes constructing and monitoring an experimental area to evaluate the most suitable options for cover layering and capping of the residue, considering the local constraints. The deposit area requires encapsulation on closure as it is designed to store a highly alkaline and saline, low plasticity silt without neutralization. The rehabilitation process generally involves reshaping the residue surface to establish a geometrically shaped configuration, lined and covered with a store-and-release vegetative cover required for plant growth. The underlying bauxite residue is isolated from receiving net percolation to reduce underflow generation. Typically, the liner consists of high-density polypropylene (HDPE) and densified soil. The impermeabilization is also fundamental to isolating the capillarity, avoiding the contamination with rising salts with high alkalinity from the residue, and possibly affecting the root zone [1]. On the other hand, capping the bauxite residue surface avoids the contamination of store-and-release cover, maintaining the subsurface water and soil quality to plant growth.

Despite the absence of a methodology considered definitive for remediation of deposits of this nature, capping systems are considered the safest and fastest method for vegetation cover and environmental impact mitigation [2].

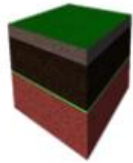
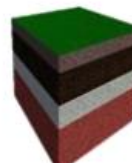
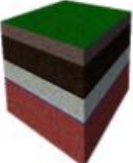
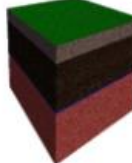
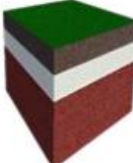
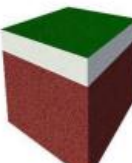
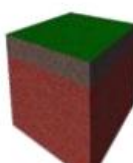
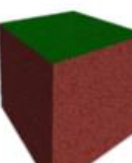
The typical approaches employed to residue management are “cap and store” or “*in-situ* remediation” [2]. Generally, *in-situ* remediation consists of adding amendments (organic or inorganic) to bauxite residue to change the critical physical and chemical properties. Nonetheless, the feasibility of this method usually regards the availability of amendments at reasonable costs [1]. The objective of this solution is to provide natural conditions where the substrate is capable of sustaining vegetation growth. Strategies to decrease pH, salinity, decreasing bulk density and enhancing aggregation have been studied, especially involving the application of gypsum combined with organic amendments [3]. The application of microbial as a bioremediation strategy has also been studied [4]. On the other hand, the “cap and store” solutions isolate the residue with mechanisms to significantly reduce the net percolation through the cover system. So, a low permeability layer of high-density polyethylene liner or compacted clay is applied, followed by a composite system with soil and drainage elements to collect and transport infiltration to the cover. This solution avoids the infiltration owing to rainfall reaching the bauxite residue, reducing the contact wastewater generation at lower rates and the risk of contamination of surrounding areas. The result of a successful “cap and store” solution is residue isolation, so it is expected that the water quality is adequate to return to the environment under legal requirements. Furthermore, the cost of implementing the rehabilitation is crucial since applying liners associated with a multi-layered cover system in a “capping and store” solution must be compared to the costs of *in-situ* remediations, where the amendments availability may significantly impact the implementation costs [2]. The estimate of closure costs forms part of the Global Industry Standard on Tailings Management, which states that the cost for closure, reclamation and post-closure of the tailings facility shall be reviewed and publicly disclosed periodically to confirm adequate financial capacity.

Addressing the high alkalinity and salinity of dust and leached bauxite residue are some of the major challenges in reducing environmental risks in closure projects. The success of different reclamation alternatives, such as capping and *in-situ* remediation of bauxite residue, was assessed in tests involving the experimental area within the Hydro Alunorte bauxite residue disposal area [2]. The author monitored the experimental areas with eight sites of 1 500 m², constructed in April 2019 inside the deposit area, and provided valuable natural regeneration monitoring, plant mortality, and wastewater quality parameters of run-off and subsurface drainage water.

2. Background Studies

Substantial studies were undertaken to understand better the future performance of cover in terms of vegetation selection, surface water management, and erosion control. The cover profile selection looked for the more excellent protocol considering the local conditions. The demand for technology was to promote a cost-effectively revegetation and promote the DRS1 decommissioning best practice regarding environmental, social, and economic passives. The tests performed in experimental areas of 1 500 m² (Table 1) were intended to indicate the most suitable closure practice for treatment, capping, and cover layouts for the DRS1 full-scale rehabilitation process. As a result, more sustainable practices were implemented in 2018 when drum filter operation was stopped on DRS1 and replaced by press filters. The progressive closure of DRS1 was started by reshaping the amorphous drum filter residue surface with cut and fill compaction using press filter residue.

Table 1. Rehabilitation profile selection [2].

Area 1A - permeable cap		Area 1B - permeable cap	
1- Drainage geocomposite above residue 2- 60cm densified soil 3- 20 cm thick final topsoil 4- Revegetation		1- 30cm layer of sand above residue 2- 40cm of densified soil 3- 20 cm thick final topsoil 4- Revegetation	
Area 2A - impermeable cap		Area 2B - impermeable cap	
1- Liner above residue 2- 30cm thick layer of sand 3- 40cm of densified soil 4- 20cm topsoil 5- Revegetation		1- Liner above residue 2- 60cm densified soil 3- 20cm thick topsoil 4- Revegetation	
Area 3A - no cap (in situ remediation)		Area 3B - no cap (in situ remediation)	
1- Amendment with gypsum 2- 30cm of topsoil 3- Revegetation		1- Amendment with gypsum 2- Revegetation	
Area 4A - no cap (in situ remediation)		Area 4B - no cap (control)	
1- 30cm topsoil above residue 2- Revegetation		1- Revegetation directly over the residue	

The sites received fertilization following the same protocols containing N, P, and K. The areas were seeded with a mix of species. The effluent sampling occurred bimonthly with the collection of run-off and data from lysimeters. Biannually, three pits of 20 cm in depth were dug for soil sampling [2]. Two years of monitoring data provided essential inputs for DRS1 rehabilitation in terms of:

- Low permeability caps negatively affected the vegetative development when compared to permeable caps;
- Area 3A (in situ remediation) had more excellent plant growth when compared to 2A and 2B (low permeability cap);
- Na, Al, and Fe concentration seems to affect vegetation development and natural regeneration in areas 3B and 4A;
- Layer permeability may affect metal concentration in subsurface drainage wastewater.

2.1 Rehabilitation Profile Selection

The experimental field performance was evaluated using an analytic hierarchy process (AHP). The objective was to identify the area with the best performance with preference to the vegetative development and the effluent characteristics over the implementation cost. The chosen alternative was the best fit for environmental performance, and cost-effectiveness should be considered a secondary criterion. The evaluation attributed different weights to the leading indicators of run-off and subsurface water: metal concentration, turbidity, and organic matter received a weight of 53.25 %, pH weighted 17.75 %, the vegetation cover index was 22 %, and the cost per square meter was 7 % [2].

Regarding pH, the median for subsurface water from areas 1A and 1B exceeded the *Conselho Nacional de Meio Ambiente* (CONAMA) 430 reference with pH above 9. Similar results were obtained for surface water median values in areas 1B, 3B, and 4B.

The run-off and subsurface water characteristics showed a dispersed metal concentration. The surface water presented higher aluminium values for 1B [12.59 mg/l], 4B [7.53 mg/l], and lower in 3A [0.59 mg/l] and 2A [0.39 mg/l]. On the other hand, the dissolved aluminium found in subsurface water were higher in 1B [28.21 mg/l], 1A [23.32 mg/l] and lower in 2A [1.41 mg/l], 2B [1.28 mg/l]. The peak for sodium in surface water were 2B [372.2 mg/l], 4A [233.9 mg/l] and lower in 4B [11.595 mg/l], 1B [1.401 mg/l]. The lower sodium in subsurface water was found in 2A [20.025 mg/l], 1B [6.339 mg/l] and 1A [1.585 mg/l].

The vegetation cover index was assessed based on the Visible Atmospherically Resistant Index (VARI). The analysis resulted in a VARI index (μ) from 43 (area 4B) to 167 (area 1B). The cost per square meter, the lowest value indicator, varied from approximately BRL 28.00 (area 4B) to BRL 203.00 (area 3B). The AHP evaluation is summarized in Table 1, with the 2A (Figure 1) technique providing the best solution for DRS1 closure.

Table 2. Rehabilitation profile selection.

Profile	1A	1B	2A	2B	3A	3B	4B
Result	0.15	0.09	0.17	0.13	0.13	0.06	0.09
Ranking	2nd	6th	1st	3rd	4th	7th	5th



Figure 1. Rehabilitation experimental areas - Hydro Alunorte.

2.2 DRS1 Reclamation

The closure design provides a set of activities detailed in a decommissioning plan for the various plant assets to be implemented by the industrial operator to fulfill requirement for the community. Therefore, the project aims to gather the procedures to achieve the safe closure of the disposal area, considering legal aspects, environmental, social, and economic conditions of the plant assets and surrounding area. The chosen solutions were implemented to establish the biological, geochemical, physical stability, good visual appearance, proper landscaping while minimizing the requirement for effluent treatment in closure and post-closure scenarios. Additionally, the closure plan is subject to revision during the operation and active care to guarantee the legislation conformance and compliance with to the key performance indicators.

The closure plan includes 11 divisions or strips within the 270 ha deposit area. The division areas vary from 6.7 ha (lane 1) to 30.5 ha (lane 5). The sequence for rehabilitation prioritized the areas with the highest potential for fugitive dust and visual impact mitigation (Figure 1). As a result, the rehabilitation starts from the center moving towards the edges. The starting point is from the oldest sectors of the deposit in the southeast (areas with no disposal since 2009), moving forwards to the southwest, and ending in the northern disposal areas. The construction sequence is presented in Figure 2.

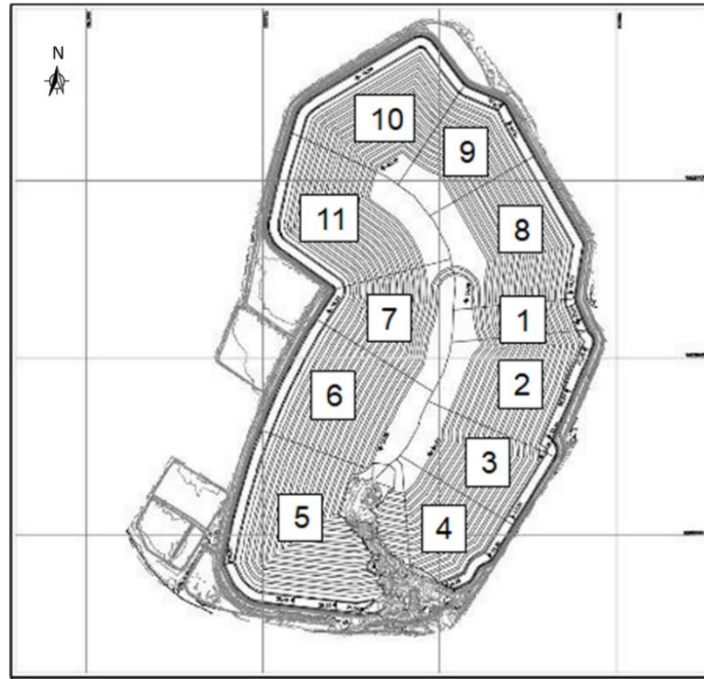


Figure 2. Rehabilitation s – DRS1, Hydro Alunorte.

The landscape design focused on physical stability, so the final configuration should guarantee:

- Slope-angles of 1V:5H, with 15 m wide berms, minimize erosion and facilitate surface and subsurface drainage in the long term. The global slope-angle is 1V:12.5H;
- Provide a 40 cm protective layer, covered with a 20 cm vegetal soil layer to allow selected vegetative root growth;
- Fitting the previous drum filter residue surface, minimizing cut-and-fill works;
- Cover the existing drum filter residue surface with a press filter residue compacted layer;
- Geometry to attend the long-term factor of safety satisfactory.

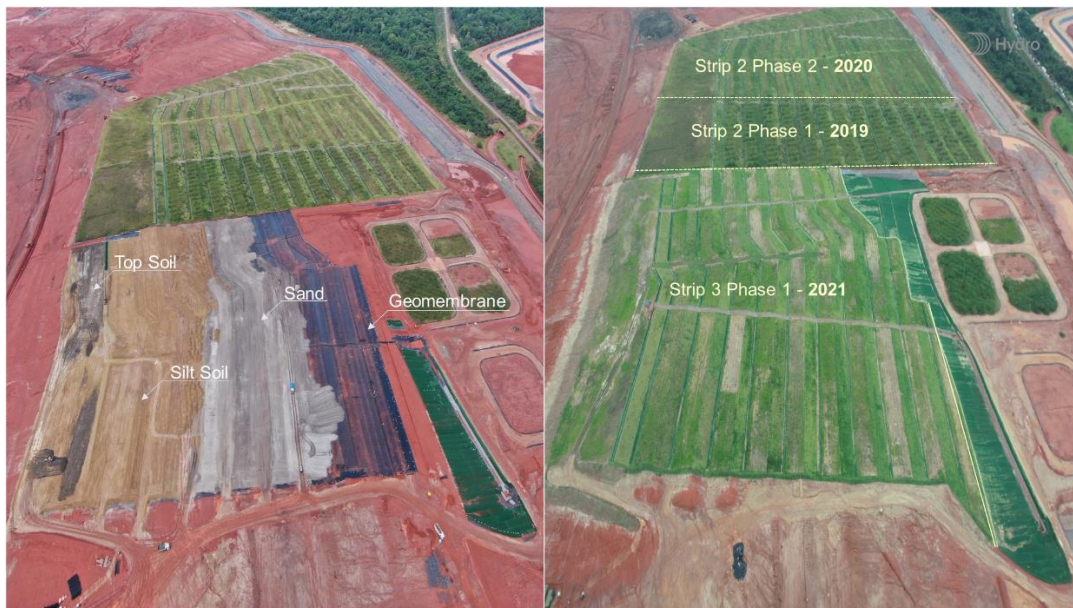


Figure 3. Rehabilitation progress – Strips 2 and 3 – DRS1, Hydro Alunorte.

The final layout is presented in Figure 4.



Figure 4. Digital Model of DRS1 Reclamation.

3. Materials and Methods

3.1 Monitoring Plan

The rehabilitation monitoring plan consists of a periodical measurement and recording of the key success indicators (KPIs). The main parameters that indicate the success of the rehabilitation progress are the surface, subsurface water, and soil quality, mortality index and natural regeneration vegetation development, and presence of mesofauna.

Table 3. Rehabilitation monitoring plan.

Parameter	Frequency
Water quality – <i>in situ</i>	Monthly
Soil monitoring	Biannual
Plants Mortality	Biannual
Natural regeneration	Biannual
Presence of mesofauna	Biannual

3.2 Water Quality

The *in-situ* sampling and result analysis followed the procedures of ABNT NBR 15.847:2010 [5] and ABNT NBR ISO/IEC 17.025 [6].

The pH of the run-off and subsurface water were measured on site with Horiba U-50 multiparameter. The collected samples were packaged in hermetically sealed recipients and sent to *Bachema* and *Magma* laboratories, accompanied by chain-of-custody reports.

The samples for analysis of metals and non-metals followed a standard procedure [2], being acidified in nitric acid (pH < 2). The metal concentration analysis was carried out using an inductively coupled plasma optical emission spectrometer (ICP-OES).

3.3 Soil Chemical Monitoring

Three composite soil samples were collected at 0.20 m depth, resulting from homogenizing and quartering processes. The preparation used deionized water. The samples were dried in an oven at 105 °C for three days. ICP OES determined aluminum (Al) and iron (Fe).

3.4 Vegetation Mortality and Natural Regeneration

The plant mortality is monitored biannually during visual inspections. The vegetation growth is monitored, and extinct species are registered on a planting map. The mortality is given by the percentage of initially planted seedlings and the number found in each survey. Likewise, the natural regeneration is measured during visual inspections, also taking notes of immigrant species found inside the rehabilitated area.

4. Results

4.1 Water Chemical Analysis

The dissolved iron found in run-off samples from strip 2 was within limits defined by CONAMA 430, namely 15 mg/l, for the entire data collection (Figure 5). The monitoring showed a peak for dissolved iron in October 2021, potentially related to external interferences such as reshaping works in residue surfaces nearby the sampling point. The iron concentration in the run-off was mainly associated with natural occurrences in soil used in the coverage of strip 2, obtained from local excavations, which has an average concentration of 8.713 mg/kg for iron.

The CONAMA 430 does not establish a limit for dissolved aluminium. Except for October 2022, the subsurface water from strip 2 showed higher dissolved aluminum values than surface water (run-off), possibly caused by the topsoil aluminium concentration of 5.940 mg/kg. Since October 2021, strip 2 has consistently shown dissolved aluminium lower than 1.59 mg/l for subsurface water and 1.00 mg/l for surface water.

Regarding pH monitoring, there is no evidence of a relation between surface and subsurface drainage circuits and the pH magnitude (Figure 6). The monitoring indicates average pH of 7.01 (standard deviation of 0.69) in samples collected from run-off. At the same time, subsurface water showed an average of 6.96 for pH (standard deviation of 0.65), demonstrating compliance with CONAMA 430 limit value, pH < 9.

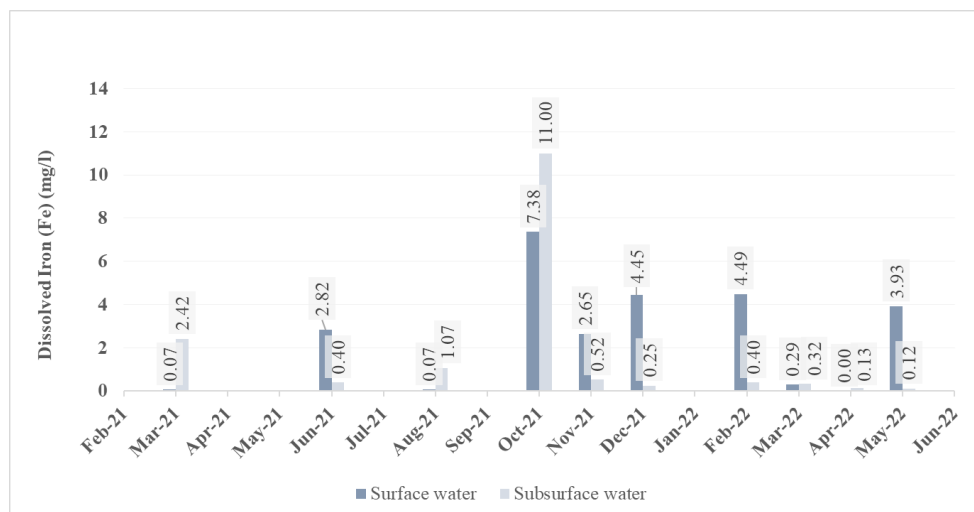


Figure 5. Dissolved Iron– strip 2 – DRS1, Hydro Alunorte.

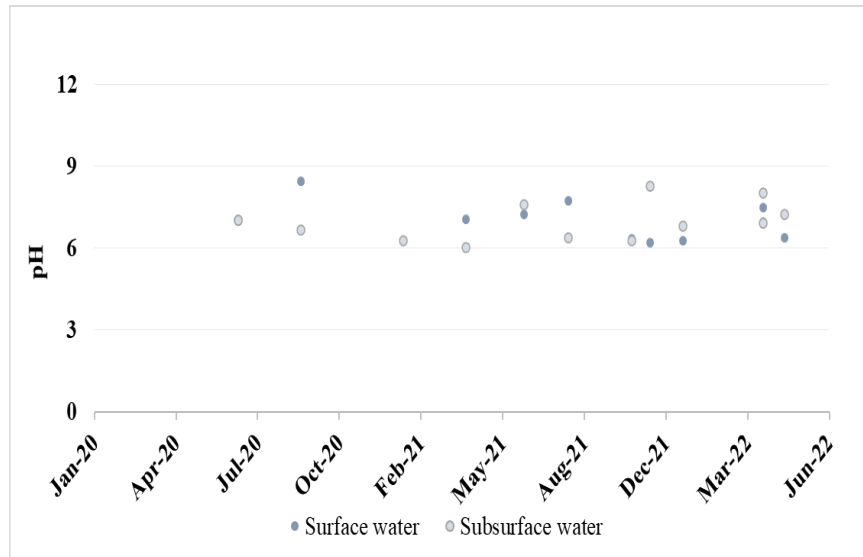


Figure 6. pH Monitoring – Stripe 2 – DRS1, Hydro Alunorte.

4.2 Soil Chemical Analysis

The elements Al and Fe concentration were found to be significant in soil samples due to the natural characteristics of the local soil. The soil employed in cover layers was obtained from foundation excavation.

The topsoil used in the coverage of reclamation strips has an average concentration of 5 940 mg/kg for aluminum and 8 713 mg/kg for iron.

4.3 Vegetation Mortality, Natural Regeneration and Mesofauna

Based on the experimental field, 29 local native species unlikely to develop deep root systems were initially selected for seeding.

The results included 12 months of monitoring since seeding. Figure 7 resumes the plant mortality rates registered for the DRS1 rehabilitated area. The graph shows the species with higher mortality rates, *Jurubeba*, *Mini Flamboyant*, and *Ucurum*, all with mortality rates higher than 90 %. On the other hand, seven species have distinctly performed, with less than 5 % mortality; these were *Sombreiro*, *Abiú*, *Marupá*, *Mamorana*, *Genipapo*, *Bacabi*, and *Cuieira*. All the selected species are from the local biome.

According to monitoring results, over 5 900 plants died out of over 26 000 seedlings. The mortality rate of approximately 32 % is slightly higher than 25.9 % observed in experimental area 2A [2]. Figure 8 shows the relation between seedlings and dead plants, individually presented by species.

The natural revegetation with native species from local fauna integration increased from 45 immigrant species found in December 2020 to 79 in January 2022. The mesofauna notes 21 species in July 2021 and 23 in January 2022 (Figure 9).

Figure 10 shows the general view of strip 2 rehabilitated area and strip 3 in progress, highlighting the visual mitigation.

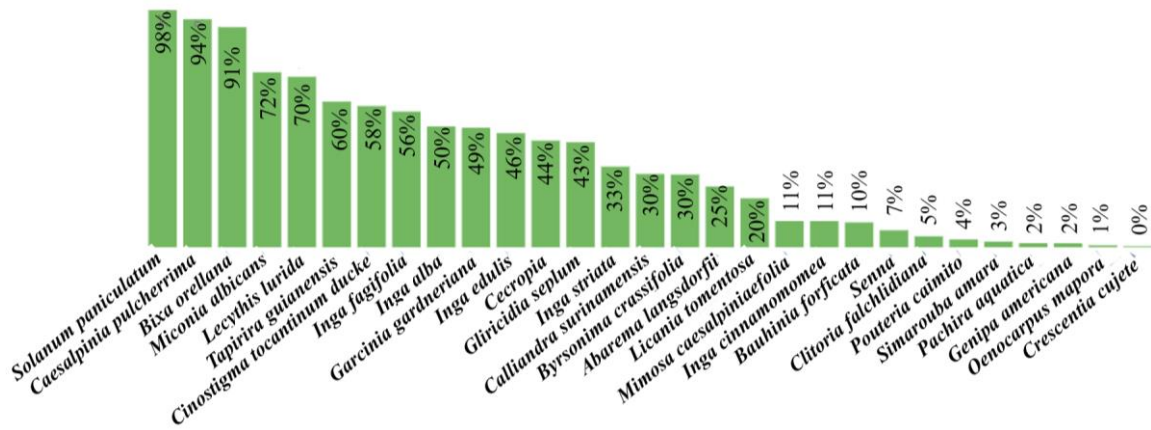


Figure 7. Plant Mortality Rates – Rehabilitated Strips 2 and 3 – DRS1, Hydro Alunorte.

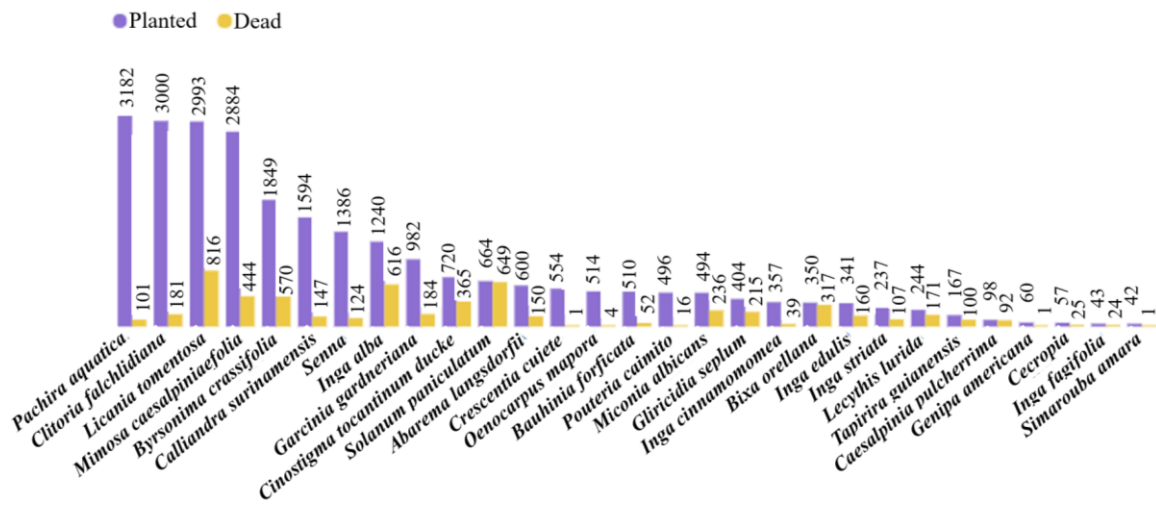


Figure 8. Plant Mortality – Rehabilitated Strips 2 and 3 – DRS1, Hydro Alunorte.

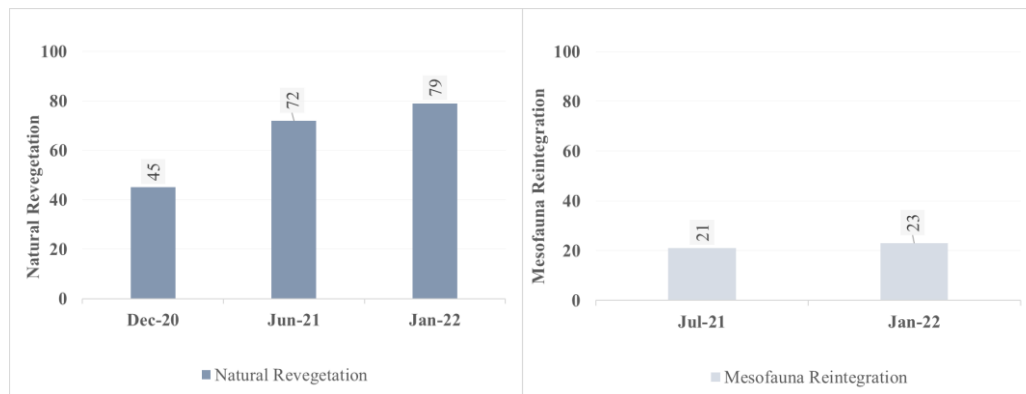


Figure 9. Natural Revegetation (a) and Mesofauna Reintegration (b) – Strips 2 and 3.



Figure 10. General View – DRS1 Reclamation, Hydro Alunorte.

5. Final Considerations

This paper described the rehabilitation method employed by Hydro Alunorte on DRS1 closure. Up to date, over 30 ha were rehabilitated, with approximately 26 000 seedlings planted, 79 immigrant plants, and 23 fauna species reintegrated into the rehabilitation area.

Based on water analysis, dissolved iron and aluminium reached peak values in October 2021, possibly due to external interferences. Nonetheless, the subsurface water showed consistently higher values of dissolved aluminium when compared to surface water, which might be related to soil origin. The pH results demonstrate compliance with the CONAMA 430 limit value of $\text{pH} < 9$ for the 12 months of monitoring for all samples from surface run-off and subsurface. The CONAMA 430 legislation was also complied with dissolved iron during the 12 months monitoring.

Hydro Alunorte shall monitor the reclamation progress to confirm the excellent rehabilitation performance while progressing the closure of the bauxite residue disposal area DRS1. The results collected to date clearly show the potential of DRS1 reintegration into the local area.

6. References

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