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Rehabilitation and Landscape Integration of a Tailings Deposit in Atacama, Chile

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Abstract **-** Phytotechnologies are technologies based on the use of plants for improving environmental problems in order to detect, degrade, remove or contain contaminants in soil, groundwater, surface water, sediments or air. The use of phytotechnologies on tailings deposits is an innovative solution to mitigate the emission of particulate material, minimize wind erosion, and to improve environmental conditions and safety. Native and endemic plants are recommended, since are acclimatized to the local environment and favour natural ecological successions. The Huasco Pellets Plant (HPP), located 5 km southwest of the city of Huasco and 700 km to the north of Santiago de Chile, produces agglomerates of iron minerals. In compliance with the requirements of the Environmental Authority, the company presented a Filtered Tailings Deposit (FTD) project with a storage capacity of 14.6 million tonnes of tailings (7.6 million m^3). The project includes the coverage of the tailings with granular material, soil and vegetation during the progressive closure to integrate the FTD into the landscape, once the operation ceases. To guarantee a successful closure of the FTD, a phytotechnological program developed with the purposes of 1) selecting plant species for the progressive closure; 2) designing and supervising the installation and operation of a plant nursery on site; 3) designing, supervising and monitoring an experimental pilot of the phytotechnological program and 4) the elaboration of a methodological guide. To the date, the phytotechnological program has achieved the selection of the native plant species *Frankenia chilensis, Jarava plumosa, Nolana sedifolia* and *Nolana divaricata*, the implementation and operation of the nursery, and the tolerance to tailings sands of 2 of the species, together with the identification of zones differentially affected by wind erosion. The main challenges for the execution of the phytotechnological program are the governance of the project, the inclusion of the FTD closure plan from the beginning of the operation, the effective communication with the community, the company´s experience in R&D projects, regulations and guidelines for the rehabilitation of mining sites and vulnerability of biological systems to climate change. We recommend that any phytotechnological program for the rehabilitation and landscape integration of a mining tailings deposit must address these challenges, in order to minimize the risk of technological implementation.

Keywords**:** tailings facility; phytotechnologies; land rehabilitation; environmental biotechnology

1. Introduction

Technologies such as the use of chemical products, vegetation or the provision of layers of earth or stone material on the affected areas, are available to control the emission of dust from tailings deposits [1, 2]. Phytotechnologies are technologies based on the use of plants, for improving environmental sanitation and conservation problems [3]. The main approach of phytotechnologies is to detect, degrade, remove or contain contaminants in soil, groundwater, surface water, sediments, or air [4]. The use of phytotechnologies in tailings deposits is an innovative solution to mitigate the emission of particulate material, minimize wind erosion, and to improve environmental conditions and safety [5]. Because plant growth and reproduction can be limited by local environmental conditions, the selection of species for phytotechnologies is a critical step. Native and endemic plants are recommended, since are acclimatized to the local environment and favour natural ecological succession [6].

A conceptual model for the landscape integration and rehabilitation – designed and developed during 2020 and 2021 by a research team of the Pontificia Universidad Católica de Chile (PUC), Pontificia Universidad Católica de Valparaíso (PUCV), Universidad de Santiago de Chile (USACH) and Compañía Minera del Pacífico (CMP) – gave rise to a Master plan for landscape integration and rehabilitation in the southern coastal border of Huasco (MPLIR), in the area where the Huasco Pellets Plant Filtered Tailings Facility (FTF) is located (Figure 1). The MPLIR considers the definition of ecological management areas for the mitigation and compensation measures proposed in the Environmental Impact Assessment (EIA), in compliance with the requirements of the environmental authority. The measures have been designed with a strategic vision at a territorial scale, which promotes sustainable and innovative development based on new uses and pioneering programs for landscape rehabilitation in Huasco. This initiative is conceived as a multidisciplinary and innovative project, focused on transforming an area impacted by mining activities into a social and environmental asset, with benefits for the ecosystem and the community. As part of the MPLIR, in 2020, CMP developed a phytotechnological program (PP), with the aim to achieve the landscape integration and rehabilitation of the site, after the closure of the FTF, that will be in operation in 2024. The four phases of the contemplates plants selection, the designing and operational supervision of a local plant nursery, the implementation of an experimental phytotechnological pilot, and the development of a guide with the PP methodology. All the activities are coordinated by CMP with the participation of the local community. To the date, the main outcomes of the PP are the selection of plant species, the implementation and operation of a specialized nursery in the city of Huasco, the determination of tolerance to tailings sands of 2 of the selected species, the identification of "hot spots" for MP emission in the study area, and the development of activities involving the community. During the development of the PP, a series of challenges have been identified, being the most decisive for the implementation of the activities, the governance of the program, the inclusion of the closure plan from the beginning of the operation of the FTF, the effective communication to generate trust in the community, the increase and consolidation of the company´s experience in the execution of R&D projects, the need for regulations and guidelines for the rehabilitation of mining sites, and the vulnerability of biological systems linked to climate change. Overall, the joint work of the company and the universities involved in the project is highlighted.

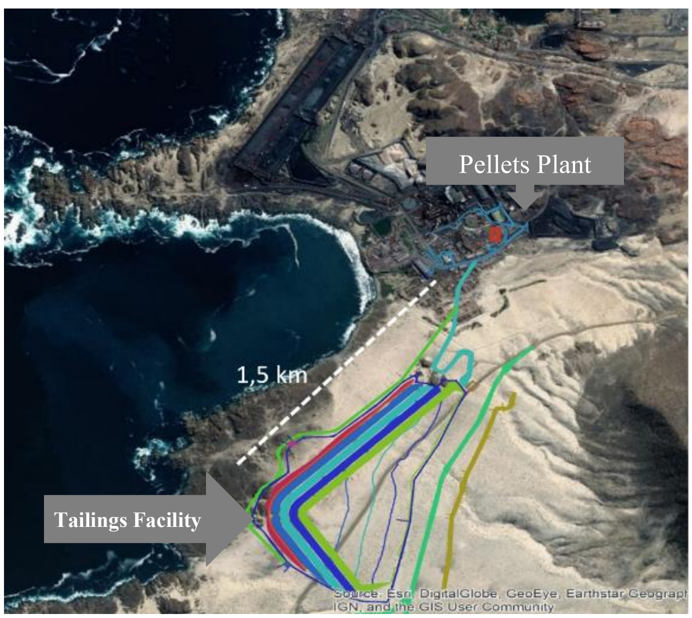

Figure 1. Area of the study site showing the location of the Pellets Plant and the location where the tailings facility will be located

2. Methodology

2.1. Plants sampling and selection

Seeds and vegetative material sampling in the study area was carried out using 50 m transects, according to [7]. The sampling sites were georeferenced, and stems, leaves and seeds were sampled, stored in plastic bags, labelled and taken to USACH. Plants collected were herborized, identified, and the relative abundance, the conservation status and the plant life strategy were documented. The criteria to select plant species for the phytotechological program were 1) The presence and abundance of the species, as well as their conservation status; 2) Reproductive potential of the plant species, experimentally confirmed in laboratory and nursery assays, and 3) Plant tolerance and ability to establish on the tailings substrate in the pilot assay.

2.2. Substrate sampling and sample analysis

Triplicate soil samples were taken at 0-20 cm depth, from different sites and were analysed as composite samples. To measure pH and electrical conductivity (EC), water was added in a to the dried sample (1:5) in shaker for 1 h at 20 rpm. Organic matter (OM) was determined according to Walkley & Black (1934) [8]. 500 mg of sample were dried for 72 h at 60°C and sieved with a 1 mm sieve. 0.5 M sodium dichromate and 10 mL of 96% sulphuric acid were added and left to stand for 30 min at room temperature. 35 mL of Milli-Q water were added to the sample, left to stand for 24 h. Absorbance at 600 nm was measured. A sucrose calibration curve was used.

2.3. Measurement of particulate material

The particulate material in saltation was determined by using Leatherman traps as established in the NCh3266-2012 [9]. Measurement points were located and recorded, and a Leatherman traps were installed and replaced each 82/83 days. A circular hole 85 cm deep and 50 mm diameter was drilled using a spiral hole with a depth equal to that of the length of the tube used as a jacket, then the sleeve was inserted into the hole, so that the upper edge emerged to the ground surface. Then, the collector tube was installed inside the jacket tube and the trap tube was placed on it by using a union coupling. The open slot of the trap tube was oriented towards the prevailing wind direction. UTM coordinates, collector tube number and date for each point were registered.

2.4. Plant propagation and tolerance

The propagation method used for the plant species was by stem cuttings and division of the rhizome, using the rooting agent Keri Root®. In total, 70 explants for each specie were grown in nursery conditions with an average light of 10 h, average temperature of 13°C and humidity of 66%. When the plants presented roots, they were transferred to a controlled growth system with an average light for 10 h, average temperature 18°C and humidity of 62%. Irrigation was carried out every 4 days per spray with a volume of 50 mL using Phostrogen® fertilizer at 0.3%. The composition of the initial substrate used for rooting was 15% coconut fiber, 20% perlite and 65% vermiculite. The plants were maintained until complete rooting and then were transplanted to the soil substrate (20% leaf soil and 80% sand). The plants for the tolerance experiments were kept in these conditions for 2 weeks, until reaching an average height of 18.5 cm. The proportions of tailings and substrate soil for the treatments of *Nolana divaricata* and *N. sedifolia* are shown in Table 1. The treatment lasted 4 weeks. The effective concentration (EC_{50}) was determined by performing a dose-response curve with the biomass data, height and number of normalized shoots, in which the minimum value corresponds to 0% and the maximum to 100% [10]. The determination of the EC_{50} was carried out by means of mathematical calculations and graphs using the GraphPad Prism 8 software (GraphPad Software, Inc., San Diego, USA).

Table 1. Proportion of tailings and soil substrate for the treatment of *N. divaricata* and *N. sedifolia*

N. divaricata		***N. sedifolia***	
Soil (%)	**Tailing sands (%)**	**Soil (%)**	**Tailing sands (%)**
100	0	100	0
75	25	70	30
50	50	40	60
25	75	0	100
0	100	-	-

3. Results and Discussion

3.1. Organic matter (OM), electrical conductivity (EC) and soil pH

Table 2 shows the pH, CE and OM of 4 soil samples collected in August 2021 at "Playa Brava" sector in Huasco. The pH between the samples showed significant differences between sites 3 and 5. Differences in the EC were observed between sites 3 and 8. The OM content showed no differences.

Table 2. pH, Electrical Conductivity (EC) and percentage of organic matter (% OM) of soil samples collected in August 2021. Different letters indicate significant differences (One-way ANOVA).

Site UTM	Average pH	Average EC (µS/cm)	Average OM (%)
279691.24 E/ 6845985.56 S	$5,7^{a}$	484^{a}	$5,07^{a}$
279719.83 E/ 6845960.16 S	$6,1^{ab}$	387^{ab}	$5,90^{a}$
279785.01 E/ 6845920.91 S	$6,4^{b}$	272^{ab}	$1,67^{a}$
279387.85 E/ 6845779.64 S	$6,1^{ab}$	251^{b}	$3,04^{a}$

3.2. Plant reproduction and community involvement

Twelve 12 plant species that were present in the study site: *Nolana divaricata, Nolana sedifolia, Franckenia chilensis, Jarava plumosa, Encelia canescens, Tetragonia marítima, Heliotropium floridum, Oxalis gigantea, Ephedra chilensis, Adesmia litoralis, Balbisia peduncularis, Chuquiraga ulicina.* Four of the species were preliminary selected (*Nolana crassulifolia, Nolana divaricata, Frankenia sp* and *Jarava plumose)* due to their propagation capacity after treatment with the rooting agent Keri-Root ® or a suspension of cyanobacteria. For *N. crassulifolia*, 100 cuttings/plant were obtained. For *N. divaricata*, 50 cuttings/plant were generated. In *J. plumosa*, the division of the rhizome generated up to 10 individuals per bush. Regarding *Frankenia* sp, 20 individuals/plant were generated. The rooting experiments showed that the treatment with the suspension of cyanobacteria improved the survival rate up to 30% for all the 4 species. The information on the plant propagation techniques was transferred to members of the community in a workshop held for the Huasco nursery workers at the Parcela Los Olivos located in Huasco, Atacama Region. The activity had the aim to involve members of the Huasco community in the phytotechnological program activities.

3.3. Plant tolerance to tailing sands

The determination of EC_{50} showed that *Nolana divaricata* was more tolerant that *Nolana sedifolia* in three parameters determined (Table 3).

Table 3. EC_{50} results for the relative biomass, relative height and relative shoots number for *Nolana divaricata* and *N. sedifolia*.

EC_{50} Parameter	***N. divaricata*** 	***N. sedifolia*** 
Relative biomass	6,4%	3,3%
Relative height	75,8%	3,3%
Relative shoots number	9,4%	3%

3.4. Monitoring of particulate material

The distribution of seven particulate material measurement points at the area were the tailings deposit of the Huasco Pellet Plant is shown in Figure 1. Results obtained during the year 2022 are shown in Figure 2.

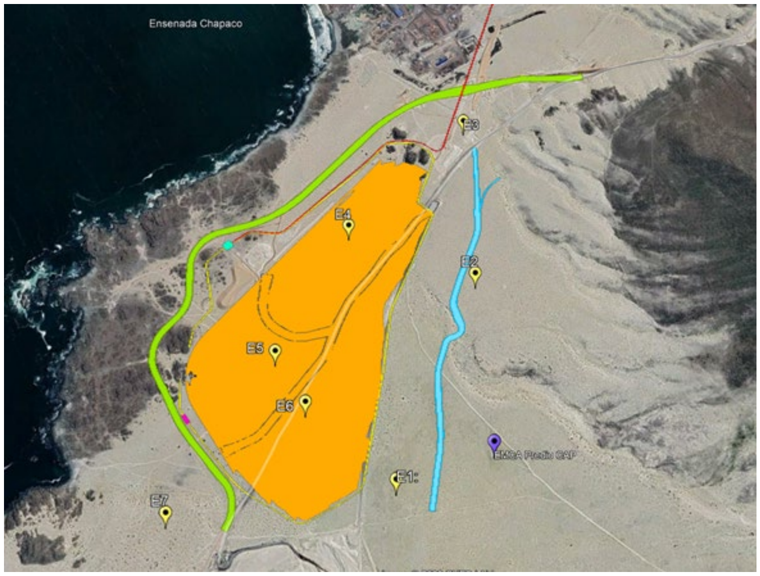

Figure 1. Monitoring points (yellow pins) for particulate material in the sector of the filtered tailings deposit of the Pellet Plant, Huasco (orange area). Lateral road (green), contour channel (light blue).

The Leatherman traps were taken to the laboratory to determine the material collected during 2022. Figure 2 shows the material collected in each trap per day, were points 1, 3 and 6 are the ones that collected the largest amount of material. Point 6 is next to the road, near an ash deposit, point 3 is the nearest to the Pellet Plant and point 1 is in the sector where the company´s air quality monitoring station is located, outside the area where the deposit will be located.

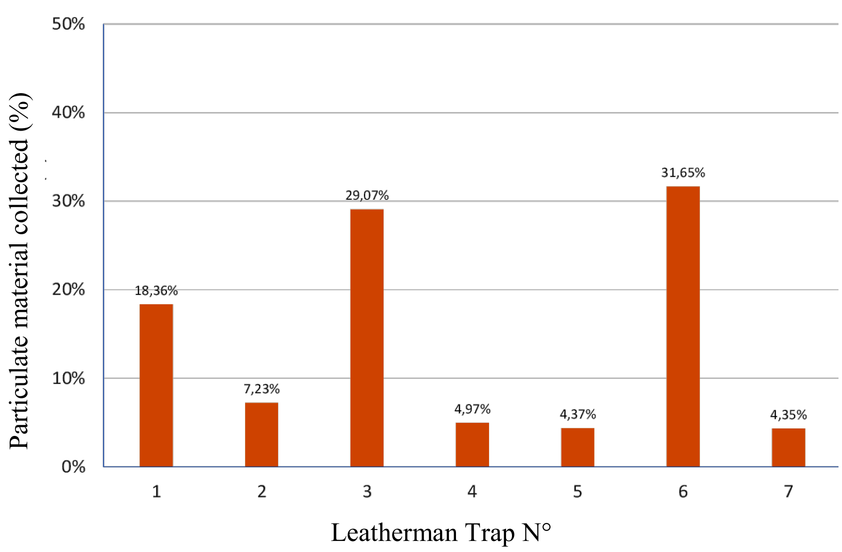

Figure 2. Average of material collected daily in 2022 in the study area.

3.5. Main challenges

The main challenges identified, that might jeopardize the successful execution of the project are the governance of the program, the inclusion of the closure plan from the beginning of the operation of the FTF and the effective communication to generate trust in the community. Secondly, other challenges arise, those that need to be addressed through the involvement of regulatory authorities and the development of research, namely the increase and consolidation of the company´s experience in the execution of R&D projects, the need for regulations and guidelines for the rehabilitation of mining sites, and the vulnerability of biological systems linked to climate change. One approach that arise by the experience during the PP development is the proposal of Rehabilitation Plans with clear objectives, consistent with the future use of land, and defined together with the communities. Remediation, in addition to being an integral component of a mining company's sustainable development strategies, is a key indicator of the company's environmental performance, as a poorly remediated mining project leaves a negative legacy for society, governments and the communities. The complexity of a mining project justifies the relevance of addressing rehabilitation as progressive projects for the different sites where the components of a mine are located, such as pits, waste rock dumps, tailings deposits, among others, considering different land uses at the end of the mine life cycle. These land uses must consider the level of intervention, affectation and resources required in the areas to be rehabilitated, so as to guarantee the maintenance of the land use previously defined in the rehabilitation objectives. The rehabilitation objectives may vary according to the conditions of each site and the options defined with the interested parties, being essential the protection of the safety and health of the people who live in the areas surrounding the site to be rehabilitated. A Rehabilitation Plan may consider the restoration of the area to achieve pre-mining ecosystem conditions, or the recovery of the area for a similar land use and ecological standards, but not identical to the original, with the establishment of habitat in degraded areas. Alternatively, a Rehabilitation Plan may incorporate activities intended to generate new land forms and uses for the benefit of the community, such as establishment of wetlands, recreational areas, urban development, forestry, industry, agriculture, or other uses. Whatever the ultimate objective, rehabilitation plans must be developed and implemented early and be an integral part of the mining project, so that they are developed progressively during the life cycle of the mine. Progressive rehabilitation implies operational and cost efficiency, for which financial and human resources must be allocated without hindering production. The costs associated with rehabilitation processes must be considered and adjusted during project planning and operation, which can ensure efficient use of capital and equipment, so for a Rehabilitation Plan to be effective and considered successful, it is essential that the rehabilitation objectives are defined together with the interested parties, and that an effective integration of the Rehabilitation Plan is carried out in the planning and cost structure of the mining operation. Finally, the Rehabilitation Plans must be prepared considering national and international regulatory aspects and the guidelines of the International Council for Mining & Metals (ICMM), which include Environmental Resilience within the four key areas defined for the development of global mining activity.

4. Conclusion

Two of the 4 central objectives of the phytotechnological program for the progressive closure of the filtered tailings deposit of the Huasco Pellet Plant have been addressed. Native plant species that are part of the local vegetation (two Nolana species, *Frankenia chilensis* and *Jarava plumosa*) have been preliminary selected for the program. The propagation of the plants has been standardized and the information has been transferred to members of the Huasco community, for their involvement in the program activities. A plant nursery in Huasco has been built, and is currently in operation to provide the plants that will be used for an on-site experimental pilot. The monitoring of the particulate material at the site where the filtered tailings deposit will be settled, showed 2 points of major potential erosion that must be addressed during the implementation of the phytotechnological program. To date, the execution of the phytotechnological program has made it possible to generate information for the integration and landscape rehabilitation of the filtered tailings deposit of the Huasco Pellet Plant, during its progressive closure. We recommend that the planning of a phytotechnology programme for the rehabilitation and landscape integration of a mining tailings deposit must consider the aforementioned challenges, in order to minimize the risk of technological implementation, including the development of Rehabilitation Plants according to the needs of the company, considering the community involvement, the regulation and the landscape integration.

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