Application of Phytotechnologies for the Control of Wind Erosion and Landscape Rehabilitation of a Filtered Tailings Deposit in the Atacama Region, Chile

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ABSTRACT: *Landscape integration of mining infrastructures, sites, and environmental liabilities is currently a fundamental area of attention in the sustainable practices of mining production. 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, in the Atacama region of Chile. As part of this model, in 2020, a Phytotechnological Program was developed that considers technologies based on the use of plants on tailings deposits as an innovative solution to mitigate the emission of particulate material, minimize wind erosion, and improve environmental conditions and safety. Native and endemic plants are recommended, as they are acclimatized to the local environment and favor natural ecological successions. The Huasco Pellets Plant (HPP), located 5 km southwest of Huasco and 700 km north of Santiago de Chile, produces agglomerates of iron minerals (pellets). 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 tons of tailings (7.6 million m3). 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 control particulate matter emissions from the FTD during the operation, closure, and post-closure stages of the facility. To meet this goal and guarantee a successful closure of the FTD, a phytotechnological program was 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 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 two 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 the vulnerability of biological systems. 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 deposit, wind erosion, phytotechnologies, landscape rehabilitation

SITE LOCATION: Geographic Database

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INTRODUCTION

Wind erosion affects soils and mining waste deposits, causing the emission of particulate matter into the atmosphere that impacts the environment, productive activities, and the inhabitants of the areas near the facilities. This problem affects massive deposits of mining waste such as tailings deposits and is of concern to mining companies and affected communities. The filtered tailings deposit of the Pellets Plant in Huasco, which began its operation in 2023, must face the challenge of operating while controlling the emission of particulate matter into the urban area during the operation, closure, and post-closure of the facility.

To determine the emissions of particulate matter, a methodology was developed that considered the geotechnical characterization of the materials that are in the site area of the filtered tailings deposit and the tailings that will be stored, along with wind tunnel tests to evaluate the performance of the materials against wind action. Subsequently, a simulation of the wind effect on the site area with and without the project was developed using computational fluid dynamic modeling (CFD), which considered the information generated in the wind tunnel tests. The results of the modeling allowed the design of a wind erosion monitoring program during the entire lifecycle of the filtered tailings deposit, which provides information on the baseline of wind erosion in the site area of the facility and background information to define measures to control wind erosion during the operation and closure stages of the facility.

Landscape integration of mining infrastructures, sites, and environmental liabilities is currently a fundamental area of study in the sustainable practices of mining production. International experience, especially in Europe and North America, shows a wide variety of methods and initiatives that aim, on the one hand, to predefine landscape quality objectives to guide the criteria for the location and configuration of activities in the territory and, on the other hand, to develop strategies for mitigation and remediation of environmental impacts (Latz, 2001; Turner, 2008). In this scenario, landscape architecture provides a multidisciplinary perspective and fundamental tools to solve the various scales of approach, both in terms of planning the areas involved, as well as in the design of spaces and programs that favor the social use of the remediated sites (Berger, 2008; Moreno, 2022).

Technologies—such as the use of chemical products, vegetation, or the provision of layers of earth or stone material in the affected areas—are available to control the emission of dust from tailings deposits (Al-Lami et al., 2019; Festin et al., 2019). Phytotechnologies are technologies based on the use of plants to improve environmental sanitation and conservation problems (Henry et al., 2013). The main approach of phytotechnologies is to detect, degrade, remove, or contain contaminants in soil, groundwater, surface water, sediments, or air (Tsao, 2003). The use of phytotechnologies in tailings deposits is an innovative solution to mitigate the emission of particulate material, minimize wind erosion, and improve environmental conditions and safety (de Souza et al., 2021). 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 they are acclimatized to the local environment and favor natural ecological succession (Tapia et al., 2017).

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 (FTD) 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, CMP developed a phytotechnological program (PP) in 2020, intending to achieve the landscape integration and rehabilitation of the site after the closure of the FTF. This facility began operation in 2024 and will end in 2030 when the full coverage of the deposit will be completed. The four phases of the PP include: plant 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 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 two 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 FTD, 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.

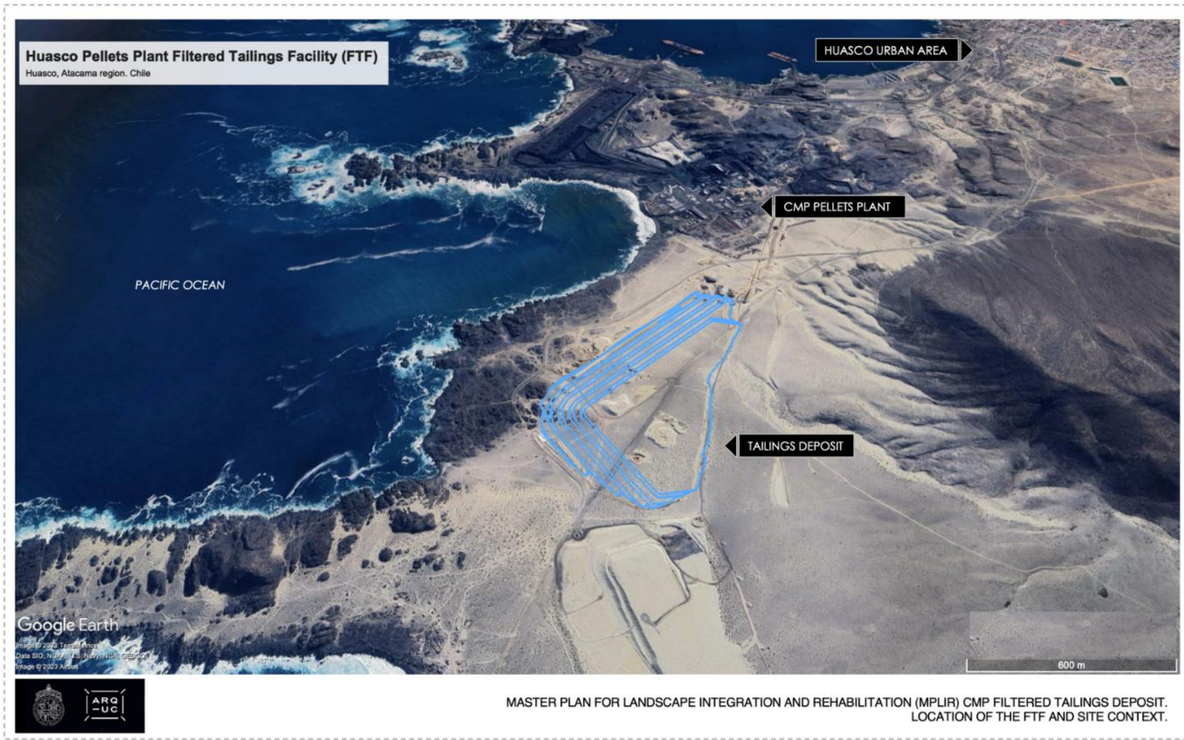

Figure 1. Area of the study showing the Pellets Plant and the location of the filtered tailings deposit.

METHODOLOGY

Landscape Integration and Rehabilitation

Strategies:

The MPLIR establishes a prospective view of the territory, which assumes the challenge of promoting sustainable and innovative development, based on new uses and pioneering programs for the environmental rehabilitation and enhancement of the coastal landscape of Huasco. The intervention strategies determine the organization of the spatial components and use programs of the Master Plan, relating to the various mitigation and compensation measures proposed. The diagram below (Figure 2) shows the relationships established between the measures, spatial components, and use programs.

First, the circulation system, comprising pathways, pedestrian walkways, and the coastal route facilitate the organization of mitigation and compensation measures aimed at restoring public accessibility to the landscape affected by the FTD. Second, the ecological management areas, consisting of buffer strips and management zones, enable the integration of compensation measures focused on implementing the phytotechnological program for soil restoration and the recovery of native and endemic vegetation representative of the coastal desert landscape. Third, the equipment system, including the interpretation center and various observation areas, organizes compensation measures designed to promote the site's tourist use and environmental education for conservation purposes.

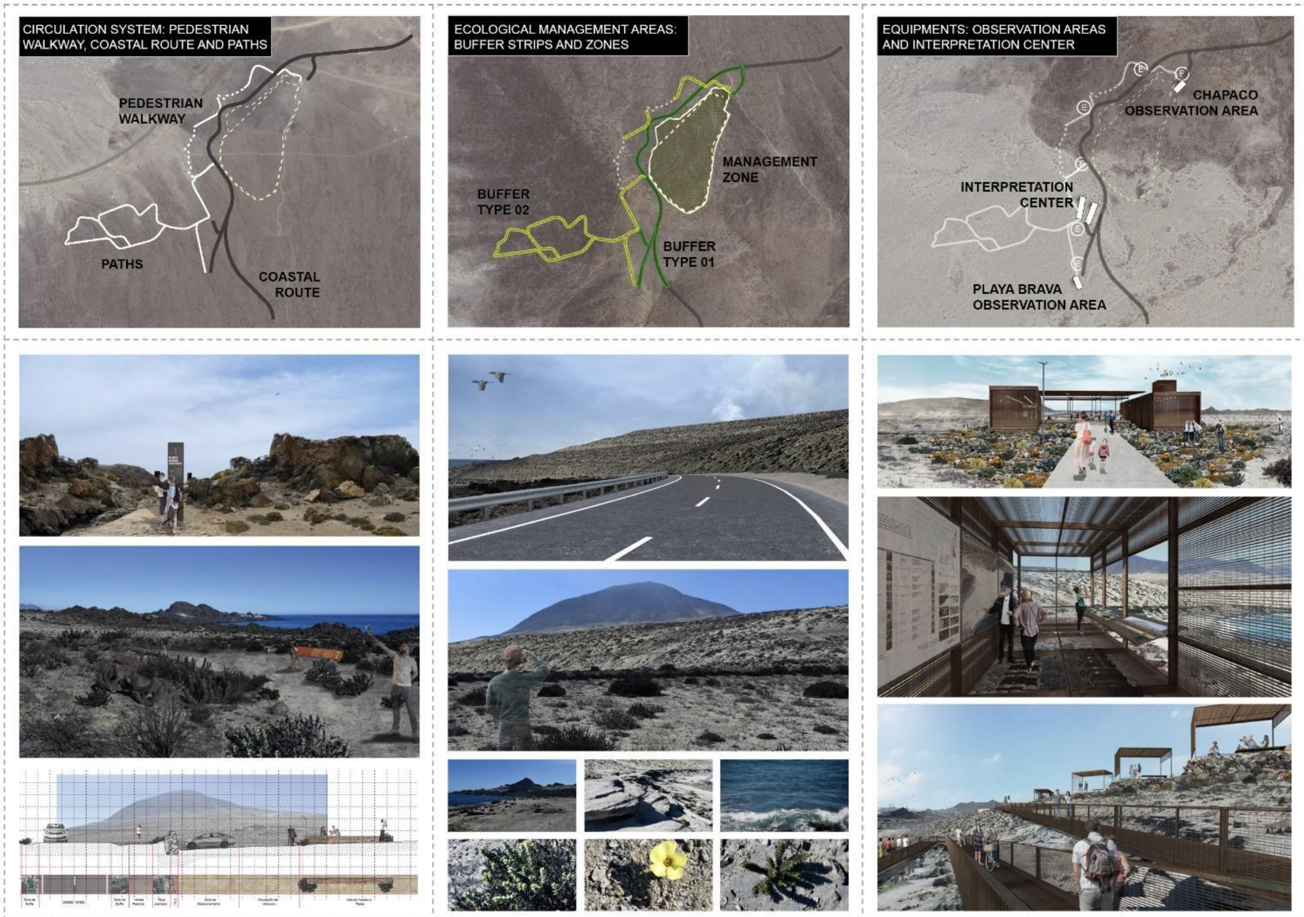

Figure 2. MPLIR integrated system of circulations, equipment, and ecological management areas, which organizes and relates the mitigation and compensation measures proposed in the Environmental Impact Assessment (EIA) (Moreno, 2022).

Architecture Plan:

The Master Plan configures an integrated system of circulations, equipment, and ecological management areas, which organizes and relates the mitigation and compensation measures proposed in the Environmental Impact Assessment (EIA), in compliance with the requirements of the environmental authority. In this way, the measures are not established as random interventions related to traditional impact compensation methods, but instead become part of a strategic vision linked to a territorial scale. This system seeks to recover, conserve, and enhance the biophysical, cultural, and aesthetic attributes of the coastal landscape, promoting sustainable tourism use at the regional and national levels, environmental education, and recreational use by the inhabitants of the community, including improving accessibility for the seaweed harvesting communities that currently inhabit this territory.

Accessibility and Tourist Use Program (trails, viewpoints, and equipment stations):

As part of the MPLIR, landscape architecture design considers the development of accessibility programs and tourist use of the site through a series of infrastructures and facilities located in different sectors, incorporating paths with interpretative signage, viewpoints, rest areas, and parking areas. All the sectors are connected by a system of pedestrian trails defined as the Coastal Promenade and also through the Coastal Route that runs through the Master Plan area in a north-south direction.

Phytotechnological Program

A phytotechnological program has been proposed, adjusted to the environmental conditions of the area, which will allow the inclusion of native and endemic plant species in the landscape architecture design to rehabilitate and reinsert the area occupied by the filtered tailings deposit, in the post-closure stage. The rehabilitation and landscape reinsertion, maintaining the vegetation density and the most abundant plant species in the area, will allow the dune to maintain its potential for wind erosion before the construction of the filtered tailings deposit and maintain effective control of wind erosion in the sector in the post-closure stage of the facility. The implementation of this interdisciplinary project will bring benefits to the ecosystem and the community, such as giving sustainable use to the surface, mitigating and compensating impacts on the landscape of the infrastructure components of the project, integrating them harmoniously into the landscape, and solving accessibility and mobility requirements of the communities towards areas of interest present on the coastal edge.

Plant Sampling and Selection:

Seeds and vegetative material sampling in the study area was carried out using 50 m transects, according to Gold et al. (2004). The sampling sites were georeferenced and stems, leaves, and seeds were sampled, stored in plastic bags, labeled, and taken to USACH. Plants collected were herborized and 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) the reproductive potential of the plant species, experimentally confirmed in laboratory and nursery assays, and 3) the plant's tolerance and ability to establish on the tailings substrate in the pilot assay.

Substrate Sampling and Sample Analysis:

Triplicate soil samples were taken from different sites at 0-20 cm depth and analyzed as composite samples. To measure pH and electrical conductivity (EC), water was added to the dried sample (1:5) in a shaker for 1 h at 20 rpm. Organic matter (OM) was determined according to Walkley and Black (1934). 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 was added to the sample and left to stand for 24 h. Absorbance at 600 nm was measured. A sucrose calibration curve was used.

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 species were grown in nursery conditions with an average light of 10 h, average temperature of 13°C, and a humidity of 66%. When the plants presented roots, they were transferred to a controlled growth system with an average light for 10 h, an average temperature of 18°C, and a 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).

Measurement of Particulate Material

Wind Erosion:

Wind erosion of soil is a natural geological process of landscape evolution, which, due to human activity, has accelerated and become an agricultural and environmental problem worldwide (Memoria Chilena, 2021).

The terms "wind erosion" and "dust emissions" are used to describe the interaction of wind and a sediment surface. Although they are sometimes used interchangeably, they indicate characteristic but complementary aspects of the same phenomenon. The effects of erosion and the consequent emission of particulate matter into the atmosphere are associated with environmental and productive sector impacts.

In wind erosion, the particles deposited on the surface are set in motion by the wind and then transported and sedimented again at a certain distance, depending on the particle diameter and wind speed. Three types of transport can be identified: rolling, saltation, and suspension (Figure 3).

Grain saltation initiates the movement of larger, heavier grains, and small dust particles. In saltation, the moving grains collide with other grains, causing the disintegration of the set of grains on the surface, presenting different degrees of mobility. Wind erosion only occurs when there are soil grains that are capable of moving in saltation. The severity of the occurrence of wind erosion depends on the balance between soil, vegetation, and climate conditions.

In Chile, mine tailings deposits are generally composed of granular materials, whose granulometries, in general, classify them as silty sands, clayey sands, or poorly graded sands.

Tailings Deposit Evaluation:

The evaluation of wind erosion in tailings deposits during the design, operation, and closure stages is a useful decision-making tool when it is necessary to define and implement mitigation measures. Evaluating wind erosion to avoid impacts on the environment, the productive sector, and the population centers located in the area of influence of the deposits.

The proposed methodology for the evaluation of wind erosion in tailings deposits is based on NCh 3266-2012 "Tailings Deposits - Characterization of the particulate matter suppressant product - Evaluation of performance properties of tailings treated with particulate matter suppressant," proposed from the development of research projects carried out at the Pontificia Universidad Católica de Valparaíso, in the period 2007-2012, and includes in situ and laboratory evaluations.

To carry out the wind erosion assessment, a characterization of the tailings deposit site and aspects of the construction project must be performed, including the location of the tailings deposit, type of deposit, geotechnical characteristics of the tailings, topography, and meteorological information of the site, among others.

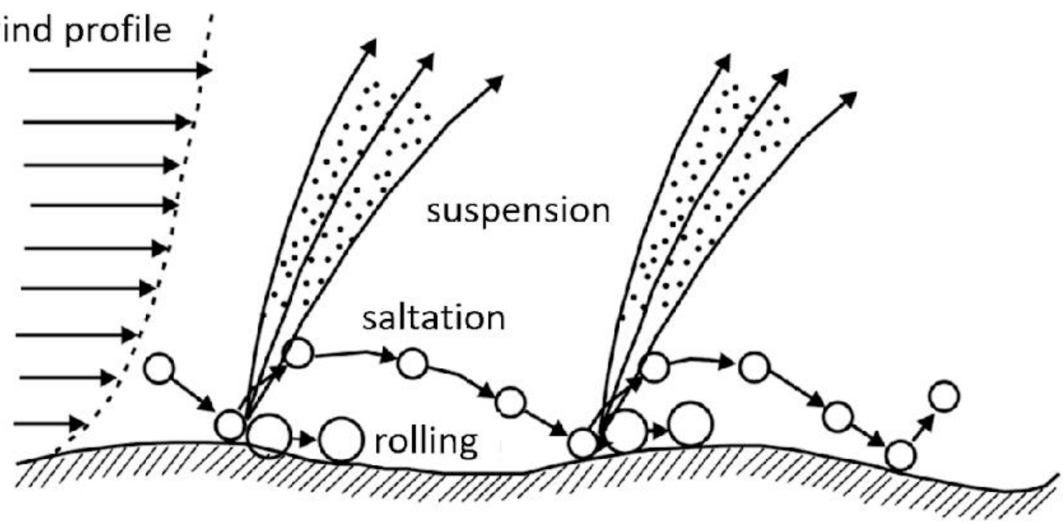

Figure 3. Types of aeolian particle transport (Buschiazzo and Airmar, 2003).

Laboratory Evaluation: The laboratory evaluation of wind erosion requires the implementation of a wind tunnel, which allows the generation of different wind speeds and the material at which its performance is to be evaluated. Laboratory testing has applications in the different stages of development of a tailings dam project, as it evaluates the behavior of granular materials under different wind speed conditions, to define the baseline and the behavior of the tailings, which can be very beneficial in the design of the deposit, because mitigation measures can be incorporated at this stage. Similarly, in the operation stage when the tailings are already being affected by the wind, it is expected to quantify the problem more quickly, or when it is required to evaluate the performance of tailings treated with different technologies to suppress dust emissions. The proposed methodology considers the analysis of the wind speeds of the site, the geotechnical characterization of the material to be evaluated, and the determination of the wind exposure time. With this information, the laboratory tests will be designed to determine the material's performance against wind effects.

On-site Evaluation: Wind erosion measurements in the facility's location area allow for determining the conditions that generate it and establishing a baseline. The implementation of a time series of measurements (i.e., before and during all stages of operation of the facility) makes it possible to contrast the effect of wind erosion in the area under study at different stages of project development. The work methodology considered the study of the characteristics of the tailings deposit location sector, such as topography, speed, and direction of the predominant wind, as well as the growth stages of the tailings deposit. With this information, the number and location of the monitoring points, as well as the frequency of the measurements were determined, establishing the work methodology for monitoring wind erosion at the tailings deposit site. Quarterly measurements have been taken in the area where the tailings dam is located since 2020, before the start of construction of the facility, collecting data on the effect of wind erosion, along with the speed and direction of the predominant wind. Measurements in the area occupied by the tailings deposit have continued after the start of the operation of the facility in 2024. To evaluate wind erosion, Leatherman traps are used (technology proposed in NCh 3266-2012), which capture the particles that the wind moves on the surface by saltation (Figure 4).

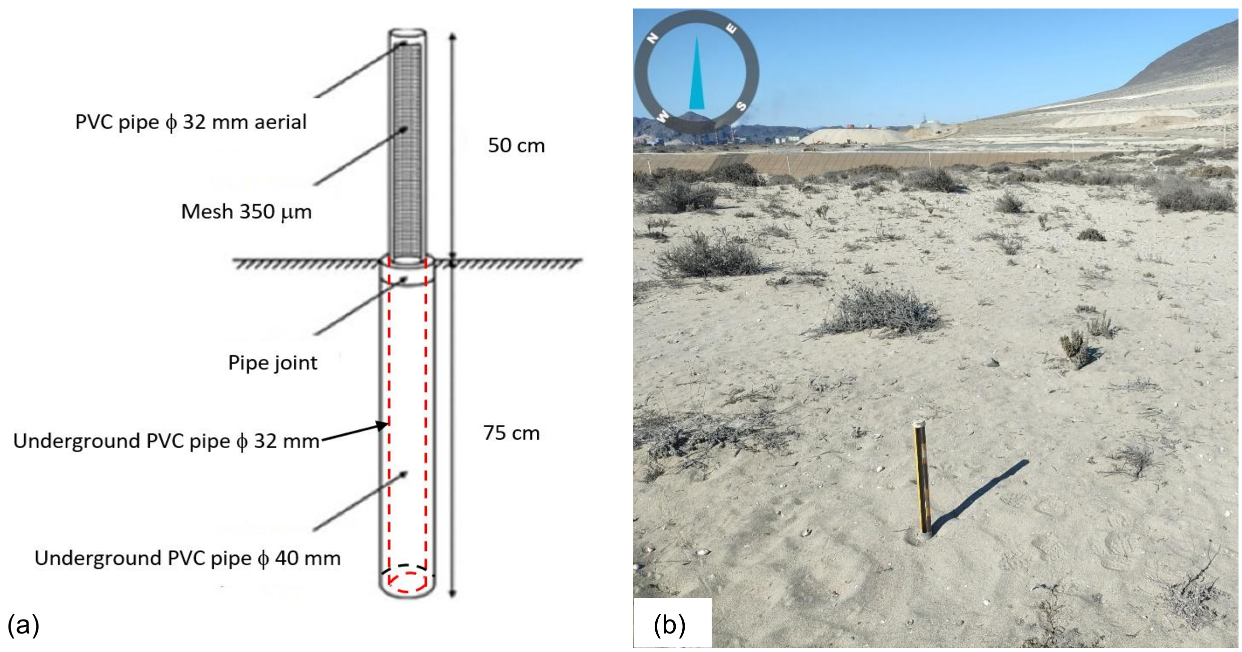

Figure 4. (a) Schematic of a Leatherman trap. (b) Leatherman trap E7.

RESULTS

Master Plan for Landscape Integration and Rehabilitation in the Southern Coastal Border of Huasco, Pilot Design Areas

The MPLIR defines three strategic sectors as pilot areas for progressive implementation (Figure 5):

- Sector 1 Chapaco Viewpoint: corresponds to the area located at the northern vertex of the filtered tailings deposit, which includes tourist equipment for the reception of visitors, parking areas for vehicles and bicycles, pedestrian paths, and landscape rehabilitation gardens with native and endemic species of the area.

- Sector 2 Interpretation Centre: corresponds to the area located on the coastal edge strip to the southwest of the filtered tailings deposit, where the pedestrian paths of the coastal edge promenade and the vehicular access that connects with the Coastal Route are located. This sector entails the most important equipment of the project, the Interpretation Center, which includes parking areas for vehicles and bicycles, pedestrian paths, and landscape rehabilitation gardens with native and endemic species of the area.

- Sector 3 Playa Brava Viewpoint: the area located where there's public access to Playa Brava, to the south of the filtered tailings deposit, which includes tourist facilities for the reception of visitors, parking areas for vehicles and bicycles, and pedestrian paths for access to various areas of tourist and environmental interest. The pedestrian circulation system that connects these three sectors, through the Coastal Promenade, contemplates the implementation of buffer strips type 2 (BS2) on its edges. Likewise, these sectors are also connected through the Coastal Route, which allows accessibility for vehicles and bicycles. On the edges of this route, the buffer strip type 1 (BS1) is implemented.

Figure 5. Shows the landscape design for three pilot areas as a part of the MPLIR (Moreno, 2022).

Phytotechnological Program

Plant Reproduction and Community Involvement:

Twelve plants species 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,* and *Chuquiraga ulicina.* Four of the species were preliminarily 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/plants were generated. The rooting experiments showed that the treatment with the suspension of cyanobacteria improved the survival rate by up to 30% for all four species (Figures 6, 7, 8, and 9). 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.

Figure 6. Plant species grown at the nursery in the Atacama Region.

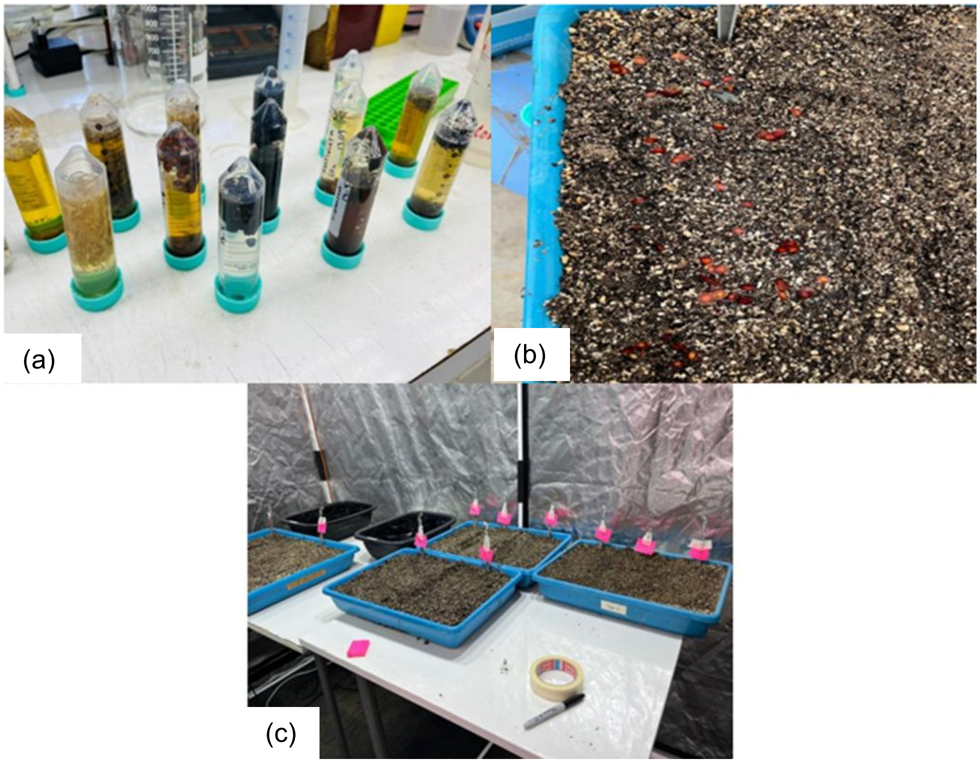

Figure 7. Methodology for seed germination: a) seeds activation; b) sowing of seeds; c) trays with the germinated seeds.

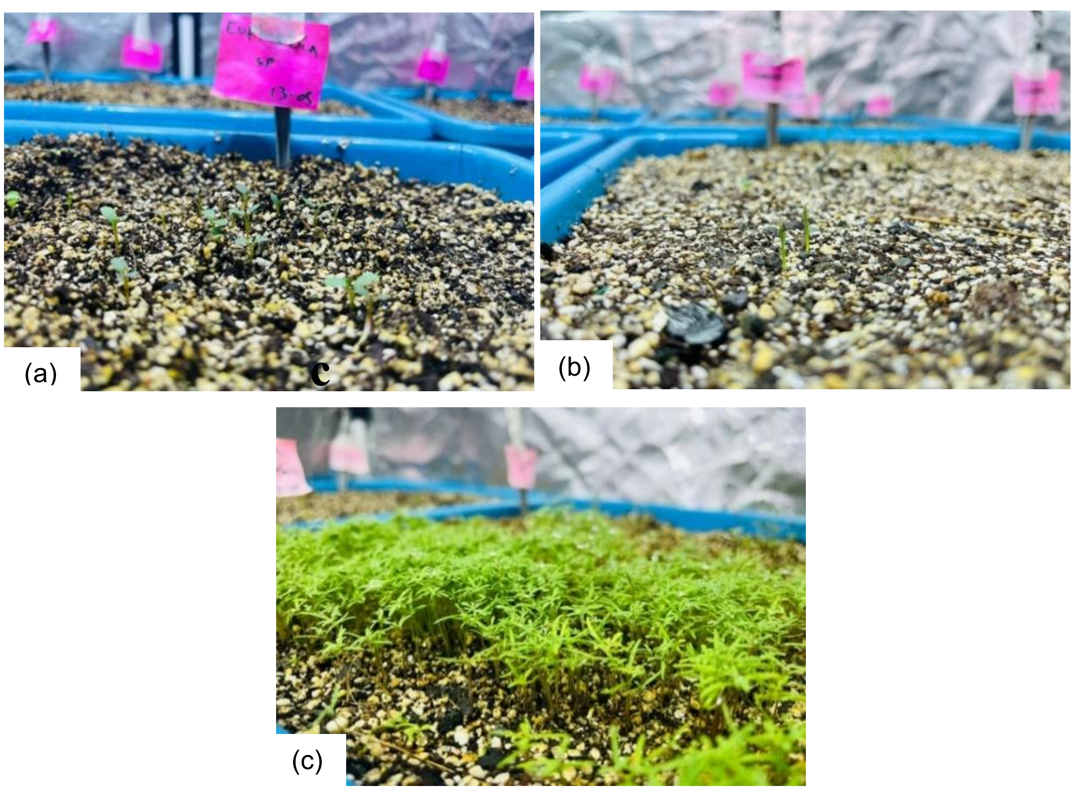

Figure 8. Seed germination of three plant species: a) Euphorbia sp.; b) Rhodophiala bagnoldii; and c) Rhodophiala advena.

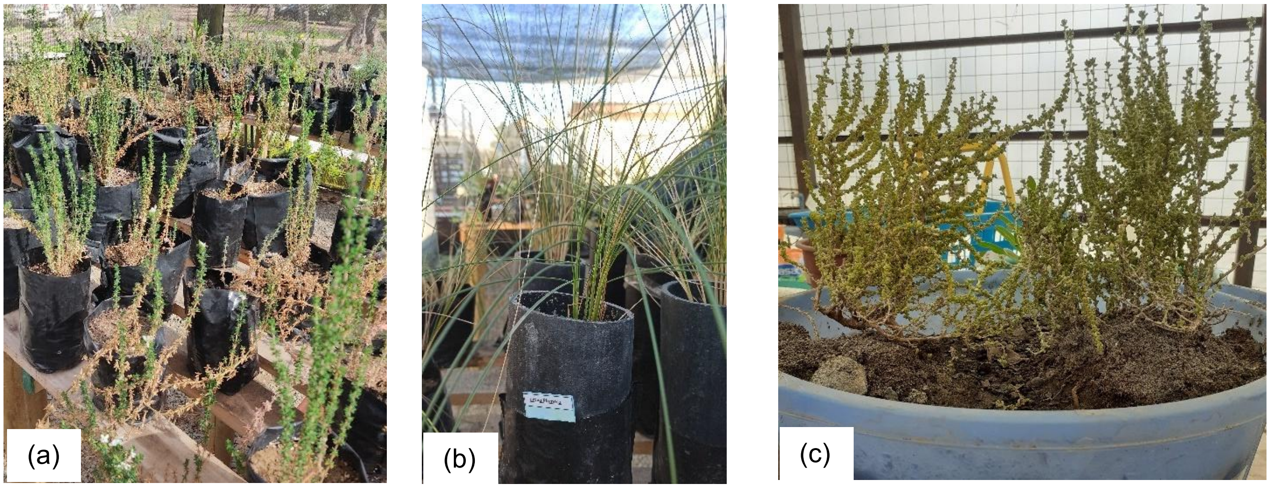

Figure 9. Plants reproduction at the experimental nursery: a) Fanckenia chilensis; b) Jarava plumosa; and c) Nolana sedifolia.

Organic Matter (OM), Electrical Conductivity (EC), and Soil pH:

Table 1 shows the pH, CE, and OM of four soil samples collected in August 2021 at the "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 1. The pH, Electrical conductivity (EC) and organic matter (% OM) of soil samples collected in August 2021.

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]

* Different letters indicate significant differences (one-way ANOVA).

Monitoring of Particulate Material

Laboratory Evaluation:

The performance of the dune sand, the tailings deposit site, and the iron tailings were evaluated regarding wind action to determine the threshold wind speed at which particle movement begins on the ground. To achieve this, a geotechnical characterization of the dune sand was performed and the amount of material capable of movement at various wind speeds was determined through wind tunnel testing.

− Geotechnical Characterization of Materials

Dune sand: The grain size distribution of the dune sand revealed that 100% of the material passed through the #10 mesh, 89% passed through the #40 mesh, 14% passed through the #100 mesh, and 6% passed through the #200 ASTM mesh. This corresponds to a poorly graded sand (silty sand) of the SP-SM classification according to the USCS. The specific gravity (Gs) of the dune sand was determined to be 2.8, with a minimum density of 1.5 g/cm^3, a maximum dry compacted density of 1.8 g/cm^3 (Proctor Standard), and an optimum moisture content of 18%.

Iron tailings: The granulometry of the iron tailings shows 96.7% of the material passing the #200 ASTM mesh, liquid limit of 29%, plastic limit of 20%, and a plasticity index of 9%, corresponding to a clay of low plasticity (CL), classification according to the USCS. Specific gravity (Gs) 3.18, minimum density 1.0 g/cm^3, maximum compacted dry density 1.9 g/cm^3 (Standard Proctor), and optimum humidity 18%.

− Wind Tunnel Tests

The tests were conducted in the wind tunnel of the laboratory at the School of Construction and Transportation Engineering of the Pontificia Universidad Católica de Valparaíso. The specimens were prepared by filling metal molds with the material to be tested at a defined density, then installing them in the tunnel, and exposing them to the established wind speed ranges for each material under study, in half-hour increments. For each test, the initial weight of each specimen was recorded, and the weight of the material remaining in the mold was recorded after each half-hour wind application cycle was completed. Each test was performed in triplicate, as shown in Figure 10.

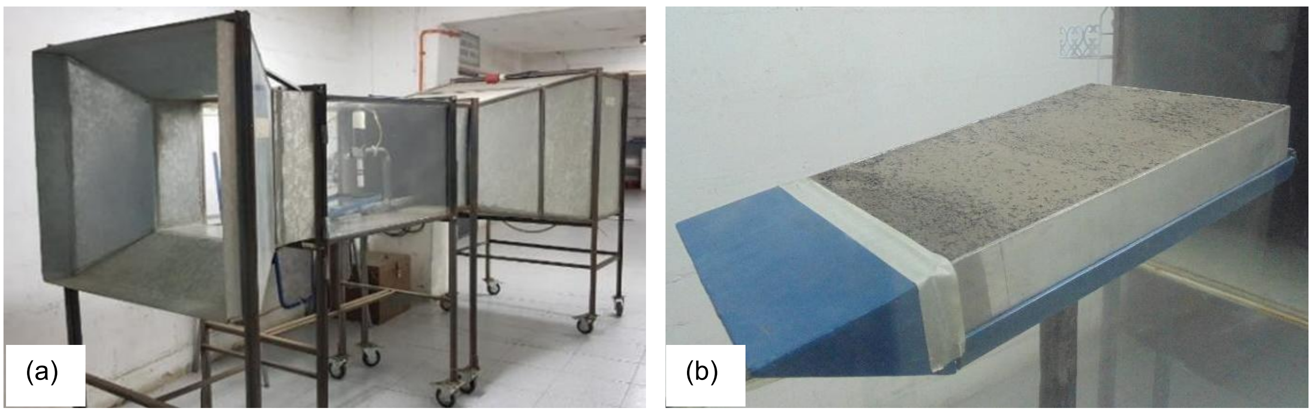

Figure 10. (a) The wind tunnel, and (b) iron tailing specimen filtered in the wind tunnel.

Dune sand: Figure 11(a) illustrates the results of the performance of dune sand specimens prepared in a dry state and at minimum density, exposed to wind speeds of 2 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, and 9 m/s, in half-hour increments. It can be observed that the threshold velocity, for dune sand at minimum density and in a dry state, is above 6 m/s.

Dry iron tailings at minimum density: Figure 11(b) shows the results of the performance of iron tailings specimens prepared in dry state and at minimum density, subjected to wind steps with velocities of 1 m/s; 3 m/s; 6 m/s; 7 m/s; 8 m/s; 9 m/s; 10 m/s; 11 m/s; 12 m/s; 13 m/s; 14 m/s, and 15 m/s, in periods of half an hour per velocity range. It can be seen that the threshold velocity, for the iron tailings at minimum density and in dry state, is above 8 m/s.

Compacted filtered iron tailings: The test specimens were prepared by reproducing the layout conditions according to the design project, for which the filtered tailings were compacted to 95% of the maximum compacted dry density (Standard Proctor) and with 18% moisture, and left to rest for approximately 15 hours before submitting them to the wind tunnel test. Figure 11(c) illustrates the results of the performance of compacted filtered tailings specimens exposed to wind speeds of 1 m/s, 3 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, 10 m/s, 11 m/s, 12 m/s, 13 m/s, 14 m/s, and 15 m/s, in half-hour increments. A better performance of the compacted filtered tailings against wind action is observed and the low percentages of material loss correspond to losses of surface moisture of the specimen due to wind action. Therefore, it was considered that the wind does not mobilize compacted filtered tailings and a defined value of the threshold velocity is not determined for this material.

− Estimated Emissions

The results obtained in the laboratory regarding the performance of the dune sand and filtered iron tailings under the action of wind, together with the information on wind characteristics in the site sector, allowed determining the erosion potential and emissions of particulate matter in the situation without the project and for each stage of the project using the friction velocities obtained through computational fluid dynamic simulations (CFD). Figure 12 illustrates the erosion potential defined for the sector in the initial situation and the final stage of the project, showing that the areas of greatest erosion correspond to the western zone and the upper edges of the reservoir in the final stage of the project.

On the other hand, the estimation of particulate matter emissions in the site area made for each stage of the project allowed us to establish that when the filtered tailings deposit project is implemented, there will be a reduction in total emissions compared to the situation without the project, both during the construction stage and in the final stage of the deposit.

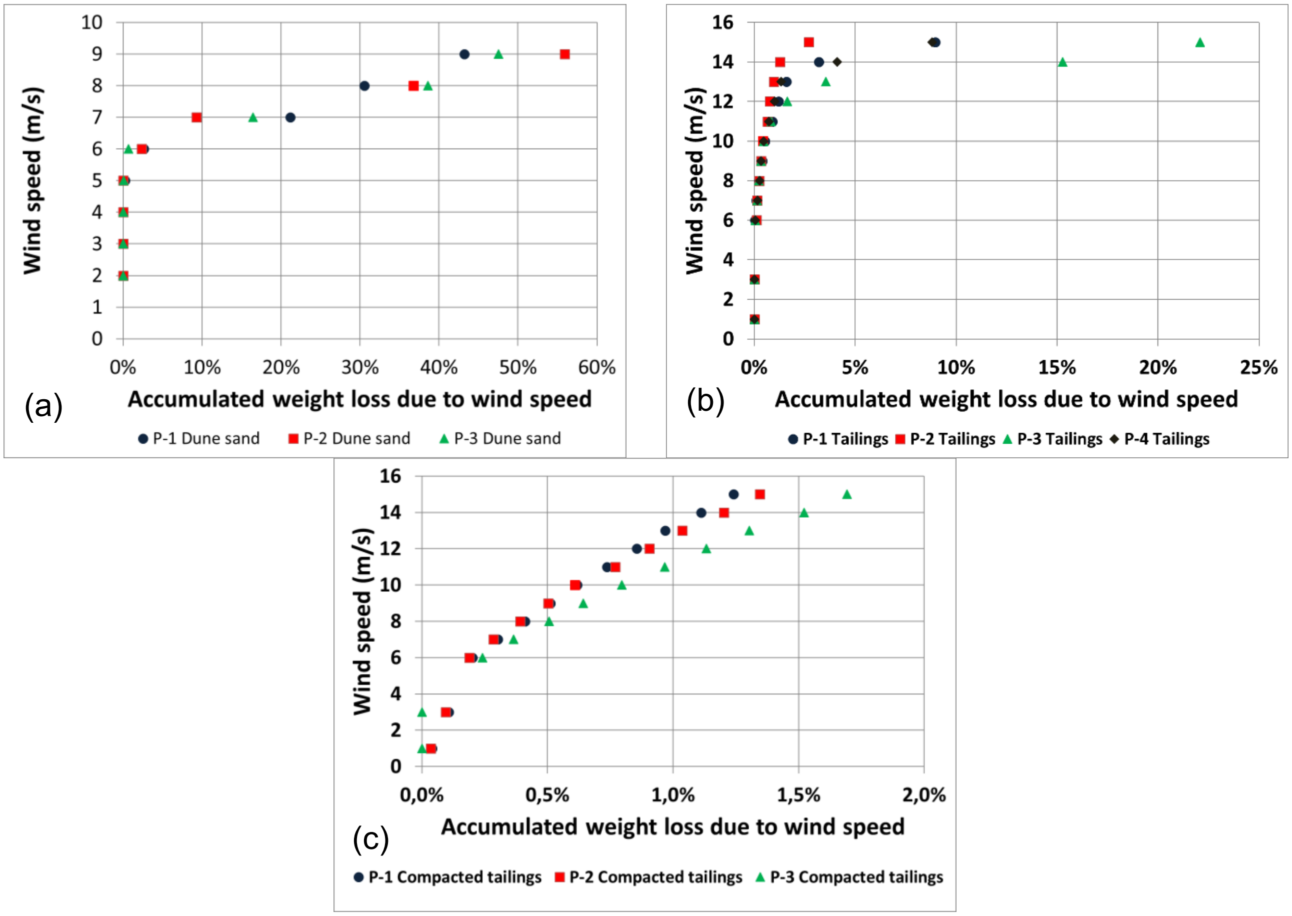

Figure 11. Cumulative material loss in percentage due to wind speed: (a) dune sand in dry state at minimum density, (b) dry iron tailings at minimum density, and (c) filtered and compacted iron tailings (PUCV 2018, PUCV 2019).

There are antecedents in the technical literature regarding the effect that variables such as vegetation typology, wind speed, vegetation cover density, and soil moisture have on the prevention and control of wind erosion, specifically by Qi Luo et al (2020) and Meng, Z., Dang, X., Gao, Y., Ren, X., Ding, Y., and Wang, M. (2018). It has been considered that incorporating in the closure and post-closure stages of the tailings deposit a cover with the substrate and vegetation present in the area under study before the construction stage of the facility, allows the dune to maintain its conformation and its erosion potential against the action of the wind during all seasons of the year. Therefore, in the closure and post-closure stages, maintaining the endemic native vegetation that is adapted to the environmental and substrate conditions of the sector ensures that the erosion potential does not increase, that wind erosion does not increase compared to the situation without the project, and that effective rehabilitation and landscape reinsertion of the sector is achieved.

According to measurements made in the field, the density of vegetation cover in the study area corresponds to 40% of the total surface area, and the height of the plants varies according to the type of plant species between 0.2 m for the smallest species and 1.0 m for the largest shrub vegetation.

The filtered tailings deposit is located in a dune field, with native endemic vegetation of shrubby and herbaceous type, which determines the baseline of the erosion potential of the sector. The erosion potential and the emissions of particulate matter in the area were determined from simulations carried out with a computational fluid dynamic (CFD) model, which used information on the topography of the sector, wind tunnel tests with dune sand and filtered tailings, as well as background information from a meteorological station installed in the area. The CFD model determined that the sector before constructing the tailings deposit had a base erosion potential between 0.006 $kg/m^2/s$ and 0.009 $kg/m^2/s$ (Figure 12a).

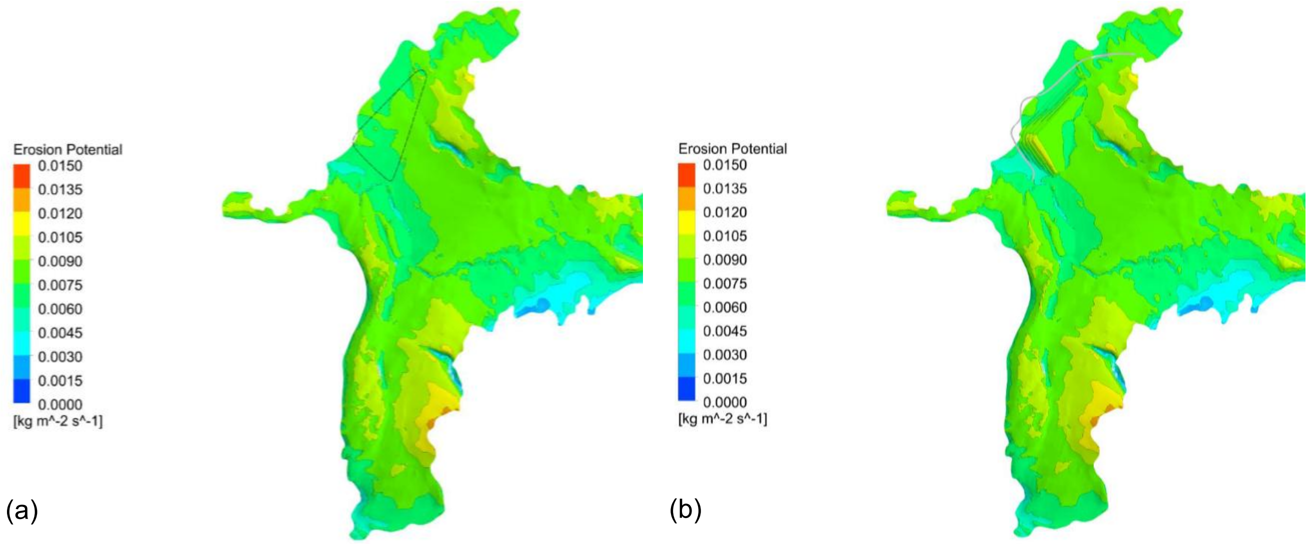

Figure 12. Erosion potential in the filtered tailings deposit site sector: (a) situation without project, and (b) final stage of the project (SYNTEC Ingeniería, 2019).

In the case of the closure and post-closure of the tailings dam, the project considers the implementation of a vegetation cover, on a dune sand substrate with the same endemic native species that were present in the sector before the construction of the tailings dam, to maintain the base erosion potential values. The CFD modeling indicated that, in a small area of the highest zone of the tailings dam, the erosion potential rises to a range between 0.0105 $kg/m^2/s$ and 0.0120 $kg/m^2/s$ in the post-closure stage (see Figure 12b), for which reason the rehabilitation and landscape reinsertion project considered the installation of rocks and coarse granular material in that sector, to control wind erosion in that specific area.

On-site Evaluation

The analysis of the tailings deposit site sector identified seven monitoring points, three within the area where the deposit will be located (E4, E5, and E6) and four outside this sector so that the measurement at these points will be continuously monitored over time (E1, E2, E3, and E7), as illustrated in Figure 13a. The analysis of the wind data recorded at the meteorological station located in the study sector established that the predominant wind direction is southwest, which defined the orientation of the Leatherman traps. Additionally, the study of wind speeds identified that these vary according to the season of the year. Thus, seasonal measurements were established and conducted every three months.

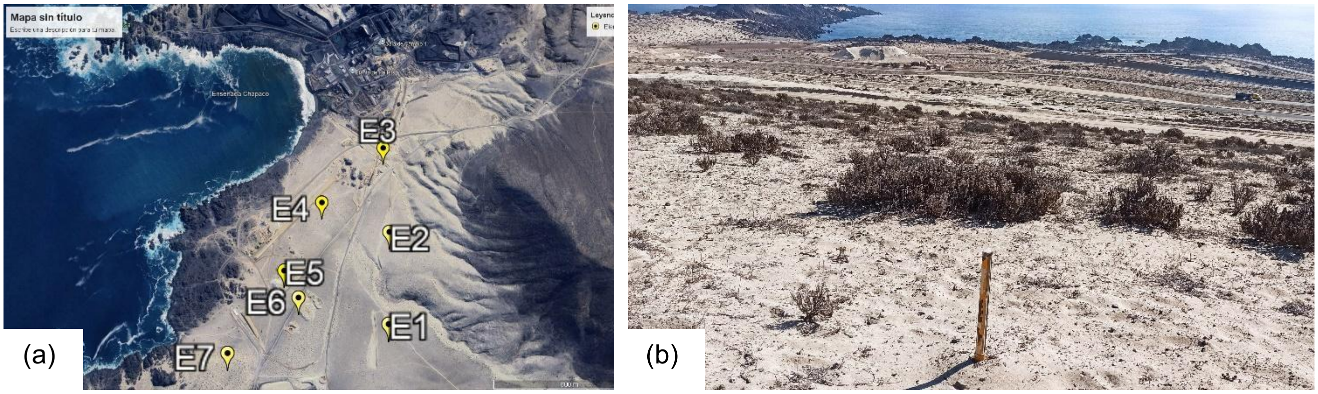

Figure 13. (a) Distribution of the seven monitoring points of salted material in the area where the filtered tailings deposit of the Pellet Plant is located, and (b) Leatherman trap E2.

Seven Leatherman traps were installed in October 2020 to determine the baseline of saltation-transported material in the area, before the beginning of the tailings deposit operation stage. Thus, seasonal measurements have been taken until September 2022, which have confirmed that the predominant wind direction is south-west, indicating that the conditions established in the modeling are accurate.

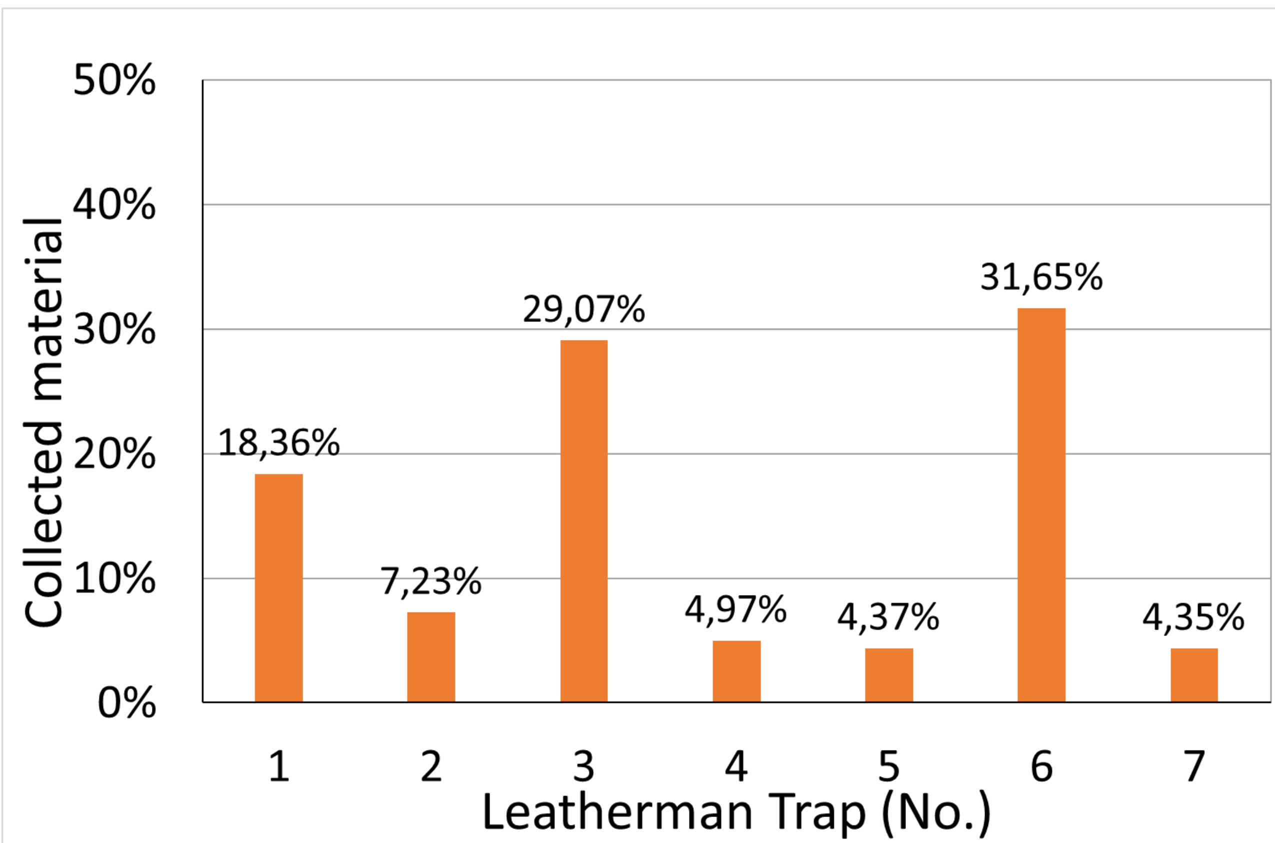

Figure 14. Distribution of total particulate matter collected in the study area during the entire sampling period (PUCV, 2022).

Figure 14 shows the results obtained from the seasonal measurements carried out between October 2020 and September 2022 in each Leatherman trap during the period studied. Preliminary analysis of these results indicates that the largest amount of material mobilized by saltation has been collected in E6, followed by E3 and E1 respectively. When comparing the location of these Leatherman traps with Figure 12a, it can be seen that these results are consistent with the erosion potential determined in the modeling carried out, as well as in E4, E5, and E7, where a lower erosion potential is presented. A particular situation is presented in E2, where the modeling indicates an erosive potential similar to the points of the greatest collection of material; however, the measurements carried out in situ do not reflect this situation, due to the density and height of the vegetation, which in this area is higher than average (Figure 13b). Since the start of the operation of the filtered tailings deposit, measurements have continued in all the installed Leatherman traps to validate the modeling carried out and to compare the effects of wind erosion in the area in the situation without a project and with a project.

CONCLUSION

The MPLIR is currently a fundamental tool for the sustainable practices of the Filtered Tailings Deposit (FTD) project, defining strategies for mitigating and remediating environmental impacts. In this challenge, landscape architecture provides fundamental tools to resolve the different scales of approach, both in terms of planning the areas involved and in the design of spaces and programs that allow the social use of the remediated sites. Through the design of facilities for tourism, recreation, leisure, and environmental education, together with topographic modeling and phytotechnology operations for slope stabilization, the Master Plan seeks to configure a space for innovation and development for the local community which in turn will become a touristic landmark at regional and national level.

Two of the four 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 preliminarily selected for the program. The reproduction 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 two 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 program for the rehabilitation and landscape integration of a mining tailings deposit must consider the aforementioned challenges 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.

The designed methodology enabled the determination, in the laboratory, of the wind speed at which the movement of particles begins, as well as the loss of material generated for each speed step for each material and condition analyzed, such as loose and dry dune sand, loose and dry tailings, and filtered tailings. This information allowed for the CFD simulation of the sector in the situation without the project, during the construction and final stage of the filtered tailings deposit project, which was incorporated in the environmental studies required by the authority for the environmental authorization of the project. These results guided the selection of the Leatherman trap test to measure the saltation material in situ. The results achieved in September 2022 have allowed for the verification of the considerations made during the design stage of the project, and have raised others that are expected to be explained when more information is obtained from the monitoring of wind erosion at the site of the iron-filtered tailings deposit. This information will serve as input to implement erosion control measures of the facility, during the stages of operation and closure of the deposit.

The interdisciplinary research work developed by the three universities, with the support of the Compañía Minera del Pacífico, has allowed the generation of new knowledge and the identification of important challenges that must be addressed in the early stages of a mining project to ensure its correct execution. These challenges include having adequate governance, the inclusion of the closure plan from the beginning of the FTD operation, and effective communication to build trust with the community. Secondly, other challenges arise that must 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. One approach that arises from the experience during the closure plans development is the proposal of Rehabilitation Plans with clear objectives, consistent with the future use of land, and defined with inclusion of the communities. Rehabilitation, 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, since a mining project leaves a legacy for society, governments, and communities. A Rehabilitation Plan may incorporate activities intended to generate new landforms and uses for the benefit of the community, such as the 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 lifecycle 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. 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 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.

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