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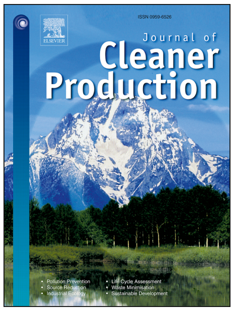

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Credit author statement

Natalia Araya: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing- original draft, Visualization,

Andrzej Kraslawski: Conceptualization, Methodology, Writing- review and editing, Supervision.

Luis A. Cisternas: Conceptualization, Validation, Formal analysis, Writing- review and editing, Visualization, Supervision, Funding acquisition.

Towards mine tailings valorization: Recovery of critical materials from Chilean mine tailings

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Abstract

The mining industry produces large volumes of mine tailings – a mix of crushed rocks and process effluents from the processing of mineral ores. Mine tailings are a major environmental issue due to implications related to their handling and storage. Depending on the mined ore and the process used, it may be possible to recover valuable elements from mine tailings, among other critical raw materials (CRMs) like rare earths, vanadium, and antimony.

The aim of this study was to investigate the techno-economic feasibility of producing critical raw materials (CRMs) from mine tailings. Data from 477 Chilean tailings facilities were analyzed and used in the techno-economic assessment of the valorization of mine tailings in the form of CRMs recovery. A review of applicable technologies was performed to identify suitable technologies for mine tailings processing. To assess the economic feasibility of CRMs production, net present value (NPV) was calculated using the discounted cash flow (DCF) method. Sensitivity analysis and design of experiments were performed to analyze the influence of independent variables on NPV. Two options were assessed, rare earth oxides (REOs) production and vanadium pentoxide (V_2O_5) production. The results show that it is possible to produce V_2O_5 with an NPV of 76 million US$. In the case of REOs, NPV is positive but rather low, which indicates that the investment is risky. Sensitivity analysis and the ANOVA run using the design of experiments indicated that the NPV of REOs is highly sensitive to the price of REOs and to the discount rate.

Keywords: mine tailings; critical raw materials; techno-economic assessment; discounted cash flow; sensitivity analysis.

1. Introduction

Mine tailings are waste from the processing of mineral ores. They are a mixture of ground rocks and process effluents generated during processing of the ores, and their composition depends on the nature of the mined rock and the recovery process used. In copper mining, tailings can account for 95-99% of crushed and ground ores (Edraki et al., 2014). Worldwide, mine tailings are produced at a rate of anywhere from five to fourteen billion tons per year (Adiansyah et al., 2015; Edraki et al., 2014; Schoenberger, 2016).

In view of the volumes of mine waste produced and the nature of the chemicals involved, the storage and handling of mine tailings is a significant environmental problem. Mine tailings are a source of serious contamination of soils and groundwater with nearby communities particularly badly affected by the results of eolian and water erosion of tailing disposal sites (Mendez and Maier, 2008). Another cause of environmental pollution from mine tailings is acid mine drainage (AMD) (Larsson et al., 2018; Moodley et al., 2017). AMD is formed from the exposure of sulfide ores and minerals to water and oxygen, once the ore is exposed, sulfate and heavy metals are released into the water (Moodley et al., 2017). AMD is considered one of the most significant forms of water pollution and the USA Environmental Protection Agency (US-EPA) considers it to be the second only to global warming and ozone depletion in terms of ecological risk (Moodley et al., 2017).

Tailing storage facilities (TSF), also called tailing deposits, are the source of most mining-related disasters (Schoenberger, 2016). Approaches to the handling and storage of mine tailings include riverine disposal, wetland retention, backfilling, dry stacking and storage behind damned impoundments (Kossoff et al., 2014). Mine tailings dam failures can have catastrophic consequences. 237 cases of significant tailings accidents were reported for the period 1971 to 2009 (Adiansyah et al., 2015). More recently, in January 2019, an accident at the Córrego do Feijão mine in Brumadinho in the metropolitan region of Belo Horizonte in southeastern Brazil killed at least 65 people with about 280 people were missing (De Sá, 2019).

To achieve a circular economy model, the valorization of mine tailings is crucial for the mining industry, which needs to improve its processes to minimize its environmental impact and close the loops (Kinnunen and Kaksonen, 2019). Different approaches to tailings valorization can be taken, such as reprocessing to extract metals and minerals, tailings as backfill material, tailings as construction material, energy recovery and carbon dioxide sequestration (Lottermoser, 2011).

Challenges that the mining industry needs to face to achieve the valorization of tailings aligned with circular economy principles include improving the rather limited knowledge about mineralogy, impurities concentration, and the quantity of tailings; developing new business models that take account of price development, lower disposal costs, and market demand; providing institutional impulse indispensable to encourage the transformation from a linear to a circular economy; technology development to make processes economically feasible since most mine tailings have low grades of different elements mixed with residues of previous processes (Kinnunen and Kaksonen, 2019; Lottermoser, 2011).

Due to the geological heterogeneity of the rocks mined and the continuous flow processes used in mineral processing, tailings deposits contain large quantities of valuable elements whose recovery could bring potential economic benefits. A number of studies have investigated the recovery of valuable elements from mine tailings (Ahmadi et al., 2015; Alcalde et al., 2018; Andersson et al., 2018; Ceniceros-Gómez et al., 2018; Falagán et al., 2017; Figueiredo et al., 2018; Khalil et al., 2019; Khorasanipour, 2015; Mohamed et al., 2017; Sracek, O., Mihaljevič, M. Kříbek, B., Majer, V. Veselovský, 2010).

As shown by recent studies (Ceniceros-Gómez et al., 2018; Markovaara-Koivisto et al., 2018; Moran-Palacios et al., 2019; Tunsu et al., 2019), among elements contained in mine tailings, there are many critical raw materials (CRMs) . Raw materials have significant economic importance and are utilized in the manufacture of a wide range of goods. In particular, critical raw materials can be applied in areas such as alternative energy production and communications devices, and they play a significant role in the development of globally competitive and eco-friendly innovations. Securing access to a stable supply of many raw materials has become a major challenge for national and regional economies with a limited production, which relies on imports of numerous minerals and metals (European Commission, 2017a).

Many studies have examined the criticality of raw materials. This study utilizes the list compiled by the European Commission (EC), where raw materials are considered critical when they are both of high economic importance for the European Union (EU) and vulnerable to supply disruptions (European Commission, 2017b). The term “vulnerable to supply disruption” means that their supply is associated with a high risk of not meeting the demand of the EU industry. High economic importance means that the raw material is of fundamental importance to industry sectors that create added value and jobs, which may be lost in the case of inadequate supply and if adequate substitutes cannot be found (Blengini et al., 2017). The most critical metals are those for which supply constraints result from the fact that they are largely or entirely mined as by-products, generate environmental impacts during production, have no effective substitutes, and are mined in areas prone to geopolitical conflict (Graedel et al., 2015).

In 2011, the European Commission (EC) published a list of 14 raw materials that are critical for emerging technologies of European industries, so-called critical raw materials (CRMs) (European Commission, 2017a, 2014, 2011). The list has been updated twice since 2011, the last update was in 2017, and it currently contains twenty-seven CRMs including 3 element groups: light rare earth elements (LREEs), heavy rare earth elements (HREES) and platinum group elements.

According to the International Union for Pure and Applied Chemistry (IUPAC), rare earth elements (REEs) are a group of 17elements that includes lanthanides, composed of 15 elements, and yttrium and scandium, which are included in this group due to the similarity in chemical characteristics. REEs can be found in over 250 different minerals (Jordens et al., 2013; Sadri et al., 2017). REEs have an important role in the transition to green technologies because of their use in crucial components such as permanent magnets and rechargeable batteries, and their use as catalysts (Koen Binnemans et al., 2013). China is responsible for almost 80% of the global supply of REEs, such monopoly has raised concerns about a possible shortage of supply, (Hornby and Sanderson, 2019; Vekasi and Hunnewell, 2019).

Other elements on the list of CRMs are platinum group elements (PGEs), which include ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum

(Pt). These metals are very rare in the Earth's continental crust, ranging from 0.022 ppb for iridium to 0.52 to Pd (Mudd et al., 2018).

Nowadays, due to the increasing demand for CRMs, new sources are being sought, and secondary sources such as metal scrap and industrial waste are attracting more attention. The use of the hitherto unexploited secondary sources can reduce demand for virgin materials and, in consequence, contribute to a decrease in mining production. One of the core principles of the circular economy is the reduction and minimization of resource use, and ways to achieve that goal include recycling and reuse of wastes (Kirchherr et al., 2017). Mine tailings from mineral processing of a certain branch of the metal industry could be used as a source in a process designed to obtain one or more critical raw materials, a simplified flowsheet of this idea is shown in Fig. 1.

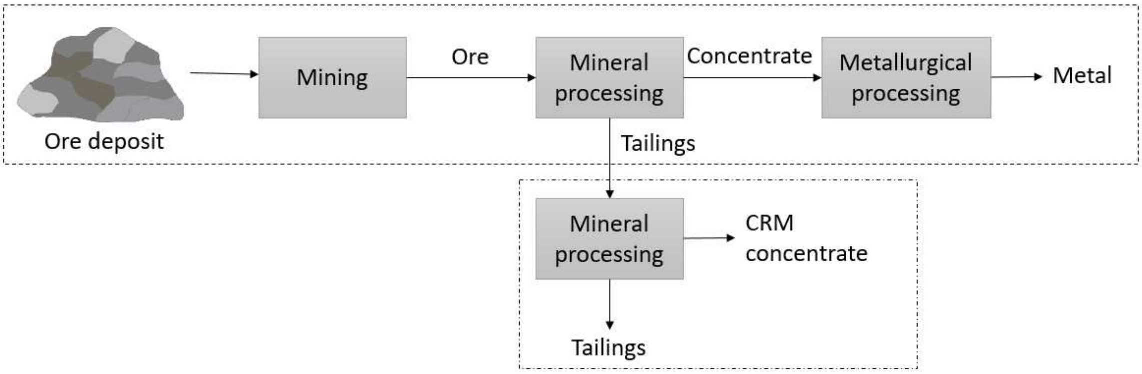

Fig. 1: Simplified mining processes flowsheet featuring conventional processes to obtain metal and the re-processing of tailings to obtain CRMs.

Chile has a long history of mining and large-scale mining started in the first decade of the twentieth century. In 2016, Chilean mining exports were valued at 30,379 million USD according to the National Service of Geology and Mining (SERNAGEOMIN), 90%

of which came from copper mining (SERNAGEOMIN, 2017). Chile is the world's leading producer of copper. Currently, a decrease in the grade of mined copper ores is being observed, which increases the amount of processed ore and, consequently, leads to greater tailings deposits for the same level of copper production. Currently, Chile produces 1,400,000 tons of mine tailings daily and there are 696 tailings storage facilities (TSF) (SERNAGEOMIN, 2018).

The objective of this study is to conduct a technical and economic assessment of the valorization of mine tailings of Chile as a source of CRMs. Therefore, the research questions addressed in this paper are:

What critical materials can be recovered from mine tailings?

What are the challenges in the production of critical materials using mine tailings as a source?

In recent years, the use of secondary sources for obtaining raw materials has gained growing importance. This research supplements these works with a techno-economic feasibility study for producing critical raw materials from mine tailings.

The data used in the study refer to mine tailings samples of 477 Chilean copper mining industrial deposits. These data have not been previously used to assess the economic potential of the recovery of critical materials.

2. Methodology

The first step to evaluate the recovery of CRMs from mine tailings is the calculation of the amount of each CRM present in tailings. The feasibility of recovery is next assessed for critical materials found in larger quantities.

In the technological assessment, technologies for processing mine tailings are first examined. If no technologies are available, technologies for processing ore, as an analogous process, are considered taking into account differences between the processing of ore and processing of waste.

In the economic assessment, the discounted cash flow (DCF) method is used to assess the feasibility of the options for the recovery CRMs from mine tailings. This method has been widely used for valuation projects (De Reyck et al., 2008; Kodukula and Papudesu, 2006; Žižlavský, 2014). DCF is a commonly adopted economic valuation technique and consists of discounting expected cash flow of a future project at a given discount rate and then summing all the cash flows of a determined period of time (Ibáñez-Forés et al., 2014; Žižlavský, 2014).

Sensitivity analysis is performed to assess the impact of various parameters on the NPV of CRMs recovery from mining tailings. Sensitivity analysis is a tool used to analyze how different values of a set of independent variables affect a dependent variable. The sale price of critical materials, operating costs, capital costs, and discount rate are the main inputs in the DCF method, then these variables are studied in the sensitivity analysis. These variables and interactions among them were also tested using a design of experiments with response surface methodology.

3. Mine tailings assessment

Mining is one of the main economic activities in Chile due to the country's favorable geochemical and mineralogical characteristics. Chile is the world's leading producer of copper, producing 5,552.6 thousand tons of copper in 2016 (SERNAGEOMIN, 2017), the world's second supplier of molybdenum, producing 62,746.1 tons in 2017, and the second producer of lithium, producing 77,284 tons of lithium carbonate in 2017 (SERNAGEOMIN, 2017). For some regions in Chile, mining is the main economic activity; most mining activity is found in the Atacama Desert in northern Chile~~.~~

The Atacama Desert is the driest non-polar desert on the earth, and its copper ore deposits are world-class porphyry copper deposits (Oyarzún et al., 2016; Tapia et al., 2018). Porphyry deposits are the principal sources of copper and molybdenum (Khorasanipour and Jafari, 2017). Porphyry deposits consist of distributed and stockwork sulfide mineralization located in various host rocks that have been altered by hydrothermal solutions into roughly concentric zonal patterns (Dold and Fontboté, 2001).

Chilean mining processing plants produce large quantities of waste every year. Tailings dams are the most common type of tailing deposit in the country (Ghorbani and Kuan, 2017). Previously, prior to the adoption of appropriate regulations, tailings were abandoned in deposits and no efforts were made to ensure the safety of the nearby communities but nowadays the handling and storage of tailings are strictly regulated. In 2011, the Law 22.551 was promulgated. It regulates the closing of mining facilities and specifies that tailings must be physically and chemically stabilized (Ministerio de Minería, 2011; SERNAGEOMIN, 2011).

In Chile, there are 696 mine tailings deposits registered in a national registry, compiled between 2016 and 2018. The registry is expected to be updated as new mine tailings facilities are opened and old abandoned tailing deposits are discovered. Antofagasta Region hosts larger mine tailings deposits (SERNAGEOMIN, 2018) because of the size of the mining sector in this region, which accounts for 47% of the contribution to Chilean mining activity. The most serious problems associated with tailings and handling and storage of tailings are related to the seismic nature of the country, and risks associated with tailings dam failure include fatalities, serious water contamination, and destruction of the land.

3.1. Characterization of mine tailings

The chemical composition of tailings in 477 mine tailings deposits is available on the website of the National Service of Geology and Mining of Chile (SERNAGEOMIN) (SERNAGEOMIN, 2018). This database contains values for concentrations of 56 elements, including 22 CRMs featuring on the latest EC list. The CRMs analyzed in the SERNAGEOMIN database are vanadium, cobalt, yttrium, niobium, scandium, hafnium, tantalum, antimony, bismuth, tungsten, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium (SERNAGEOMIN, 2018).

Chemical composition in each mine tailings deposit is different and it depends on the type of mineral rocks mined and the processes used in the plant. In the geochemical characterization of Chilean tailings, it can be noticed that most tailings deposits have a high percentage of silicon oxide or ferric oxide due to the type of minerals processed (SERNAGEOMIN, 2018).

Data in the SERNAGEOMIN database are classified by the current status of the tailings deposits: active, inactive, and abandoned. In the methodology used in this study, only inactive and abandoned tailings were analyzed, because their volume and chemical composition do not change over time. In the case of active tailings, although their volume is greatest, their chemical composition may change over the course of years, which is why they have not been considered in this study. Mine tailings of the Antofagasta Region are examined because the tailing volume storage is greater in this region than in other regions. The TSFs analyzed cover 16 inactive deposits. The location of mine tailings of the Antofagasta Region can be seen in Fig. 2.

Fig. 2: Tailings storage facilities in Antofagasta Region, blue represents inactive or abandoned deposits and red is for active deposits.

CRMs found in larger quantities are given in Table 1. The sum of REEs was also calculated, to produce REE concentrate or mischmetal, which is an alloy of REEs. The sum of REEs does not consider scandium because it is separated in a different process.

Table 1: Total tonnage and uses of CRMs present in inactive tailings deposits of the Antofagasta Region (16 deposits).

CRMs	Tons	Uses
Vanadium (V)	46,110	Most of the vanadium produced is used in ferrovanadium or as a steel additive. Another use is as vanadium pentoxide.
Cerium (Ce)	22,886	Cerium is used as a catalyst converter for carbon monoxide emissions, as an additive in glass for reducing UV transmission, and in carbon-arc lighting.
Cobalt (Co)	16,940	The main uses of cobalt are in battery chemicals for Ni-Cd, Ni-metal hydride and Li-ion battery types, superalloys, hard materials, catalysts, and magnets.
Yttrium (Y)	16,039	Yttrium is used for energy-efficient fluorescent lamps, in the treatment of

		various cancers, in aerospace surface and barriers, as a superconductor, in aluminum and magnesium alloys, and in-camera lenses.
Neodymium (Nd)	14,880	Neodymium is used to create high-strength magnets for computers, cell phones, medical equipment, electric cars, wind turbines, and audio systems. It is also used in the glass and ceramic industries.
Lanthanum (La)	10,253	Lanthanum is used in nickel metal hydride rechargeable batteries for hybrid automobiles, in high-quality camera and telescope lenses, and in petroleum cracking catalysts in oil refineries.
Scandium (Sc)	9,359	Scandium is used to increase strength and corrosion resistance in aluminum alloys, in high-intensity discharge lamps, and in fuel cells to increase efficiency at lower temperatures.
Niobium (Nb)	4,823	Niobium is used in high strength low alloy (HSLA) steels as ferroniobium and in superconducting magnets.
Antimony (Sb)	3,751	Principal uses for antimony are in alloys with lead and tin, and in lead-acid batteries.
Samarium (Sm)	3,456	The main use of samarium is in cobalt-samarium alloy magnets for small motors, quartz watches, and camera shutters. Samarium is also used in lasers.
Gadolinium (Gd)	3,357	Gadolinium is mainly used for NdFeB permanent magnets, lightning applications and in metallurgy.
Praseodymium (Pr)	3,245	Praseodymium is used in NdFeB magnets, ceramics, batteries, catalysts, glass polishing and fiber amplifiers.
Dysprosium (Dy)	2,705	Dysprosium is used mainly and almost inclusively in NdFeB magnets.
REEs (total)	82,254	

3.2. Technology Assessment

A literature review was conducted to investigate the available technologies for the recovery of critical raw materials from mine tailings. If no technologies are available for tailings processing, then those used for processing of primary ores are considered as a reference. It is important to notice that mine tailings are already in the form of slurry or paste, depending on the percentage of water present, so there are no mining costs, which represent approximately 43% of operating cost in a mine (Curry et al., 2014).

Existing technologies for CRMs production are briefly described in Table 2. Most of these technologies are for primary ores. Some applications for secondary sources such as industrial waste and mine tailings exist (Abisheva et al., 2017; Binnemans et al., 2015; Figueiredo et al., 2018; Innocenzi et al., 2014; Jorjani and Shahbazi, 2016;

Peelman et al., 2016), but they should be treated as emerging technologies. Significant further development of these new technologies is required before they are suitable for industrial-scale usage (Kinnunen and Kaksonen, 2019).

In spite of the low concentration of REEs in comparison to end-of-life consumer goods, mine tailings are a potential source of REEs because of the large volumes of mine tailings, which mean that the total amount of recoverable REEs could be high (Binnemans et al., 2015). Several processes have been proposed for the recovery of REEs from mine tailings. Peelman et al. (2018) have proposed a method for the recovery of REEs from mine tailings from apatite mineral with an REE content of 1200-1500 ppm using acidic leaching followed by cryogenic crystallization and solvent extraction. They achieved a 70-100% recovery of REE.

Table 2: Available and emerging technologies for CRMs processing.

CRMs	Production process
Rare earth elements	-Acidic leaching-cryogenic crystallization-solvent extraction from mine tailings with apatite and monazite. (Peelman et al., 2016). -Bioleaching for REEs extraction from low-grade sources. (Peelman et al., 2014). -Solvent extraction to recover REEs from mine tailings of gold and tellurium mining (Tunsu et al., 2019). -Use of solvent impregnated resins (SIR) to recover REEs from low concentration solutions (Onishi et al., 2010; SUN et al., 2009; Yoon et al., 2016).
Antimony	-Crushing and pyrometallurgical methods for primary ores (Anderson, 2012). -Crushing and hydrometallurgical methods like leaching and electrodeposition (Anderson, 2012).
Cobalt	-Bioleaching of sulfidic tailings of iron mines. (Ahmadi et al., 2015). -Mineral beneficiation, comminution, flotation, smelting, leaching or refining for sulfide ores (European Commission, 2017b). -Calcination, pyrometallurgical process, hydrometallurgical methods for lanthanides ores (European Commission, 2017b).

Niobium	-Gravity separation, froth flotation, magnetic and electrostatic separation, and acid leaching depending on the ore (European Commission, 2017b).
Vanadium	-Extraction of vanadium as a co-product to iron from vanadium slag includes bearing, roasting, acid leaching solvent extraction, ion exchange, and precipitation (Xiang et al., 2018). -Desliming-flotation from low-grade stone coal (European Commission, 2017b). -Preform reduction process (PRP) based on a metallothermic reduction of vanadium pentoxide (V_2O_5). (Miyauchi and Okabe, 2010).

There are no processing plants using copper mine tailings as a source of CRMs. Therefore, technologies used for primary sources are assumed to be also applicable to the processing of mine tailings. Based on the content of the mine tailings analyzed, two feasibility studies are conducted; the first for producing rare earth oxides and the second for vanadium recovery, using mine tailings as a source.

The extraction process for REEs, in a general form, includes three steps: mining and comminution; ore beneficiation processes consisting of flotation, gravity and magnetic techniques to generate REE concentrate; and hydrometallurgical methods to extract REE compounds (Sadri et al., 2017). Hydrometallurgical methods include cracking of REE concentrate; leaching, neutralization and precipitation processes; and separation and purification techniques such as solvent extraction. Solvent extraction allows recovering REEs with a high degree of purity, moreover, a variety of solvent extraction reagents is available. For secondary waste, selective extraction of REEs is required from solutions with a high content of other species (Tunsu et al., 2019).

A life cycle inventory and impact assessment of the production of RE oxides from primary bastnasite and monazite has been presented for the Bayan Obo mine in Inner

Mongolia, China, in (Koltun and Tharumarajah, 2014). The study found out the mining and beneficiation stage accounts for 6.98% of energy consumption and 6.51% of water consumption. When processing mine tailings, there is no mining stage, so the values were adapted. Adapted values of energy and water consumption to obtain RE oxides from waste material are included in the supplementary material.

Primary ores of REEs are usually treated with alkaline pressure leaching or sulfuric acid roasting. However, mine tailings are a low-grade source of REEs, so these technologies may not be economically feasible. Chloride-based hydrometallurgical processes may be a potential alternative to traditional capital intensive hydrometallurgical processes based on high temperature and pressure (Onyedika et al., 2012) and they could be a suitable option for REE recovery from tailings at economically viable capital and operating cost.

In the case of vanadium, it is mainly produced as a co-product from the vanadium slag before the steel converter. The main vanadium products are vanadium pentoxide (V_2O_5) and ferrovanadium (FeV) (European Commission, 2017b). Other sources of vanadium are stone coal, steel scrap, and fossil fuels.

The mine tailings analyzed in this study have a CRMs content that varies between 80-214,000 grams per ton of tailing. In Chile, there are currently no projects providing for the use of mine tailings as a source of CRMs, nor approved initiatives for the production of CRMs from primary ores.

3.3. Economic Assessment

The economic assessment is done in two main steps. The first step focuses on the economic potential of CRMs found in inactive mine tailings as an in-situ value, considering the monetary value of the CRMs to assess the feasibility of CRMs production. The second stage concentrates on the analysis of the feasibility of CRMs production using mine tailings as a source.

Prices of critical materials may differ from one source to another. In addition, the prices of some critical materials are not publicly available as they are traded privately. To calculate the economic potential of inactive mine tailings deposits, the following prices were used, see Table 3.

Table 3: CRMs prices in July 2018

Critical material	Price ($US/kg)*	Critical material	Price (US$/kg)*
Antimony	8.51	Neodymium metal ≥ 99.5%	68.0
Cerium metal ≥ 99.5%	7.00	Neodymium oxide ≥ 99.5%	66.7
Cerium oxide ≥ 99.5%	5.59	Praseodymium metal ≥ 99%	125.00
Cobalt	87.5	Praseodymium oxide ≥ 99.5%	81.6
Dysprosium metal ≥ 99%	268.57	Samarium metal ≥ 99.9%	15
Dysprosium oxide ≥ 99.5%	226.80	Scandium metal ≥ 99.9%	3,458
Gadolinium metal ≥ 99.9%	44.00	Scandium oxide ≥ 99.95%	1,079
Gadolinium oxide ≥ 99.5%	20.94	Vanadium (as V2O5 80%)	40.00
Lanthanum metal ≥ 99%	7.00	Yttrium metal ≥ 99.9%	36.5
Lanthanum oxide ≥ 99.5%	7.80	Yttrium oxide ≥ 99.99%	4.60

* Sources: (Mineralprices.com, 2018),(Thenorthernminer.com, 2018), (LME, 2018).

The economic potential of CRMs recovery was calculated as the fraction of each CRM in the tailings multiplied by the mass of each TSF for the 16 TSFs studied. The economic potential is a reference value for the total REE value of the mine tailings. The economic potential of these TSFs is shown as supplementary material.

To assess the feasibility of CRMs recovery, the DFC method was used to calculate the NPV and IRR for REOs production and V_2O_5 production using mine tailings. The NPV is the difference between the present value of cash inflows and the present value of cash outflows in a particular period of time. IRR is the discount rate at which the NPV of future cash flows is equal to the initial investment. NPV and IRR are metrics used in capital budgeting and decision-making. The calculation does not include external factors such as inflation. To obtain the NPV and IRR for the options assessed, capital costs and operating costs of projects with similar characteristics were used.

Capital costs, also referred to as capital expenses or CAPEX, represent the investment made for the project, which includes costs of the development phase which, among other costs, comprises the purchase of the equipment, building a manufacturing plant and the cost of product launch. The investment represents the first cash flow in the DFC method.

Operating costs, operating expenses or OPEX, are expenses incurred during the lifetime of the project. In the case of a mining project, these would include the cost of labor, water, and energy, maintenance, spare parts, and indirect costs (Bhojwani et al., 2019).

The first option assessed is the production, using mine tailings as a source, of the following rare earth oxides (REOs): cerium, lanthanum, neodymium, yttrium, samarium, gadolinium, praseodymium and dysprosium. Scandium is also considered as REE but it has different properties and a different production process, which is why it was not assessed together with the above mentioned REEs.

The second option assessed is vanadium as the production of vanadium pentoxide (V_2O_5). It is due to the fact that vanadium is the main CRM found TSFs in the Antofagasta Region (see Table 1).

3.3.1. Feasibility of Producing rare earth elements using mine tailings as a source

For REOs production, we have considered only REEs found in larger quantities. Due to the lack of data about similar projects that use mine tailings or industrial waste as source material, we used data from a Canadian project that produces rare earth oxides (Hudson Resources Inc, 2013) from primary sources to produce of neodymium, praseodymium, lanthanum, and cerium. Data used for NVP calculation are shown in Table 4.

Table 4: Data for REOs project

Data	Value	Unit
Capital cost	342,514,448	US$
Life of mine	20	years
Operating cost	13,080	US$/ton REOs
REOs Price	22,000	US$/ton REOs
Production capacity	4,000	tons REOs/year
Annual increase (OPEX)	1.5	%
Annual increase (PRICE)	1.5	%
Discount rate	10	%

The price used to calculate NPV corresponds to the weighted average for REOs; cerium, lanthanum, samarium, gadolinium, praseodymium, dysprosium, and yttrium oxide, which is 37 USD/kg of REOs produced, 40% was discounted to reflect the difference between REO concentrate and separated individual rare earth oxide prices, so the price used for NPV calculations is 22 USD/kg, as in the report it was used as a reference price. The grade of REEs corresponds to the average REEs grade in all the deposits analyzed. In the mine tailings covered by the analysis, the average grade is lower than in most primary ore processing projects, so the production was reduced accordingly.

It is important to note that operating costs and capital costs are referential values. In the case of mine tailings, costs related to extracting mineral ores should not be considered since tailings are materials that have already been mined and processed.

The NPV is 672,987 USD which means that the projected earnings generated for this proposed REOs production exceed the anticipated costs and the overall value for the project is positive. However, even though the NPV is positive, its value is too low to invest in a project of such a magnitude. The IRR is 10.03% which is almost the same as the discount rate chosen for the project, this confirms that the project is not highly profitable. Cash inflows and outflows are included as supplementary material.

3.3.2. Feasibility of producing vanadium using mine tailings as a source

Vanadium is the main CRM found in mine tailings in the Antofagasta Region. There are 46,110 tons of vanadium in inactive TSFs, but active tailings in this area have the potential for ca. 900, 000 tons of vanadium.

Capital and operating costs for vanadium production are taken from a preliminary economic assessment study for the Gibellini vanadium project (Lee, 2018). This project has been designed as an open pit heap leaching operation to obtain vanadium pentoxide (V_2O_5). The Gibellini project is designed for processing of low-grade minerals, so it is suitable for mine tailings, but in this study, production is reduced because the grade in mine tailings is lower in mine tailings. The values used for the calculation of NPV and IRR are given in Table 5. The values of NPV and IRR for vanadium production from Chilean mine tailings are shown in the supplementary material.

Table 5: Data for vanadium project

Data	Value	Unit
Capital cost including 25% contingency	116,760,000	US$
Life of mine	14	years
Operating cost	14,767	US$/ton V_2O_5
Vanadium pentoxide price	40,000	US$/ton V_2O_5
Production capacity	1,000	tons V_2O_5/year
Annual increase (OPEX)	1.5	%
Annual increase (PRICE)	1.5	%
Discount rate	10	%

The NPV is 76 million US$ and the IRR is 21%, these values indicate that the project is profitable as the NPV is positive and the IRR is higher than the discount rate. Cash inflows and outflows are shown as supplementary material.

3.5. Sensitivity analysis

In this study, a sensitivity analysis was performed on four parameters: capital cost, operating cost, critical materials price, and the effect of the discount rate on NPV for the examined options. The objective of the sensitivity analysis is to understand the uncertainty in the NPV for the examined parameters. These parameters were chosen because they are the key components in the DCF method.

Sensitivity analysis determines how different values of one or more independent variables affect a dependent variable under a given set of assumptions. Sensitivity analysis is the last stage of the process of assessing and selecting a technological alternative (Ibáñez-Forés et al., 2014). Sensitivity analysis studies how several sources of uncertainty contribute to the entire uncertainty of a mathematical model.

In the DCF method, the discount rate is the rate used to convert the future value of a project cash flows to today's value. The discount rate is adjusted to the risk associated with a project. Therefore, the higher the risk, the higher the discount rate (Kodukula and Papudesu, 2006). Risk is associated with the uncertainty of a project. In business, risks may have a positive or negative effect. The discount rate was varied to acknowledge that mining projects deal with uncertainties that can be included in the model by choosing a higher discount rate.

Mining commodity prices always show greater volatility than those of any other primary products (Foo et al., 2018). Prices of critical materials may experience price spikes due to their instability caused by the risk of supply disruption. Critical materials have inelasticity element in their prices, this means that the demand for these materials is not highly affected by the price (K. Binnemans et al., 2013; Leader et al., 2019). Critical materials are needed in technologies, such as clean energy technologies, in which there are not substitutes for the critical materials needed (Leader et al., 2019).

The price of each critical material assessed was considered as an important parameter that contributes to the overall uncertainty of the project.

Since capital costs and operating costs used in this study are referential values, and they are further used as inputs in the DCF method, it was necessary to address the variability of the real values of these parameters vis-a-vis the values used here.

Capital cost, operating costs, and prices varied between -30 and 30% of the original value. The discount rate varied between 0.05 and 0.3.

The results of the sensitivity analysis for the REOs price are shown in Figure 3. It can be seen that for every 5% increase in the price of the REOs, the NPV increases by 38 million US$. NPV is highly sensitive to changes in REO prices. NPV becomes negative when the price of REOs is below 22 US$/kg, making the project financially unviable.

The NPV is less sensitive to changes in operating costs than price; NPV decreases to 21 million US$ with an increase of 5% in operating costs. The results of the sensitivity analysis of the NPV to the capital cost show that as the investment cost increases by 5%, the NPV decreases by ca. 15 million US$.

The discount rate varied between 0.05 and 0.3. The NPV is not a linear function of the discount rate, the value considered was 0.1. When the discount rate is 0.11, NPV decreases by approximately 21 million US$. With a discount rate higher than 0.1, NPV becomes negative, making the project unviable.

Results of sensitivity analysis of NPV for vanadium pentoxide production are shown in Fig. 3. When the price increases by 5%, NPV increased by ca. 14 million US$. When the price drops by 26%, NPV becomes negative and the project unviable.

Results of the sensitivity analysis of NPV to operating costs show that NPV is slightly sensitive to changes in operating costs. When operating costs increase by 5%, the NPV decreases by ca. 5 million US$. Sensitivity analysis of the NPV to changes in capital cost shows that with an increase of 5% in the capital cost, the NPV decreases by ca. 5 million US$. The values of NPV are very similar for both operating costs and capital costs.

The sensitivity analysis of NPV to changes in the discount rate shows that if the discount rate increases by 0.01 from the value of 0.1 used to 0.11, the NPV decreases by 10 million US$ approximately. When the discount rate is higher than 0.21, NPV becomes negative.

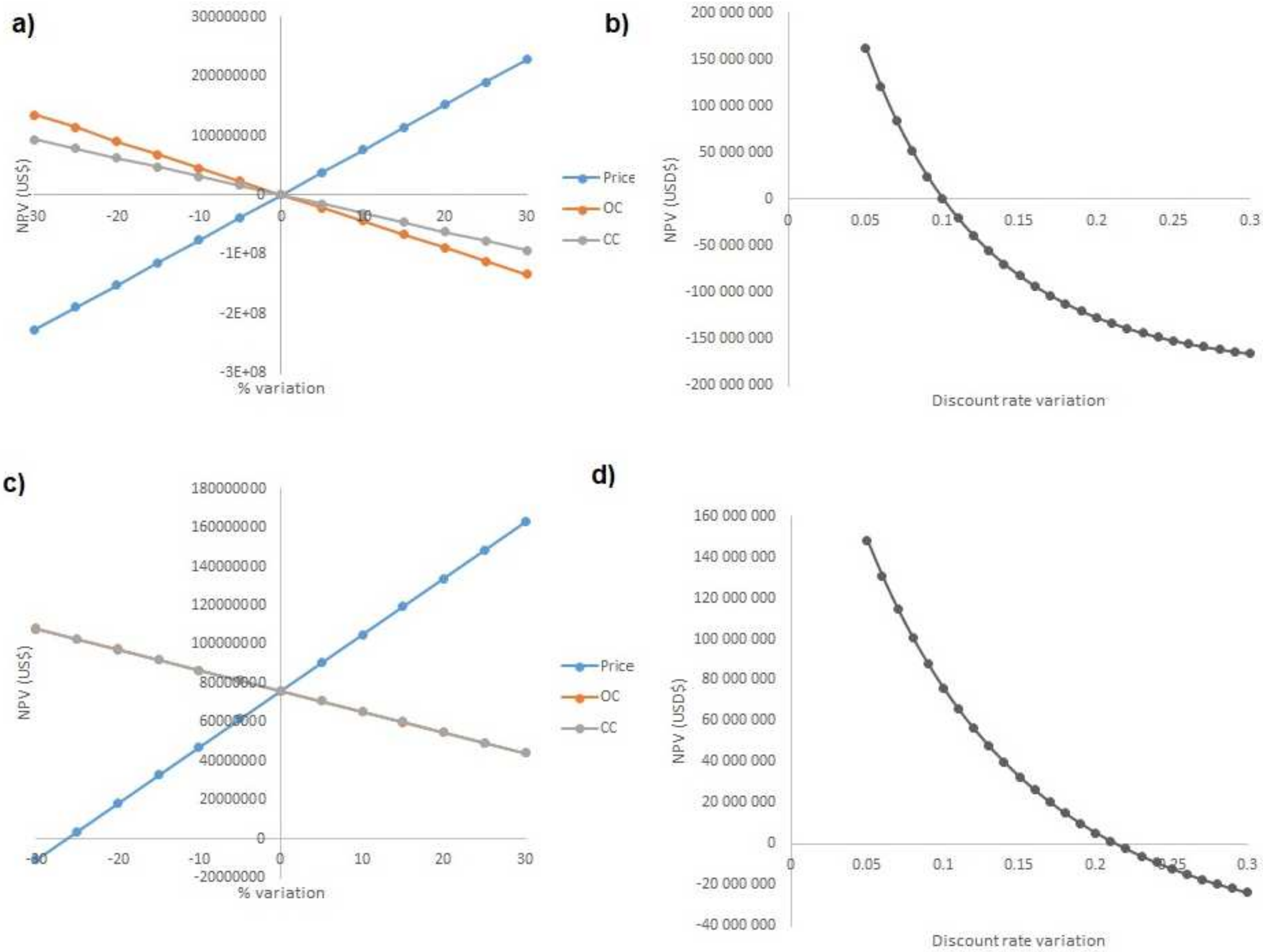

Fig. 3: Sensitivity analysis, a) Sensitivity of the NPV (REOs project) to the price of REOs, operating costs and capital costs; b) Sensitivity of NPV to discount rate in REOs project; c) sensitivity of NPV (vanadium project) to the price of V_2O_5, operating costs and capital costs; d) Sensitivity of NPV to discount rate in vanadium project.

Results show that under certain prices, operating costs and capital costs, it is possible to invest in producing CRMs using a secondary source such as mine tailings.

The parameters analyzed in the sensitivity study may change simultaneously. Therefore, their interactions were analyzed using design-of-experiments together with response surface methodology. In the analysis of the NPV of both projects, REOs production and V_2O_5 production, four factors and three levels were considered. The factors are: the price, capital costs (CAPEX), operating costs (OPEX), and the discount rate (i). The levels correspond to the value used in the economic assessment, then low and high levels for the same value were multiplied by 0.85 and 1.15, respectively, which means the experimental design results are valid in the range between -15% and +15%. A percentage of 15% was chosen to ensure a good adjustment. The values tested for the discount rate are 0.05, 0.1, and 0.15. ANOVA results show which parameters and interactions influence the NPV by analyzing the p-value. For the p-value < 0.01 all linear parameters and the interaction with the discount rate were significant. Also, the statistical analysis confirms that price and the discount rate are the parameters exerting greater influence. Regression models obtained have the following form:

$$NPV = a + b\ CAPEX + c\ OPEX + d\ price + e\ i + f\ i^2 + g\ CAPEX\ i + h\ OPEX\ i + j\ price\ i$$

The values for a, b, c, d, e, f, g, h and j are -17.6, -0.9103, -59.55, 67.1, -1766, 14323, 0.0, 242.9, and -299.5 for REOs project, and 47.64, -0.9932, -12.572, 12.572, -1143.3, 5717, 0.828, 49.63, -49.625 for V_2O_5 project, respectively. The units for NPV and CAPEX are MUS$, OPEX and price are kUS$/ton, and the discount rate is dimensionless. The R-squared values or the coefficient of the regressions were $R^2 = 98.17\%$, $R^2{}_{adj} = 97.99\%$, and $R^2{}_{pred} = 97.79\%$ for REOs project, and $R^2 = 99.95\%$, $R^2{}_{adj} = 99.95\%$, and $R^2{}_{pred} = 99.94\%$ for the V_2O_5 project. The R^2 for both projects are over 98% which means that at least 98% of the variation of the NPV can be explained by the model. Also, excellent values of adjusted R^2 and predicted R^2 were observed which suggests that the number of parameters is the model is correct and that the model is able to produce high quality predictions. The ANOVA results and Pareto graphics are included in the supplementary material. Also, supplementary material gives the results of the design-of-experiment and response surface methodology for the IRR which behaves differently from the NPV.

4. Discussion

Mine tailings are waste obtained from the processing of a rock with a view to obtain one or more products that will be refined to finally get a metal(s) that is needed. Tailings should be stored in facilities where they are disposed in accordance with the regulations binding in each region, otherwise, the consequences to the environment can be devastating.

The lack of a long-term consideration of the entire life-cycle of a mine and the instability of mine projects contribute to irreversible mineral losses and resource sterilization. With this knowledge in mind, further research should address new strategies to anticipate the future use of material beyond the closing of a mine (Lèbre et al., 2017). Mine waste hierarchy goes from prevention as the most favorable option to treatment and disposal as the least favorable options; if waste cannot be prevented then reuse and recycling are needed (Lottermoser, 2011). Nowadays most mine tailings go to the treatment and disposal phase. In the Sustainable Development Goals, the World Economic Forum suggests the re-use of tailings, these goals are meant to be achieved by 2030 (World Economic Forum, 2016). The reprocessing of mine tailings is also an element of the transformation from a linear to a circular economy that the mining industry must face.

Reprocessing mine tailings to obtain critical materials reduces the dependency on reserve extraction (El Wali et al., 2019).

Other approaches to mine tailings management from a circular economy point of view include recovering water from mine tailings, which helps to reduce the reliance on seawater (Cisternas and Gálvez, 2018). Recovering water or reducing the amount of water in tailing diminish the need to pump water, which decreases energy consumption and greenhouse gas emissions involved in pumping water to high altitudes, where mines are usually located in Chile (Araya et al., 2018; Herrera-León et al., 2019; Ramírez et al., 2019). Another approach is to use mine tailings as cementitious materials and pigment for sustainable paints (Barros et al., 2018; Vargas and Lopez, 2018).

There have been conducted several studies on new technologies or processes to recover CRMs from secondary sources such as mine waste (Alcalde et al., 2018; Andersson et al., 2018; Figueiredo et al., 2018; Khalil et al., 2019; Markovaara-Koivisto et al., 2018; Peelman et al., 2018). Most of these studies are carried out at laboratory and pilot plant scale. Nevertheless, the literature on the recovery of CRMs from mine tailings is constantly growing. It is due to the fact that new sources of CRMs are urgently needed as their importance in the global economy is constantly growing. Moreover, the utilization of wastes such as mine tailings, instead of mineral deposits, is essential from a circular economy point of view. Therefore, extrapolation of the potential of these technologies is immensely needed.

Results show that mine tailings facilities of the copper industry in Chile store valuable elements such as CRMs. Therefore, the early evaluation of geochemical content, identification of suitable technologies, and an economic analysis will help to find more sustainable alternatives to CRMs production.

The DCF is a widely used method of financial assessment, but it is not a decisive metrics for making a final decision on real investment. In order to ensure the robustness of assessment, sensitivity analysis was performed to analyze the effect of the possible fluctuations of market prices, capital and operating costs on the analyzed options of CRMs production. It has been found out that the discount rate and both capital and operating costs play critical roles in economic decisions in different areas (Choi et al., 2018; Cisternas et al., 2014; Santander et al., 2014).

Reprocessing mine tailings will also have an impact on the environment. Due to the nature of chemical and physical processes, mineral processing is water and energy intensive, some quantities of solvents and reagents are used and at the end of the process, there will still be waste that should be stored in a tailing facility. The mining waste obtained after the reprocessing of tailings should be stored in a tailing facility complying with the regulations designed to protect people and the environment.

5. Conclusions

There are 696 tailings storage facilities in Chile, mainly from copper mining, which is the biggest mining industry in the country. The biggest TSF has the capacity to store 4,500,000,000 tons of tailings. Currently, there are some initiatives for recovering metals of interest from mine tailings, but such initiatives are all in the early stages of feasibility assessment. This study provides valuable information for the assessment of the techno-economic feasibility of industrial-scale critical materials recovery from copper industry tailings.

Copper production will continue to grow as the copper grade decrease. Therefore, the volume of mine tailings that are produced every year will increase as well. Mine tailings are a worldwide environmental problem as they can generate acid drainage, and cause air pollution and soil contamination. Yet, mine tailings contain several valuable elements, among them critical raw materials. Therefore, the use of mine tailings as a secondary source would help mitigate shortages in critical raw materials by minimizing the reliance on primary sources.

Chilean copper mine tailings have substantial economic potential as a source of critical materials such as vanadium, cobalt, rare earth elements and antimony. Minerals contained in Chilean mine tailings from copper production are mostly silicates with a low grade of CRMs; currently, no approved projects exist that consider mine tailings as a source of CRMs. Although mine tailings have a low grade of CRMs, their already stored quantity is enormous. In addition, prices of critical raw materials can be very high, and these factors could make a future production of CRMs from mine tailings feasible.

Two options of producing CRMs using mine tailings were assessed; production of rare earth oxides (REOs) and production of vanadium pentoxide (V_2O_5). The DFC method was used to evaluate the economic feasibility of both operations. The NPV and IRR for the production of REOs are positive, which means that the project is feasible. Nevertheless, the NPV is low for an investment of this scale and the IRR is close to the discount rate value. The sensitivity analysis of the NPV of REOs production from mine tailings showed that NPV is highly sensitive to the discount rate and REO prices. Results of the ANOVA confirm that the discount rate and price are the most significant variables influencing the NPV behavior.

Vanadium pentoxide production is feasible for an investment of 14 years, as the NPV is 76 million US$ and the IRR IS 21% for V_2O_5 production. Vanadium is the main CRMs found in tailings in the Second Region in Chile. It is concluded that producing CRMs using inactive tailings and later tailings from the active mining processes may be a feasible option to ensure profitable use of mine tailings and to diversify CRMs supply.

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Fig. 1: Simplified mining processes flowsheet featuring conventional process to obtain metal and the re-processing of tailings to obtain CRMs.

Fig. 2: Tailings storage facilities in Region II, blue represents inactive or abandoned deposits and red is for active deposits.

Fig. 3: Sensitivity analysis, a) Sensitivity of the NPV (REOs project) to the price of REOs, operating costs and capital costs; b) Sensitivity of NPV to discount rate in REOs project; c) sensitivity of NPV (vanadium project) to the price of V_2O_5, operating costs and capital costs; d) Sensitivity of NPV to discount rate in vanadium project.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: