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Review

Submarine Tailings in Chile—A Review

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Abstract: This review aims to understand the environmental impact that tailings produce on the land and marine ecosystem. Issues related to flora, fauna, and the environment are revised. In the first instance, the origin of the treatment and disposal of marine mining waste in Chile and other countries is studied. The importance of tailings' valuable elements is analyzed through mineralogy, chemical composition, and oceanographic interactions. Several tailings' treatments seek to recover valuable minerals and mitigate environmental impacts through leaching, bioleaching, and flotation methods. The analysis was complemented with the particular legislative framework for every country, highlighting those with formal regulations for the disposal of tailings in a marine environment. The available registry on flora and fauna affected by the discharge of toxic metals is explored. As a study case, the "Playa Verde" project is detailed, which recovers copper from marine tailings, and uses phytoremediation to neutralize toxic metals. Countries must regularize the disposal of marine tailings due to the significant impact on the marine ecosystem. The implementation of new technologies is necessary to recover valuable elements and reduce mining waste.

Keywords: underwater tailing dumps; environmental impact; mining waste

Citation: Rodríguez, F.; Moraga, C.; Castillo, J.; Gálvez, E.; Robles, P.; Toro, N. Submarine Tailings in Chile—A Review. *Metals* **2021**, *11*, 780. https://doi.org/10.3390/met11050780

Academic Editors: Jean François Blais and Fernando Castro

Received: 24 March 2021
Accepted: 9 May 2021
Published: 11 May 2021

1. Introduction

The intensive exploitation and the decrease in copper deposits' grades will cause a shortage of oxidized copper resources in Chile [1–3]. It is expected that copper production by hydrometallurgical methods will go from 28.8% in 2017 to 11.6% by 2029, while the copper that is processed by pyrometallurgical operations should increase from 71.2% to 88.4% [4]. The tailings produced by froth flotation are a mixture of water, ground rocks, and chemical reagents and represent 95–99% of crushed ores; this means that for each ton of copper obtained through froth flotation, 151 tons of tailings are generated [5]. Globally, mining tailings occur at a rate of five to fourteen billion tons per year [6,7].

In Chile, tailings have been mainly produced by the copper and gold industries, and to a lesser, the iron and zinc industries [8]. The government plan only covers 37 abandoned tailings, but according to Sernageomin (Spanish acronym of National Geological and Mining Survey), there are about 800 tailing deposits, mainly in the Antofagasta, Atacama, Coquimbo, and Metropolitana regions [9].

The tailing pollutants correspond to a long list, but the most important for the environment are copper, chromium, nickel, zinc, lead, arsenic, cadmium, and mercury [8]. The tailings dam management is essential to prevent contact between the ecosystem and the population. Damps exposed to climate events have a potential risk of contamination [10].

This interaction may be due to the different difficulties that these dumps present, such as infrastructure, landslides, and location. Natural processes, such as acid drainage, in sulfide tailings, dumps exposed to oxygen and water, causing contamination of surface and underground waters [11–13]. Due to the problems mentioned above, the mining industry is looking for alternative methods of waste management. Although there are several tailings treatments to recover valuable elements, such as leaching, bioleaching, and froth flotation, these treatments only partially help the severe environmental impact of mining waste deposits [14].

An option that has attracted attention to the management of surface tailings is the disposal of the seabed. Submarine tailings have minimum maintenance, geochemical and geotechnical stability, and another series of advantages for mining waste management [15]. The disposal of underwater tailings appears to be an attractive option in contrast to on-land tailing. The on-land dumps are perpetual, expensive, and structurally and environmentally risky [16]. This alternative is supported from a technical perspective, but the practice is complex, especially from the environmental legislative framework. Submarine tailings, as mentioned above, can also be a big problem for the ecosystem. For example, on Chile's coasts, the deposits produce large accumulations of material with a significant impact on marine life due to heavy metals and high sedimentation and turbidity [17].

This review provides an understanding through technical reports and empirical studies on the current impact on the ecosystem of disposal of underwater tailings in Chile and other mining countries. However, the method of discharging waste from mining operations is debatable. The operational advantages of the tailings disposal on the seabed seduce mining plants that operate near the coasts.

2. Legislative Framework

Currently, only fifteen mines in six countries (Chile, France, Greece, Indonesia, Norway, and Papua New Guinea) manage subsea tailings. Five countries have existing legal frameworks for such operations. Chile does not yet have specific laws to protect the marine ecosystem from mining tailings [18]. In Chile, the environmental authority evaluates each mine's impact in operation, but legally it cannot prevent the disposal of tailings on the Chilean coast. The major international initiative for protecting the oceans against anthropogenic pollution is the London Protocol of 1996. The previous version of the London Protocol was the London Convection (1972) is the first world effort to protect the marine environment from pollution sources. The document calls for measures to avoid the sea's pollution due to the dumping of waste and other matters. Eighty-seven countries currently participate in this agreement; Chile has participated since 26 September 2011 [14]. The updating from one agreement to another was because the London Convection listed materials that could not be deposited at sea. The London Protocol prohibits any deposition of "inert inorganic geological material" in the sea. Almost all minerals and rocks are part of geological and geochemical cycles. Only a few mineral materials could be classified in a geological sense as inert; for example, quartz, rutile, and zircon [17]. It is important to note that the London Protocol does not cover discharges from land-based sources such as pipes and drains, waste generated by the regular operation of ships, or the placement of mining materials, as long as the disposal is not contrary to the objectives of the Protocol. Therefore, the London Protocol does not necessarily apply to tailings disposal systems. The mining organizations argue that mining tailings are of geological origin, and are hence "inert." Therefore, it would not be expressly restricted to the London Protocol [19]. In October 2008, due to pressure from non-governmental organizations, the London Protocol's governing bodies agreed to a more detailed assessment of the mine tailings. Thus, the effective control of submarine tailings discharges will be communicated to the relevant agencies. The agreement is included in the United Nations Environment Program—UNEP.

3. Historical Background

In several countries, and especially in northern Chile, most mining operations and tailings disposal are carried out near the mine. However, the tailings disposal has turned out to have certain exceptions in managing waste from ores processing by froth flotation. Countries like Chile, Peru, Norway, Canada, the Philippines, Spain, and Indonesia have active or abandoned underwater tailings on the coasts and at the submarine level [20]. The underwater tailings of Chañaral Bay, Chile, and Ite Bay, Peru, are examples of the lack of scientific studies that can damage the marine environment. Potential environmental disasters caused a change towards the surface disposal of the tailings [21]. Nowadays, society's pressures on surface tailing dumps have driven research on sustainable mining waste discharge to the seabed.

The cases of tailings discharged to the seabed with the most significant impact on Chile's mining activities environment and communities are described below.

3.1. Underwater Tailing Dumps in Chile

3.1.1. Chañaral Bay

Ramírez et al. carried out a study on heavy metals speciation in a large Chañaral Bay coastline area. Tests determined the large concentration of heavy metals such as Cu, Cd, Fe, Mn, Ni, Pb, Zn, and As in the Chañaral bay's beaches due to the tailings deposited by the El Salvador plant from Codelco [22]. In the last century, investigations were carried out on the marine environmental impact resulting from the disposal of copper mine tailings on the Atacama region's coasts. Approximately 130 million tons of tailings have been discharged on the shore of Chañaral bay. These discharges formed artificial beaches more than 7 km long. These underwater tailings deposits from the El Salvador copper mine have hindered port activities, seriously affecting marine ecosystems and social life in the Chañaral population [15].

In 1989, a claim by the population of Chañaral against Codelco forced the company to stop the tailings deposition in Chañaral Bay. Codelco had to build a surface tailings dump called Pampa. This dump is currently the facility for the discharge of residues from the El Salvador concentrator plant. At present, the tailings in Chañaral Bay are in the same conditions deposited in the past and are sources of heavy metal contamination for the environment.

3.1.2. Chapaco Bay (Huasco)

The small Chapaco bay (Huasco, Atacama Region) was a place for the disposal of mining tailings from the iron pelletizing process. The Pellet Plant residues from CAP mining company were discharged directly into the sea from June 1978 and continued for more than 18 years. Mining wastes were piped from the plant to the rocky intertidal zone of Chapaco Bay. The average rate of waste discharge was 118 t/h of clay and iron ore. The sea suffered continuous turbidity in the water. The subtidal zone caused continuous sedimentation by non-native material [23]. However, Stotz et al. 1994 did not give relevance to these marine tailings discharge's environmental impact. The authors explain that no active chemical reagents were added during the processing of the iron ore. Electromagnets' magnetic mineral was concentrated, which allowed the discharged material to be classified as "inert solid waste" [24].

In 2015, the Pellet plant presented an environmental impact study (EIS) to the Chilean environmental authority to update and improve their marine tailing dump. The project consisted of the construction and operation of an enhanced deep underwater tailings deposition system. The system was based on two big pipelines (twin pipes) that will alternately conduct the tailings. The new waste deposit was located approximately 6.6 km offshore and more than 200 m below sea level, southwest of Chapaco Bay [25]. The EIS presented by the Pellet Plant details the main physical and chemical characteristics of the tailings. The analyses show that this mining residue is geologically inert. The chemical composition of the solid and water phase of the tailings presents the same chemical characteristics that they had in the natural environment from which they were extracted. Thus, mining waste is below standards or within the reference criteria. Therefore, solids and water subjected to the pellet plant's grinding and concentration processes are not adverse to the environment. Eco-toxicological studies show that the material does not react or release substances that may be harmful to aquatic life under environmental conditions. Consequently, for the environmental studies of 2015, the tailings of the Pellet Plant are entirely assimilable for the concept of "geological origin material". Therefore, they are classified as substances that can be dumped into the sea, with only a physical impact [24].

In 2019, the Chilean Environment Superintendence carried out a series of inspections of the Pellet Plant. Various breaches of the Environmental Qualification Resolutions that regulate this company were revealed. The audit focused on verifying compliance with obligations on aspects related to the management of atmospheric emissions, the impact on soil, the impact on renewable natural resources, and the effects on the marine environment. The latter having the most significant negative impact. The environmental authorities of Chile ordered the Pellets Plant to cease its tailings discharge operations in Chapaco Bay [10].

3.2. Background of Submarine Tailings in the World

3.2.1. The Ite Bay, Peru

A case like Chañaral Bay was carried out on the marine coast of Ite Bay, Peru. From 1960 to 1997, copper porphyry tailings were transported from the Cuajone and Toquepala mines through the Locumba River. The mining waste was drained by gravity to Ite Bay. The residues had an average of 4% pyrite and low arsenic concentrations associated with sulfide minerals. The difference with Chañaral bay is that there was enough water available here to start successful remediation. From the material dumped on the coast, a wetland was built [20]. After the tailing disposal ceased in 1997, the Southern Peru Copper Corporation began a remediation campaign. The Locumba river was cleaned, and a cover was installed in Ite Bay. Using the alkaline water from the Locumba river, it was possible to protect the coastal wetlands from oxidizing tailings. The flora that developed locally in alkaline water infiltrated in the oxidizing tailings was transplanted to remediation cells. In 2004, about 90% of the tailing dump was covered for wetland, except the central delta and some areas near the coast [26].

3.2.2. Island Copper Mine, Canada

Island Copper was one of the first mining operations to implement tailings disposal at sea. For 25 years, Island Copper Mine tailings were discharged to a basin of 100 to 200 m depth. Although Island Copper always had a good reputation, environmental problems were evident in the long term. Poling et al. report tailings suspension and outcrop, asphyxiation of benthic fauna, high copper and arsenic concentration in mollusks, and heavy metals contamination by forming acid drainage. Moreover, the tailings were displaced at a lower depth due to ocean currents [25].

In 1996, the Canadian Department of the Environment published a report with decades of environmental data of the Island Copper mine. It was concluded that there was a permanent seabed alteration due to mining tailings. As a result, special regulations for the locality were revoked in 2002. From this year, the disposal of tailings on the coast of Canada was prohibited [27].

3.2.3. Black Angel Mine, Groenlandia

The Black Angel mine operated between 1973 and 1990. The mine used seawater for the zinc and lead ore flotation process. The tailings were disposed of in the sea, specifically in the Affarlikassa fjord. After a year of operation, too-high Pb, Zn, and Cd concentrations were detected in the Qaumarujuk fjord [28]. Geochemical, mineralogical, and oceanographic studies have shown mining residues with significant amounts of non-stable minerals [29]. Since the mining operation's cessation, scientific studies have shown that contamination persists and has significant long-term effects on the benthic macro-fauna by heavy metals [30,31].

3.2.4. Marcopper Mine, Philippines

The Marcopper mine (Marinduke, Philippines) is dedicated to the processing of copper ores. It is a mine notorious for constant accidents in its underwater tailing dump. Carr et al. carried out toxicological and chemical analyses in different areas of the Marindunke coast. Very high concentrations of heavy metals (Cu, Co, Pb, Cd, Ni) were detected in mollusks. The definitive cessation of the tailings discharge is unknown since its environmental authorities have not carried out a serious study on the ecosystem [32,33].

3.2.5. Norway Case

In Norway, diverse mining companies are found on uneven terrain, making tailings disposal on land often unsuitable. Since these mining sites are also located near fjords, the subsea disposal system has become common in Norway, with 11 inactive subsea tailings sites, seven active, and two applications in the process [34].

Recently, direct relationships between benthic biodiversity and ecosystem function have been described, suggesting that anthropogenic or naturally caused variations in biodiversity can result in essential changes in ecosystem functioning. Therefore, understanding the impacts of anthropogenic activities such as underwater relatives on pelagic and benthic biota and substrate type, habitats, and heterogeneity is essential to assess possible changes in ecosystems and the environment and effects on related ecosystem services.

Tailings disposal in the marine environment in Norway takes place in deep waters, where remoteness and difficult access, particularly in terms of cost and logistics, severely limit our understanding of its biodiversity. However, Ramírez-Llodra [34] recognize several important categories of impact by this tailings disposal system, which turn out to be: hyper-sedimentation, the toxicity of the marine environment due to metals, process chemicals, changes in organic content and grain size, sediment plumes, and turbidity; and materials for suspension, upwelling and breakage of slopes.

4. Mechanism and Stability of the Tailings Disposal System

The general concept of DSTP proposes that the tailings move by gravity through a pipeline from the plant to a mixing/deaeration tank, the tailings are mixed with seawater in a ratio of approximately 1:1.5 per cent. volume. The mixing tank is generally located on the same shoreline.

The difference in density between the tailings and seawater will be equalized by introducing seawater into the tank through a feed pipe. The seawater intake is usually carried out at depths of more than 60 m to ensure an adequate mixing density. After mixing, the diluted glue will flow through a subsea pipe with a density of approximately 1100 kg/m^3.

The depth of the tailings outlet must be appropriate to the local characteristics, but in most cases it is carried out at minimum depths of 30 m below the seabed. This is due to the fact that the exit point is below the deepest sunlight zone (euphotic zone), also the zone where currents driven by the coastal wind can occur. The angle of the submerged pipe, as well as the submarine slope, should be approximately 12° [35].

Because the mix of tailings and water deeper than 50 m is denser than seawater, after discharge, the tailings will flow down the sea slope. This great movement is called shale flow.

The tails will be deposited along the flow path. Eventually, a density equal to that of seawater is reached at the periphery of the density stream and some of the liquid fraction and some of the finer particles will escape at this point and create an underground plume in the water column. This occurs due to nonconformities of density in the water column.

The remaining solids in the shale flow, especially the coarse fraction, will continue to move down the slope. In the well (main deposition zone), a dilute plume with vertical expansion may occur, which is known as a nepheloid layer.

Eventually, the sediment escapes from the subsurface shadow and settles to the bottom of the ocean. The process of density flow and plume formation is consistent with the pattern that describes how sediments are transported from their terrifying origins [36].

Based on the above, the modulation of the performance of the tails is carried out based on the performance of the terrigenous sediments that flow from the estuary of the rivers to the deep ocean basins to maintain their stability in deep waters and to not achieve sedimentation of these fines that, with the nautical movement of the marine currents, reach the surface and consequently come into contact with living beings.

5. Impacts on the Ecosystem

The environmental impacts of subsea tailings disposal operations are described below. The need for environmental evaluation, the negative impact on flora and fauna, and the adversities that the social environment may suffer from these marine tailing dumps are highlighted.

5.1. Environmental Impact

As already mentioned, Chilean mining is concentrated in the north of the country. The associated environmental impacts of mining have a long history. Millions of tons of mine tailings have been disposed of in coastal basins and bays [37]. As more mines are exploited nearshore, the disposal of mine tailings on the ocean floor is increasingly likely.

Although the discharge of tailings to the sea occurs in a few countries (Chile, France, Greece, Indonesia, Norway, and Papua New Guinea), the marine environment's impacts repeat specific patterns. The warming, acidification, and deoxygenation of the oceans are the main impacts on the ecosystem [38].

Climate Change, Acidification, and Deoxygenation of the Oceans

The environment of the oceans is changing rapidly. Marine ecosystems at the continental level are highly vulnerable to climate-related factors. Thus, changes such as warming, acidification, oxygen loss, and nutrients have been detected [37]. The effects are intense and cumulative with direct human action, such as oil extraction and spills, pollution, and eventual underwater mining [39]. On the other hand, mining tailings can alter the seafloor further, exacerbating climate-related disturbances to the oceans [40]. These cumulative effects are likely to become widespread, altering the properties of the habitat. Ecological functions (e.g., biodiversity, calcification by habitat-forming species such as cold-water corals) and ecosystem services (e.g., nutrient cycling, carbon adsorption, and fish production) will be irretrievably affected [41].

5.2. Flora

Flora and fauna, and the social environment, are affected by the mining tailings' contamination. The main flora of the marine environment is algae. Algae retain heavy metals, shorten their life cycle, and are food for living beings; they also cause serious disease. For many years, seaweed has served as plant food for humans thanks to its health benefits, providing high fiber, vitamins, minerals, and oligo-elements. Some minerals in the algae are Na, K, Ca, Mg, and P, and some oligo-elements are Fe, Cu, Zn, and Mn [42]. Marine algae are also used to manufacture pharmaceuticals, cosmeceuticals, nutraceuticals, biofuels, and cheap raw materials. Chile is the leading exporter of seaweed in Latin America. Thus, they have implemented new political measures and regulations to improve cultivation and to not affect fishers [43]. Chile is in the 12th place of the world aquaculture producers, contributing to salmon, trout, and seaweed production. The chemical composition of algae includes carbohydrates, proteins, and bioactive molecules. Algae biomass is an attractive resource, as it is used for alginate production and as a feeding medium for abalone mollusks.

This type of flora is affected by the pollution caused by mining companies, affecting the aquaculture sector [44].

An example of environmental contamination by mining tailings occurred in the Valparaíso region (Chile). The accident was caused by the Andina mine (from Codelco). Approximately 50 cubic meters of tailings were dumped into the Blanco river in the Aconcagua Valley. Serious problems were caused in the population and the ecosystem by chemicals and a large amount of powdery solid material [45].

5.3. Fauna

Disposal of mining tailings to the sea becomes a significant environmental challenge for industries that choose to use this waste management method. Large volumes of potentially toxic waste must be managed appropriately [46]. On the other hand, heavy metals can become bioavailable, which leads to significant changes in the ecosystem, whether biotic or abiotic [47].

Two types of ecosystems can be affected by tailings' disposal in the sea, benthic and pelagic. The benthic is made up of organisms associated with the seabed. It encompasses the abyssal trenches from the intertidal region; this includes infauna, epifauna, coral reefs, and seagrasses. The pelagic ecosystem consists of all the organisms that inhabit the middle waters of the oceans and seas. The species in this area are fish, phytoplankton, zooplankton, and predators [48–50]. The disposal of tailings in the sea has a more significant impact on the benthic fauna because they directly contact the seabed. Mining waste will affect its surface (epifauna) or within the substrate (infauna). Infauna is at risk as they ingest sediment and process its organic content [51,52]. Benthic fauna can be affected in the following ways [53]:

- Suffocation due to tailings material moving downhill or in response to accumulated tailings falling.
- Increase in suspended sediment.
- Change in the habitat of the benthic ecosystem due to the presence of tailings.
- Exposure to heavy metal contaminants and reagents from previous processes.

On the other hand, pelagic organisms such as zooplankton (meroplankton, holoplankton) can carry out vertical migrations up and down the water column. Diel vertical migration (DVM) is massive migration to the surface that occurs throughout the day, representing the most massive documented migration in biomass [54,55]. These migrations generate patterns and ranges, which are essential to determine marine systems' structure and dynamics. The changes in the flow of organic matter between the bottom and the surface are essential for transporting carbon, other substances, and pollutants and the organisms that will later be consumed by humans [51,56].

The pelagic ecosystem is an essential food source due to the diversity of organisms that compose it, from phytoplankton and zooplankton to crustaceans, fish, and marine mammals. These organisms are found in the ocean's euphotic zone (sunlight arrives) and are a vital source of organic carbon for the seabed. Pelagic impacts generated by tailings disposal can indirectly affect benthic organisms, such as organic matter and food supply limitation. The risk of biological impacts depends on the levels of toxicity, turbidity, and sensitivity of the organisms. On the other hand, they could also bioaccumulate pollutants in organisms [24].

According to Compañía Minera del Pacífico (CAP), the Chapaco cove biotic environment comprises zooplankton but showed less seasonality and variability in location than phytoplankton. The data on ichthyoplankton's taxonomic composition showed no evidence that the larvae or eggs of the critical commercial species have been impacted by tailings discharge in the Chapaco cove [24]. The subtidal benthic fauna of the Chapaco cove is made up of small nematodes and polychaetes, physiologically adapted to low oxygen conditions. Abundance, biomass, richness, and diversity are lower near the current tailings discharge than most reference transects [22].

Mining tailings deposited on the intertidal coasts of northern Chile were found to reduce the number of sessile species drastically. The decrease in marine species is probably due to the tailings' mechanical effects [57]. The low concentration of dissolved oxygen of the Subsurface Current of Peru-Chile contributes to decreasing species, richness, and abundance [17].

6. Considerations for Submarine Tailings Management

6.1. Mineralogy and Geochemistry Related to Mining Tailings

The biggest problem caused by mining residues is the elimination of polluting waste into the environment. One of the soil's primary pollutants is acid mine drainage (AMD) caused by the sulfide minerals' atmospheric oxidation in the tailings [58]. Thus, together with the limited land space, the option of underwater tailings is reevaluated to give more significant environmental and socio-economic stability [59]. In Chile, the deposit of mining tailing dumps on the marine coast becomes increasingly common due to the lack of land. However, this generates contamination problems, damaging flora and fauna caused by the tailings' metals. In coastal ecosystems, estuaries are vital for invertebrates, fish, and birds, critical to maintaining them for ecological and economic reasons. Nevertheless, these waters are directly affected by chemical contamination caused by the mining tailings disposed on the coastal edges [60].

A clear example is Chañaral Bay, which has been affected by coastal tailings on beaches and rivers for many years. The mining residues produced by the El Salvador plant have directly affected the Chañaral Bay, polluting its waters with high copper content, affecting biological diversity, particularly in the formation of marine algae [61]. The tailings in the estuarine environment are fine sediments with high concentrations of organic and shallow oxygen. This fact is important because the micro and macrofauna are present. The highest level of porewater copper was found in the smelly water bay (1449.59 μg Cu^{2+}). In the same location, the highest labile seawater copper concentration was 41.42 μg Cu^{2+} [62].

Another example is the Coquimbo region, which is also affected by contamination from mining waste. The Elqui River has been affected by smelter slag and low-grade dumps. These environmental events were provoked by copper and silver mining in the 19th century. These wastes contain heavy metals such as arsenic and cadmium. The ecological damage was due to the lack of laws regulating mining activities in the country. However, this began to change when environmental law was created in 1994. The disposal of mining waste also caused AMD, rich in copper, zinc, and arsenic. A geochemical sampling determined high Cu, As, Zn, and gypsum contents in fine-grained sediments contaminated by acid drainage. This drainage goes directly to the Toro River, which has a high Cu and As content in its waters, causing alteration and fracture in rocks. This water pollution directly affects agricultural lands, causing a conflict between mining companies and farmers [63].

In 2019, Tripodi studied two abandoned tailing dumps in Taltal city, analyzing the abundance of valuable and toxic species. Mineralogical studies in both tailings identified the presence of minerals of economic value. X-ray analyses were carried out to know more accurately the mineralogy present in the sample. The results showed various species, such as Chrysocolla, Atacamite, Pyrite, Chalcopyrite, Gold, Quartz, Feldspar, Chlorite, and Pyroxene Tourmaline, Gypsum, Black copper, Magnetite, Hematite, Limonite, Apatite, among others. Among the most polluting elements are mercury, arsenic, lead, zinc, nickel, manganese, cadmium, chromium, copper, and selenium. The heavy metals found in the tailings can cause kidney problems, cancer, dermatological, vascular, digestive, and immune diseases. Among the valuable elements, silver, gold, and copper were found [17].

6.2. Oceanographic Processes

It is essential to emphasize environmental impact studies' performance to determine the feasibility of selecting the site to discharge the submarine tailing dumps. The studies must be very rigorous on the hydrology and topography of the area, together with the abiotic (environmental) and biotic (ecology) properties. These studies should be carried out because the already submerged tailings constitute a potential source of dissolved heavy metals and chemical reagents from the flotation process. The tailing's dumps can affect the sea's microbial biomass, which leads to a decrease in its assimilative capacity because of vital ecosystem services such as nutrients and the carbon cycle. These investigations can achieve adequate information on the dynamics of abiotic and biotic systems within the sea, which can last years [51].

It allows the understanding and prediction of the sea processes, such as ocean circulation, heat distribution, interaction with the atmosphere and climate. With these studies, it can be shown that ocean currents determine the movement of tailings in the water and the extent of their impact. On the other hand, currents that pass over the seabed would influence the tailings column's footprint and re-suspended tailings. Midwater currents would be important because they would act in the lateral transport of tailings, affecting the pelagic ecosystem [24].

According to the Pellets plant's environmental impact study, the Chapaco Cove (underwater arrangement more than 200 m below sea level) presents a system of marine currents influenced by winds and tides in the water column's upper layers between 0 and 50 m. The dump is also affected by the Peru–Chile marine current, flowing south at a depth of 300 m. During the measurement period (2011–2012), some effects on the sea's thermal structure in Chapaco, due to the "La Niña" phenomenon. The "La Niña" phenomenon decreases surface waters' temperature in the Pacific, Andean, and Caribbean regions. With the information obtained, it is inferred that the deepest area of the tailings deposit would not be affected by upwelling events in deep waters, increasing intensity when the La Niña phenomenon occurs. On the other hand, the "El Niño" phenomenon, where surface water temperatures increase, would not affect the deep waters of Chapaco. This is because warmer surface waters increase the water column's stratification, limiting the entire coast's upwelling process [64,65].

A bathymetric study is significant for underwater tailings disposal. Bathymetry consists of measuring the depths of the seabed to determine the topography. The measurements and geographic locations are combined in a surface map and elevation map, where both are representatives of the actual seabed. The bathymetry analysis from the area allows for obtaining essential and detailed information on the seabed shape and structure, where its geological and geomorphological structure is emphasized [24]. The geomorphology of the Chapaco cove has morphological features dominated by irregular rocky edges. It also includes the limited presence of offshore platforms, a low elevation of the coastal mountain range, and wind sand covers development. Regarding the underwater morphology, it can be emphasized that the continental shelf of the Chapaco cove is approximately 6.5 km wide and a slope between <1 and 3°; that is, a horizontal relief. Fine tailings have been deposited on the rocks in the depressed areas surrounding the Chapaco cove and the Morro Negro hill [17].

7. Mine Tailings Management Options

The management of mining tailings is an essential part of regulating the governmental organizations that supervise and control mining activities' environmental impacts in each country. The place chosen as a landfill will have restrictions, which will influence the waste disposal options. Tailings disposal is traditionally arranged in the form of dams, onshore tailings, and subsea tailings disposal. However, some of these options are not allowed in some countries. The tailing's disposal option's choice depends on the waste's physical and chemical nature, the mine topography, climatic conditions, and economic considerations for its final disposal [66].

On the other hand, the success of tailings disposal on land or in marine dumps is determined by climatic conditions and seismic activity. For example, in areas of frequent tectonic activity and high rainfall, there will be an increased risk of dam failure [67]. Due to the difficulties that can arise in the construction of tailings damps on land, it is open to the option of choosing the disposal of waste from the froth flotation process in the oceanic zone. However, it is also necessary to consider that tectonic or oceanographic conditions impact the sea's tailings disposal. Thus, topographic, economic, environmental, and social considerations play a fundamental role in mineral concentration operations for tailings placement [25]. There are at least 3500 mining tailings damps worldwide, but they are not without environmental and public safety concerns. The main problems include the footprint, land loss (useful in other activities), contamination of surface and groundwater, and the facilities' stability. There have been 138 significant failures recorded in mining tailings damps [68].

Kwong et al. [68] compared the ecosystem impacts of onshore tailings versus tailings discharged in the sea. The advantages and disadvantages of both types of mining waste disposal are shown in Table 1 [69].

Table 1. Advantages and disadvantages of land and sea tailings management methods.

	Sea Management	Land Management
Advantage	• Small land footprint. • Low investment and operating costs. • Minimal post-closure treatment and maintenance is required. • Acid drainage formation is not a problem.	• Applicable in most mining sites. • The abundant supply of experienced staff. • Opportunity for tailings reprocessing. • Tailings confined to a known spatial area.
Disadvantages	• Burial and asphyxia of the benthic fauna. • Mobilization of tailings and release of pollutants. • Unknown impact on deep oceans. • Difficult reprocessing of tailings. • Restricted to mines located near the coasts. • High cost of environmental investigations before mining exploitation. • Possible contamination of marine food webs that can affect coastal communities.	• Availability of soil is required. • Acid drainage formation. • Post-mine maintenance and monitoring. • Water discharge requiring water treatment. • High cost of construction and maintenance.

8. Reprocessing of Mining Tailings

The mining activity has produced a large volume of tailings that have been placed in tailing dumps for decades. In Chile, the historical dump tailings contain relatively high copper grades. Copper recovery for these mining tailings' reprocessing is imminent by froth flotation or hydrometallurgical techniques [70].

8.1. Mining Tailings Leaching

Leaching is a promising technology for recovering valuable metal to tailing reprocessing, even for very low-grade elements [71]. There are mine tailings that contain more copper (0.3% to 0.4%) than some low-grade mineral deposits [72]. The grade of valuable material in mine tailings opens the way for hydrometallurgical studies that offer great potential for treating some mine tailings [73].

8.1.1. Leaching in Acid Medium

Different researchers have studied the processing of mining tailings by acid leaching. Wang et al. conducted an acid leaching study of mine tailings from Yangla (China). The study was carried out in a stirred reactor at 300 rpm, a sulfuric acid concentration of 0.5 mol/L, and 75 °C. Copper recovery was 53% [74]. On the other hand, Antonijevic et al. carried out an acid leaching study from Bor tailings (Serbia) with 0.3% copper. This study was carried out in a stirred reactor with a sulfuric acid concentration of 0.6 mol/L, achieving recoveries of up to 70% [75].

Bai et al. studied the leaching of refractory flotation copper tailings from Zambia. Variables such as the amount of concentrated sulfuric acid, leaching temperature, and leaching time on leaching efficiency were investigated. The optimal leaching conditions were 85 kg/t concentrated sulfuric acid, a leaching temperature of 68.5 °C, and 4.36 h. The leaching efficiency under these conditions was 85.9% [11].

8.1.2. High-Pressure Leaching

Han et al. conducted a high-pressure leaching study from Bor (Serbia) tailings. The sample contained chalcopyrite as the primary copper contributing phase. The tests were carried out in an autoclave reactor (Nitto Koastu, Japan). The experimental conditions were 0.5 mol/L sulfuric acid solution, the pressure of 0.8–2.0 MPa, and the temperature of up to 180 °C. The results show a recovery of 94.4% of copper [76–78].

8.1.3. Leaching in Ammoniacal Medium

An ammonia solution turns out to be helpful in dissolving copper oxide and carbonate minerals contained in tailings. Therefore, species such as chrysocolla ($CuSiO_3$*$2H_2O$) and malachite ($CuCO_3$*u$(OH)_2$) can be selectively dissolved with an ammonia solution [79]. You-Cai et al. studied ammonia leaching from tailings. The main copper species contained in the residues were chrysocolla, malachite, and cuprite. Leaching was carried out in a reactor at a stirring speed of 350 rpm, an ammonia concentration up to 3 mol/L, and 30 °C temperature. The copper recovery after this experiment was 70.6%. The authors demonstrated that oxidized and carbonate copper ores found in froth flotation tailings could be recovered using the ammonia leaching method [13].

8.2. Bioleaching

Bioleaching is a polyphasic interfacial interaction between minerals, microorganisms, and a leaching solution [80]. Bioleaching is based on microorganisms' ability to transform stable compounds into extractable and soluble elements [81]. This process is a way to facilitate sustainable mining and prevent the formation of AMD. Microbial oxidation can transform insoluble metals contained in tailings into soluble metals [81–84]. Some prokaryotic microorganism species can catalyze the oxidative dissolution of sulfur minerals, mainly used to recover base metals such as copper, nickel, cobalt, zinc, and gold. In recent years, this technology has been used to recover metals from tailings due to its low cost and care environment [85]. However, not all sulfur minerals are accessible to bioleaching, such as chalcopyrite. The use of reductive bioleaching requires elemental sulfur to act as an electron donor for bacteria that reduces ferric iron minerals [86].

Falagán et al. carried out a study of metal recovery by bioleaching tailings from two mines currently operating in Spain and Serbia. A microbial consortium was used, and elemental sulfur was added to the residues. The maximum extraction of copper was 90% at 45 °C. The dominant microbial consortia in the two leached residues were Acidithiobacillus caldus and Sulfobacillus thermosulfidooxidans [80].

Liu et al. [82] performed bioleaching experiments in Pb–Zn–Cu tailings. Sulfur oxidizing bacteria were used, such as T. thiooxidans, active at a low pH and resistant of concentrated heavy metals. These same bacteria can catalyze the oxidation of elemental sulfur, causing acidification and solubilization of metals. After 13 days, metals can be removed from the tailings, with efficiencies of 98.08% for Zn, 96.44% for Cu, and 43.52% for Pb.

Seleznev et al. [87] conducted a study to recover precious metals from a plant's tailings in the Southern Ural Mountains and Murmansk region. The authors studied two different sites located in Russia's Southern Ural Mountains and Murmansk Region. Bioleaching tests were carried out in columns, and precipitation of base metals (copper, nickel, and zinc). The final residue was cyanided to recover gold. A mixed bacterial culture of Acidithiobacillus Thiooxidans and Acidithiobacillus Ferrooxidans strains was used. The tailings were leached for six months. Copper and zinc recoveries were 70%. Gold recovery of 65% was achieved [88].

8.3. Froth Flotation

Froth flotation is a separation technique used in the mineral processing industry. Particles are separated according to their surface-physicochemical properties [89,90]. Many elements can be recovered from the tailings through flotation processes; this includes metallic, non-metallic, and precious elements like rare earth metals [12].

Videla et al. [12] carried out a study about tailings treatment through froth flotation, applying ultrasound waves. Laboratory tests were carried out with copper sulfide tailings from the El Teniente mine (Chile). The residues contained around 0.12% copper in the form of chalcopyrite. The effect of ultrasound was found to increase the recovery of fine and ultrafine copper by 3.5%. The ultrasound causes cleaning of the surfaces of the particles, allowing the reagents OrePrep X-133 (foaming agent) and Aero 343 (collector) to have higher efficiency in the process.

Santander and Valderrama [91] published a study on the recovery of pyrite contained in copper concentrate tailings. It is relevant to recover the pyrite before disposing of the tailings to the deposits since it oxidizes, producing AMD. The laboratory tests used tailings from the Atacama region (Chile). Variables such as pH, collector and foam dosage, conditioning time, and flotation stages were analyzed. The tailings were conditioned with 30 g/t of the collector, 20 g/t of foam, 10 min of conditioning time at a pH of 8. It was demonstrated that a flotation circuit with cleaning stages achieves recoveries of 70% of pyrite. The proposed process can generate an economic benefit (concentrated with a grade of 90% pyrite), and incidentally, contribute to caring for the environment.

Rocha et al. [92] report a study on the froth flotation of iron ore tailings. Tailings obtained from a dam located in Mineração Usiminas (Brazil) were used. The reagents used in the Flotation tests were alkyl-ether-monoamine as a collector, corn starch, and cassava flour as depressants. It was determined that the variation of pH from 10 to 8 resulted in a higher iron recovery and increased the silica in the concentrates. The best depressant was cassava flour, since it increases iron recovery compared to ground corn and generated less silica in the concentrates.

Abaka-Wood et al. [93] report the recovery of rare earth elements from tailings through froth flotation. Sodium oleate with hydroxamic acid was used as a collector and sodium silicate with starch as depressants. It was discovered that the recovery of rare earth oxides improved with the incorporation of the Sodium oleate collector giving it higher selectivity. The depressants turned out to be a fundamental piece in froth flotation, generating a recovery of 63% of rare earth oxides.

Babel et al. [94] published the result of a study to recover Zn from southern Chile's tailing. Flotation is used for the recovery of sphalerite, with a high selectivity towards gangue minerals. The test used MIBC as a frother, Danafloat 507-B as a collector, $CuSO_4$ as an activator and KCN as a depressant. The researchers obtain a low sphalerite recovery despite having an excellent overall liberation. They proposed an optimized test work procedure for the future.

8.4. Mixed Processes

The Playa Verde processing plant is located approximately 3.4 km from Chañaral (Chile). Playa Verde processed the tailings discharged into the Chañaral bay from 1938 to 1975. When the tailings reached the sea, they were subjected to tides, waves, and sedimentation on the original sediment, which gave shape to metallic sand beaches. The sands on the beach contain a reserve estimated 35 million tons, with a copper grade of 0.24%. The project consists of extracting the tailings deposited in Playa Grande (Chañaral) by dredging and obtaining cathodes and copper concentrate. The tailings will then be returned to the same beach under environmental conditions. The seawater will come from tailings dredging; it will consist of a reverse osmosis plant of 12.5 L/s [95]. The process consists of sand preparation, acid leaching, solvent extraction, and electrowinning to produce copper cathodes. The leaching gravel will be subjected to a flotation process to obtain copper concentrates. The project has a useful life of 7 years, it is planned to exploit 5 million tons per year, and copper production of 8640 tons per year is estimated [96,97]. In addition to recovering copper, the project wants to reconstruct the relief of the beach. The returned tailings will give a better environmental condition to an area that has been affected by more than 40 years of tailings disposal. The plant's waste will be sanding with a minimum copper and arsenic content, which does not risk the population's health.

9. Conclusions

The pollution of the ecosystem due to the impact caused by underwater tailings in Chile and the countries that practice it is indisputable, and at the same time, this type of practice should be restricted. However, scientific evidence suggests that there is potential for subsea tailings management. It is necessary to have accurate information on the chemical and mineralogical composition and oceanographic studies essential for understanding and predicting the sea's behavior before the final disposal of mining tailings.

The impact on the marine fauna of the tailings is significant. Pelagic and benthic ecosystems can be profoundly affected, but there is still uncertainty about biophysical processes. The flora can also be significantly affected by tailings. Pollution of water and the seabed can produce the bioaccumulation of heavy metals in seaweed mainly. The protection of the marine flora is essential, since it is a vital resource in food, pharmaceuticals, cosmeceuticals, biofuel nutraceuticals, and the commercialization of low-cost raw materials. The protection of marine flora and fauna is essential for Chile, which is among the leading seaweed exporters and number 12 worldwide in aquaculture production.

Proper management of marine tailings would allow mining waste to be given a second chance, with positive environmental, economic, and social benefits. Projects such as Playa Verde in Chañaral can be a feasible proposal for the economic benefit of old mining waste, and incidentally, recovering the coastal edge that has been affected for almost four decades. A technology for proper tailings management is phytoremediation. Certain plant species can tolerate heavy metals, and through their roots, they could stabilize the seabed. Phytoremediation is a much more profitable and soil restorative technique compared to other conventional methods.

Finally, even though Chile has signed the London Protocol, it is impossible to prohibit the discharge of mining tailings into the sea. Legal voids have allowed the disposal of tailings in the marine environment at mining sites, such as the Pellet Plant in Huasco Bay.

Author Contributions: F.R., C.M. and N.T. contributed in research and wrote paper, P.R., E.G. and J.C. contributed with research, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Pedro Robles thanks the Pontificia Universidad Católica de Valparaíso for the support provided.

Conflicts of Interest: The authors declare no conflict of interest.

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