

Article

Economic Evaluation of Bioremediation of Hydrocarbon-Contaminated Urban Soils in Chile

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Abstract: Technical advances have converted bioremediation into a large-scale ecosystem service suitable for the treatment of polluted soils worldwide; however, its application in Chile is scarce. The main hurdles that must be addressed include the capacities of such approaches for the treatment of polluted soils, the lack of knowledge about key factors affecting bioremediation costs and the lack of a legal framework to regulate this activity. In this study, the economic performance of the bioremediation of chronically hydrocarbon-polluted urban soils based on bioaugmentation, biostimulation or the combination of both approaches projected to an industrial scale was evaluated. The cost of bioremediation ranged between USD 50.7 and USD 310.4 per m³ of contaminated soil. In addition, the items and activities that had the most significant impacts on the final bioremediation cost, such as compost for biostimulation and bacterial growth media for bioaugmentation-based approaches, were identified. The projected costs were compared against an extensive database of 130 soil bioremediation projects. The bioremediation treatment costs fell within the top 60% of the more expensive projects, highlighting the high effort involved in bioremediation of chronically contaminated soils. This framework can facilitate the decision making of entrepreneurs, consultants, researchers and governmental authorities when launching initiatives to develop a local bioremediation industry capable of cleaning up a high number of polluted sites in Chile.

Keywords: microbial bioremediation; cost of bioremediation; bioremediation industry

1. Introduction

Petroleum-derived hydrocarbons are the main hazardous compounds causing the contamination of extensive areas of soil and water. The pollution is more frequent at areas near to oil wells and sites devoted to the production, distribution, manipulation, disposal and especially storage of petroleum-derived products. Inadequate management, monitoring and maintenance have led to contaminated sites, generating a potentially permanent source of diffuse pollution that represents a significant health risk for neighboring communities. Historically, conventional techniques for restoring polluted soils have mainly consisted of excavation, removal and disposal of contaminated materials into waste-dumped or hazardous-waste landfills [1,2]. The volatility of the hydrocarbons during removal and management operations constitutes a health risk, especially for workers during excavation, handling and transportation. Microbial

communities in soils possess metabolic and physiological flexibility for adaptation to environmental challenges [3]. The input of contaminants usually impacts the structure and function of the soil microbiome, reshaping microbial communities towards the selection of species that can survive and cope with the toxicity of the contaminants [4–10]. Emergent species within the disturbed communities usually share enhanced physiological and substrate degradation capabilities, oxidizing, transforming, immobilizing or binding the contaminants [11–15]. This metabolic flexibility of soil microbiota present in the environment provides a platform for microbial bioremediation as a valuable ecosystem service [16]. In addition, the biodegradable nature of hydrocarbons and the ubiquitous distribution of hydrocarbon-degrading microorganisms have underlined the efficacy of microbially driven bioprocesses for the restoration of polluted ecosystems [17–21]. Currently, there is an increasing need for alternatives in cleaning up contaminated sites worldwide. For instance, it has been estimated that there are 500,000 and 340,000 contaminated sites in the U.S. and Europe, respectively [22,23]. China has over two million hectares of abandoned sites in more than one hundred old industrial cities that require environmental restoration before redevelopment [24]. It is in this context that full-scale bioremediation projects have been successfully applied, mainly in Europe, North America and, more recently, China [25,26]. As a result, the global industry related to bioremediation services has systematically spread, becoming an industry worth USD 35 billion in 2009 [27]. The growth of the global bioremediation market has accelerated in recent years, reaching USD 91.0 billion in 2018, and it is expected to grow to USD 186.3 billion in 2023 [28].

The main sources of soil contamination in Chile are mining activities (30.9% of total sites), including deposition of metals and metalloids, and agro-industrial activities (30.1% of total sites), including petroleum products, pesticides, fertilizers and urban waste (24.2% of total sites) [29]. Regarding contamination by metals and metalloids, the geological evolution specifically associated with the Andes has resulted in an overwhelming proportion of metallic ore deposits being located in the northern part [30]. Chilean porphyry copper deposits have a low ore grade but exist in huge volumes and, together with the lack of regulations, this has encouraged several large-scale mining operations to leave a legacy of contaminated areas [31]. It has been previously reported that these polluted sites include 740 tailings, of which 23.3% are abandoned [32]. Soil contamination associated with agricultural and forestry production systems includes excessive utilization of fertilizers and pesticides, resulting in diffuse contamination across nearby areas [33,34]. The contamination of soils by other chemicals, such as petroleum derivatives and organochlorines, has mainly been associated with industrial activities outside the boundaries of cities. However, with the growth of the urban population, they have been absorbed by urban areas, such as in Valparaíso, Concepción and Santiago, and there are also cities with industrial activities, such as Quintero, Puchuncaví and Talcahuano [1,35–39]. Despite the urgent need for sustainable clean-up processes, applications of microbial bioremediation in Chile are scarce. Recently, the Chilean government evaluated 19 projects designed to restore metal and hydrocarbon-polluted soils, among which only 8 projects (42%) focused on bioremediation. Several factors may explain why bioremediation is not commonly used. Currently, Chile is the only Organization for Economic Co-operation and Development (OECD) country that does not have a soil protection regulation, which would regulate the maximum permissible concentrations of contaminants [40,41]. Bioremediation may entail higher costs in comparison to conventional techniques, such as the confinement of contaminants in authorized places. The high variability in the physical, chemical and microbiological properties of soils requires the design of site-tailored treatments [42,43]. In addition, the lack of directives, regulations, definitions of methodological tools, process standards and requirements for contaminated soils have hindered the application and development of a local bioremediation industry.

The aim of this study was to provide insights into the comparative costs of five approaches for bioremediation of long-term hydrocarbon-polluted urban soil, including biostimulation, bioaugmentation and the combination of both, highlighting the key factors that influence the costs associated with each approach. Since each contaminated soil has

specific characteristics, this study is a guide to developing the cost assessments of bioremediation processes. This framework will facilitate the decision making of entrepreneurs and consultants when performing a risk–cost–benefit analysis. This study will help to trigger governmental authorities to generate environmental policies, regulations and standards for contaminated soils, as well as launching initiatives to develop an environmentally safe and robust local bioremediation industry capable of cleaning up different polluted sites in Chile.

2. Materials and Methods

Economic evaluation was based on treating chronically contaminated soil, taking the soil conditions of the Las Salinas site (Viña del Mar, Valparaiso Region, Chile) as a reference. The Las Salinas site is a contaminated brownfield that was subjected to petroleum industrial activity for more than eight decades. During this long period, the contamination pressure not only affected the diversity and community structure of soil, but also hampered the ecosystem function and its natural resilience. In such environments, the remaining contamination is often enriched with heavier and more structurally complex fractions of hydrocarbons, due to volatilization or solubilization of volatile fractions and the degradation of lighter alkanes [44]. The more recalcitrant compounds can also be sorbed to the soil matrix, decreasing their bioavailability and the biodegradation rate and extent [44–47].

In general, three main approaches have been widely used for restoring hydrocarbon-contaminated soils [1,48]. The first technology, called biostimulation, includes the enhancement of the metabolic activity of native microbial communities by providing limiting nutrients, such as phosphorous, nitrogen or oxygen, and further modification of environmental factors [1]. The second approach is based on the addition of hydrocarbon-degrading microorganisms, frequently applied when native microbial communities lack the metabolic capabilities or when their activity is unable to trigger significant biodegradation rates [49]. A third approach is based on the addition of stable organic amendments, such as compost, which has been applied with success across pilot- and full-scale applications [44,50,51]. The analysis presented here was based on the bioremediation of chronically contaminated soils, such as those currently present at Las Salinas, in which there is no evidence of persistent degradation processes over time. Therefore, the economic assessment was based on the addition of compost, the addition of hydrocarbon-degrading microorganisms as well as a mixture of both approaches, for which experimental results were previously published [52]. In this study, the bioremediation was addressed by five treatments. Briefly, the first two were based on bioaugmentation, with the addition of five hydrocarbonoclastic strains (named BA), and also the same treatment with the addition of permanent air venting (BAV). The selected hydrocarbonoclastic bacterial strains for bioaugmentation were *Acinetobacter* sp. DD78, *Acinetobacter* sp. AA64, *Acinetobacter* sp. AF53, *Pseudomonas* sp. DN36 and *Pseudomonas* sp. DN34. These strains were previously isolated from hydrocarbon-contaminated soil (Valparaíso, Chile) and possess the ability to degrade a wide range of hydrocarbons [53]. *Acinetobacter* sp. DD78 possess the ability to produce biosurfactants, which can help improve the bioavailability of the hydrocarbons for biodegradation [54]. The following two treatments were based on biostimulation with the addition of compost in two different ratios, 9:1 (*v/v*) and 3:2 (*v/v*), named BE1 and BE4, respectively. The fifth treatment considered was the combination of bioaugmentation and biostimulation, using a mixture of soil and compost with 3:2 (*v/v*) ratio (BAE).

To determine the feasibility of bioremediation as an industrial activity, an economic evaluation was made based on the results of the bioremediation strategies projected to industrial scale. The projection considered the implementation of an on-site hydrocarbon soil bioremediation process in a square one-hectare field with 10 biopiles of 100 m length each. The biopiles were designed to be trapezoidal with 2 m height, 5 m width (base) and 2.5 m width (top), with a 5 m space between each pile (Figure S1). A potential decrease in the bulk density was assumed to be 25% after construction. Each biopile has a total volume of

750 m³ of material that was covered with a High-Density Polyethylene (HDPE) membrane to conserve moisture, minimizing leachate production and gas emissions. It was projected that bioremediation process at an industrial scale would take 20 weeks, assuming one week of preparation and one week of dismantling the biopiles and associated materials, as previously observed (unpublished). An additional period of ten weeks was also considered for contingencies and maintenance. Therefore, each bioremediation cycle treats between 3750 and 6250 m³ of soil, depending on each strategy (Table S1). The proposed equipment and supplies required for the construction of biopiles and soil movement were two front shovel loaders with 2.5 m³ buckets each. Since water content is one of the most critical factors that regulates microbial activity during bioremediation, all treatments include a system for irrigation that uses one spray truck of 20 m³ that periodically moistens the soil.

To determine the initial capital for each treatment, we considered that bioaugmentation-based approaches required infrastructure with higher-technology equipment and cost-intensive installation efforts than those required by biostimulation-based approaches. Indeed, a set of bioreactors was included for bioaugmentation and air injection treatments covering two stages. An initial stage of preinoculation where sufficient biomass is grown for inoculating bigger reactors that contain the biomass to be incorporated into the soil. Five jacketed bioreactors of 0.3 m³ with blowers of 0.0075 m³ s⁻¹ and six jacketed bioreactors of 15 m³ equipped with blowers of 0.4 m³ s⁻¹ were considered for preinoculation and inoculation stages, respectively. Calculations for culture volume added for bioaugmentation was determined on the basis that each strain reaches a density of 10⁶ CFU g⁻¹, value that is 10-fold higher than those levels of cell density of hydrocarbon-degrading microorganisms at which bioremediation will be negligible [55]. Based on bacterial counts made in preliminary laboratory experiments [52], each strain requires one jacketed reactor, except for *Acinetobacter* sp. AA64, which requires two. On the other hand, biostimulation-based approaches require neither biomass reactors nor blowers. Instead, they need machinery to build biopiles, including a front shovel loader and a spray truck. A similar trend was observed when installation services costs were calculated. The cost of installation services was determined by adding the costs of installation of equipment, instrumentation and control, piping, electrical wiring, infrastructure, yard improvements, services, land, engineering and supervision, infrastructure expenses, contractors fees and contingencies (Table S2), and calculated according to suggested values [56].

The determination of operation costs included variable costs, fixed costs, indirect production costs and administrative and sales expenses. Variable and fixed costs enclosed direct raw materials and manpower, respectively. For treatments requiring bioaugmentation, all materials for preparation of Bushnell Haas (BH) medium and monitoring microbial grow were included. The BH broth medium contains (in grams per liter of Milli-Q water): KH₂PO₄, 1; K₂HPO₄, 1; NH₄NO₃, 1; MgSO₄, 0.2; CaCl₂, 0.020; FeCl₃, 0.050. For biostimulation treatments, the supply was assumed to be compost. For every treatment there are several common costs, such as water, diesel and electricity.

The fixed costs considered remuneration for direct and indirect labor, building maintenance, publicity, machinery depreciation and many supplies and services. The incomes, as well as costs, were calculated based on the number of treatments instead of a time scale. Calculations of operating incomes of each treatment were estimated based on the breakeven–total-cost formula as (Fixed costs + Variable costs) = Total revenue = Breakeven, and (Quantity sold × Unit selling price) = Breakeven. Calculations of variable costs per unit produced and the unit selling price were estimated based in the following formula Profit = Unit Sales × (Unit Sales – Variable unit costs)—Total fixed costs. An estimation of contribution margin ratio was made based on ten years life expectancy of each equipment. As every treatment lasts twenty weeks, it was considered that 200 treatments were performed along life expectancy. Revenue estimations were made considering investment costs and the future return of investment in different time lapses (1 to 10 years).

In addition, an extensive cost analysis of 130 soil bioremediation projects was located, reviewed, and evaluated using a collection of peer-reviewed literature, federal and state

agency reports (Table S3). This analysis included bioremediation with either hydrocarbons or a mixture of hydrocarbons and other contaminants, such as organic solvents, halogenated organic compounds and heavy metals. Projects were classified according to the bioremediation strategies, in the following categories, “bioventing”, “biostimulation”, “solvent vapor extraction”, “phytoremediation”, “thermal treatments”, and “bioaugmentation”. In addition, two extra categories were included. The category “various treatments” employs a combination of more than one treatment. The second category, “other”, is a treatment that was not included in the list.

3. Results

Economic assessment was made based on the results of bioremediation of five treatments to clean-up chronically hydrocarbon-contaminated soils, based on bioaugmentation, biostimulation or combination of both technologies [52]. The first approach was bioaugmentation, with the addition of five hydrocarbonoclastic strains (named as BA). The second technology was bioaugmentation with the addition of permanent air venting (BAV). The following two approaches were based on biostimulation with the addition of compost in two different ratios, 9:1 (*v/v*) and 3:2 (*v/v*), named BE1 and BE4, respectively. The fifth treatment was the combination of bioaugmentation and biostimulation, using a mixture of soil and compost with 3:2 (*v/v*) ratio (BAE). The analysis of the start-up capital, defined as the resources required to acquire the assets needed for each bioremediation approach, resulted in a high difference between bioaugmentation and biostimulation treatments. Among all five treatments, bioaugmentation-based approaches were those with the highest start-up capital. The complete start-up capital of BAE and BA was USD 1,822,159, whereas the capital of BAV was USD 2,150,961 (Table S2). In contrast, the complete start-up capital required for biostimulation-based approaches, BE1 and BE4, was an order of magnitude lower than those technologies with bioaugmentation, due to the fact that there is no requirement for equipment, such as reactors and blowers, decreasing costs of installation.

The estimated cost of the bioremediation of chronically hydrocarbon-contaminated soils, assuming that the investment is recovered after five years of operation, ranged between USD 50.7 and USD 310.4 per m³ of contaminated soil (Table 1). Biostimulation with 10% compost (BE1) was the treatment strategy with the lowest cost (USD 50.7 per m³), followed by biostimulation with 40% compost (BE4, USD 131.7 per m³). The estimated costs for treatment per m³ of soil of both strategies that exclusively involved addition of bacterial cultures, BA and BAV, were USD 141.8 and USD 153.9, respectively. BAE was evaluated as the most expensive technology (USD 310.4 per m³ of contaminated soil) due to the high technological level required to provide the bacteria to ensure the bioaugmentation of only 3375 m³ of soil per bioremediation cycle (Figure 1). The analysis encompassed the estimation of product costs, period costs, liabilities and obligations. Projections showed that product costs represent the largest cost for all treatments, reflecting the importance of the selection of raw materials, such as compost and bacterial growth media for biostimulation and bioaugmentation-based approaches (Table S4). The largest item of product cost was the direct material that ranged from USD 17.5 to USD 174 per m³ of bioremediated soil, contributing to 35% and 56% of total costs of BE1 and BAE, respectively (Figure 1). The direct material cost, mainly based on compost, was USD 12.3 and USD 74.1 for biostimulation with 10% and 40% of compost, respectively (Table 1). Each cycle using biostimulation with 10% was more cost effective due to lower compost addition and the treatment of 5625 m³ of contaminated soil, whereas biostimulation with 40% of compost applied higher compost concentration (four-fold) and treated only 3750 m³ per bioremediation cycle (Figure 1). For biostimulation approaches, manufacturing overhead cost was the second largest contribution to the total costs. In contrast, in bioaugmentation approaches, provision and covering assets were the second and the third largest item costs, suggesting that the technological level of bioaugmentation has a significant impact on its economic performance. The provision cost of bioaugmentation treatments is almost two-fold higher than the provision cost of biostimulation, mainly due to an increase in

monitoring and quality control. In addition, there is a high level of costs for equipment and machinery for the culture of microbial strains (Tables S2, S4 and S5).

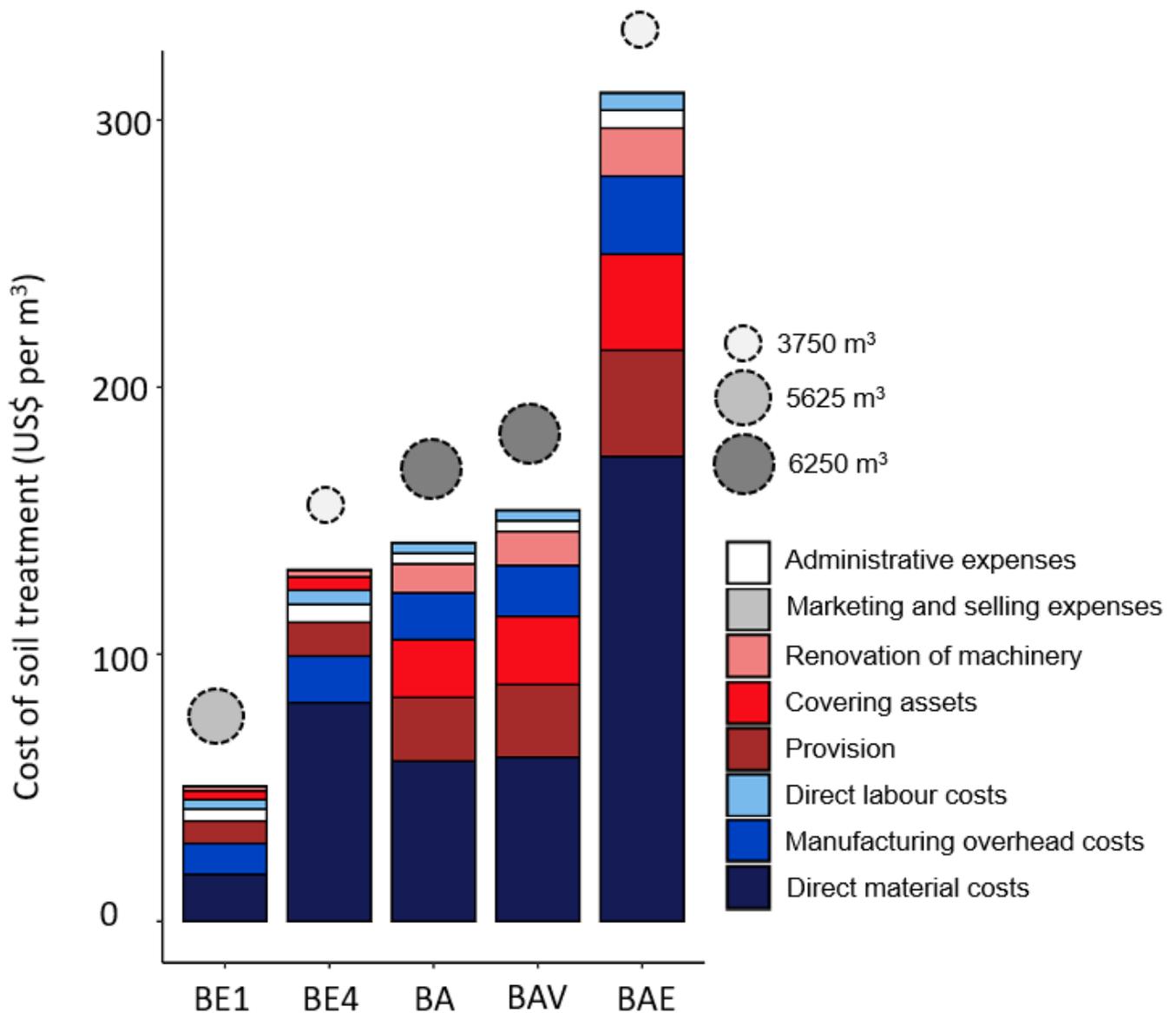


Figure 1. Estimated cost for bioremediation of chronically contaminated soils using different strategies projected to industrial scale. Colors indicate type of cost contributing to the total bioremediation cost. Blue tones show products' costs. Direct material costs are shown in navy blue, manufacturing overhead costs in blue and direct labor costs in light blue. Red tones indicate items included in liabilities and obligations as follows: Marron shows provision, red shows covering assets, and salmon shows renovation of machinery. Marketing and selling expenses are shown in gray. Administrative expenses are shown in white. Dotted line circles shown the quantity (in m³) of soil treated per 10 biopiles of each treatment.

Table 1. Estimated costs per m³ of contaminated soil treated by different bioremediation approaches.

	Items	BE1	BE4	BAE	BA	BAV
Products' costs	Direct material costs	USD 17.5	USD 81.9	USD 174.0	USD 59.9	USD 61.4
	Direct labor costs	USD 3.5	USD 5.3	USD 6.3	USD 3.8	USD 3.8
	Manufacturing overhead costs	USD 11.6	USD 17.4	USD 29.2	USD 17.5	USD 19.0
Period costs	Administrative expenses	USD 4.5	USD 6.7	USD 6.7	USD 4.0	USD 4.0
	Marketing and selling expenses	USD 0.2	USD 0.4	USD 0.4	USD 0.2	USD 0.2
Liabilities and obligations	Covering assets	USD 3.3	USD 4.9	USD 36.0	USD 21.6	USD 25.5
	Provision	USD 8.4	USD 12.6	USD 39.8	USD 23.9	USD 27.2
	Renewal machinery	USD 1.6	USD 2.5	USD 18.0	USD 10.8	USD 12.7
	Total	USD 50.7	USD 131.7	USD 310.4	USD 141.8	USD 153.9

Furthermore, different scenarios for recovery assets were simulated. When the time length of the start-up investment recovery increased to ten years, the cost per m³ of treated soil decreased more significantly for the bioaugmentation treatments than for the biostimulation treatments (Table S6). All these aspects have unequal impacts on the economic performance of the different bioremediation technologies, highlighting the relevance of this analysis, especially for evaluating profitability under incipient market conditions, such as those for bioremediation in Chile.

Cost of Bioremediation in Chile and Other Countries

Our results were calculated using average costs in Chile; therefore, they may be highly influenced by domestic dynamics of unrelated sectors rather than those sectors related to the nature of bioremediation. In order to compare our results to worldwide bioremediation operations, we reconstructed an extensive analysis of 130 bioremediation projects of contaminated soils. The analysis included different types of contaminants (e.g., hydrocarbons, organic solvents, halogenated organic compounds, heavy metals), as well as diverse remediation approaches including biostimulation, bioventing, bioaugmentation, solvent vapor extraction and thermal treatments (Table S3).

We determined that the cost of bioremediation was highly variable and ranged between USD 0.5 and USD 1820 per m³ of treated soil. All the projects that registered costs of < USD 2 per m³ of treated soil were associated with treatments based exclusively on biostimulation, and these treatments only removed 50% of hydrocarbons (Table S3). In contrast, projects that reported costs higher than USD 700 per m³ of treated soil involved treatments of a diversity of contaminants, such as BTEX, VOC, PAHs and heavy metals, using a variety of approaches, including biostimulation, bioaugmentation and thermal treatments (Table S3). The distribution of costs of the projects seems to be more influenced by the type of remediation treatment than the type of contaminants in the soil. The 40% of those projects with lower cost (36) were based on bioventing (20), biostimulation (10), solvent vapor extraction (5) and phytoremediation (1). The 60% of projects with higher costs (94) involved approaches such as bioventing (27), thermal (26), solvent vapor extraction (13), biostimulation (12), bioaugmentation (1), other (6) and combined (9) treatments. Costs calculated in our projections fall within this last group, highlighting the important effort involved in bioremediation of chronically contaminated soils (Figure 2). In general, this effort requires reshaping the soil microbiota and dramatically strengthening their biodegradation capabilities towards the most recalcitrant and less bioavailable fractions. In contrast, several projects belonging to the 40% of lower cost are based on bioventing and biostimulation, mainly oriented to metabolize more easily biodegradable pollutants. The cost of our more expensive treatment, BAE (bioaugmentation and biostimulation), was within the top 20% more expensive projects of the dataset, which are enriched by physicochemical aggressive techniques, such as thermal treatments and solvent vapor extraction (Figure 2).

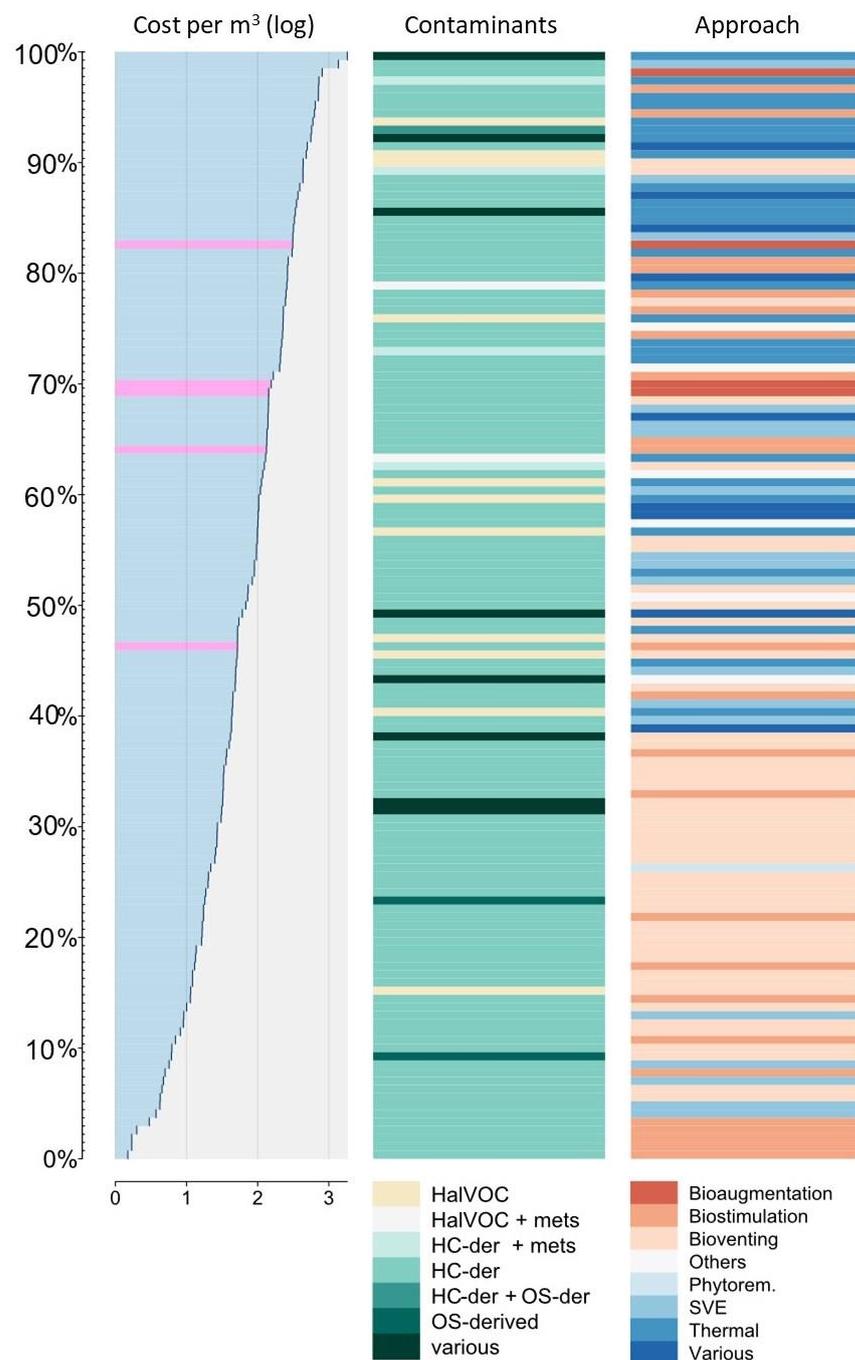


Figure 2. Distribution of the cost of bioremediation across a set of 135 projects around the world. The bar chart in the left shows costs of bioremediation sorted from the cheapest (0%) to the most expensive (100%), and the cost for bioremediation is expressed in USD per m³ of contaminated soils in logarithmic scale. The contaminants column indicates the type of contaminants in the treated soil as the following. “HC-der” indicates soils contaminated with hydrocarbons-derived compounds; “HalVOC” indicates soils contaminated with halogenated volatile organic compounds; “mets” indicates soils contaminated with metals; “OS-der” indicates soils contaminated with organic solvent compounds. The approach column indicates the technique used for soil bioremediation. Abbreviations: Phytorem—phytoremediation; SVE—solvent vapor extraction; Thermal—thermal treatments.

4. Discussion

Far from being a silver bullet, there is not a single bioremediation approach that is useful in all hydrocarbon-contaminated sites [57]. Thus, appropriate characterization of the

polluted soils and the adaptation of bioremediation techniques on a case-by-case basis are essential [58]. Adjustments should consider several factors, including technology-specific components, contaminants (type, concentration, aging and distribution), and the physico-chemical properties of the soil. As a result of the variability, the design and implementation of bioremediation projects have a direct impact on their capability to evaluate the economic performance, converting this into a daunting task [43]. An initial guide for the evaluation of costs of different bioremediation approaches, such as the one presented here, is relevant not only to compare these alternatives to projects based on excavation and disposal, which is rather easy to grasp, but to integrate this information through management practices to ensure the technical and economic feasibility of bioremediation projects, where the decision making is empirical rather than knowledge based.

This study indicated the cost of bioremediation of chronically hydrocarbon-contaminated soils by different approaches in a country with neither developed environmental remediation industry, nor economic policies that help to determine the treatments costs. The cost of the bioremediation of chronically hydrocarbon-contaminated soils was estimated to be between USD 50.7 and USD 310.4 per m³ of soil. Among those, biostimulation with 10% of compost (BE1) was found to be the most cost-effective treatment. Except for BE1, all other bioremediation costs ranged on values that have been previously reported for biopile bioremediation of hydrocarbon-contaminated soils [59]. Our results showed that biostimulation-based treatments have lower costs than their counterparts using bioaugmentation. Specifically, the comparison between all bioaugmented treatments and BE1 revealed that the last treatment, though effective in hydrocarbon biodegradation [52], showed a significant reduction in direct material costs, provision and covering assets. This highlights the properties of compost, which is the mature product of composting, a bioprocess that transform solid organic substrates into relatively stable, organic-rich material via microbial communities [60]. Amendments with compost are considered a blend between the addition of nutrients and microorganisms with enzymatic composition and metabolic capabilities to biodegrade persistent compounds [50]. The first production of compost based on organic urban waste was dated as early as about 6000 years ago, when humans transitioned from being gatherers and hunters to breeders and farmers before establishing themselves in urban settlements [61]. Since then, compost has been widely applied in agricultural fields as a source of limiting nutrients for crops, such as nitrogen and phosphorus [62–65], amendments to reducing soil-borne crop diseases [66,67], and as a way of enhancing soil fertility by increasing natural nutrient cycling [68] in both conventional and organic agriculture [69]. The applications of compost have expanded to other fields, such as control of soil erosion [70], carbon sequestration [71], greenhouse gases biofiltration [72] and enhanced bioremediation [46,73]. Indeed, their application in bioremediation of organic contaminants has exponentially increased over the years [74,75]. However, in Chile, compost currently maintains a low price, since it does not compete with alternative uses besides turf/grass industries and organic-based agriculture. Therefore, the potential impact of higher demand for compost on the cost of biostimulation-based bioremediation remain to be examined in further detail. In contrast, the requirements of equipment and supplies for cultivation of high volumes of microbial biomass, as well as monitoring and quality controls converts bioaugmentation to a more expensive process. These results should be analyzed cautiously as a higher control level of remediation, including addressing the level of success of bioaugmentation and/or biostimulation in supplying hydrocarbon-degrading microorganisms, which may increase the efficiency of the process, but also may raise the bioremediation costs. Further analysis towards analyzing the impact of critical variables on the efficiency and efficacy of bioremediation are beyond the scope of the current work, however, they remain to be examined in future.

The economic evaluation of microbial bioremediation of chronically contaminated soils presented in this study will contribute to improvements in the understanding of how costs vary for each bioremediation approach, and therefore, they may be used as an input for risk–cost–benefit analysis. This is especially relevant in an industry that focuses its efforts on facing environmental remediation liabilities that occurred in the past instead of producing new products or rewarding shareholders [43]. As a whole, the absence of regulation and

laws governing the maximum permissible concentrations of contaminants in soils converts the traditional “the polluter pays” to the predominant paradigm in Chile, preventing the advent of alternative paradigms that integrate ecosystem services, such as microbial bioremediation, as a valuable input to support ecological restoration. Furthermore, this framework will help to address similar challenges that other productive sectors have historically faced in Chile, where the controversial tradeoff between economic growth and environmental pollution is still rather frequent [76]. As with many other current sustainability challenges [77], it becomes relevant to establish a debate about regulations and incentive policies to encourage the implementation of local bioremediation industry capable to clean up a high number of polluted sites. Undoubtedly, the technical and scientific dimensions of the debate will have a positive impact on the recent Framework Law for Soils (Ley Marco de Suelos) that, after twenty years of discussion, has advanced to the discussion of several issues, including climate change, land management, land degradation and the prevention of soil contamination [41].

5. Conclusions

During the last few decades, the use of microbial bioremediation as a technology to restore polluted sites has been increasingly applied worldwide. Despite its several technical advances, and the growing need for improved technologies to effectively restore contaminated environments, bioremediation has been scarcely used in Chile. In the present study, the cost of five different bioremediation strategies based on biostimulation and/or bioaugmentation for removing hydrocarbons from chronically contaminated soils in an industrial projected scenario were estimated. The results identified compost and bacterial culture media as the items with the highest cost for biostimulation and bioaugmentation-based approaches, respectively. The comparison of the projected costs with an extensive database of 130 soil bioremediation projects indicate that the treatment costs fall within 60% of the more expensive projects, highlighting the high effort involved in bioremediation of chronically contaminated soils. An initial guide for the evaluation of costs of different bioremediation approaches, such as the one presented here, is relevant not only to compare these alternatives to projects based on excavation and disposal, which is rather easy to grasp, but to integrate this information through management practices to ensure the technical and economic feasibility of bioremediation projects, where the decision making is empirical rather than knowledge based. This framework will also facilitate a debate about regulations and incentive policies to encourage the implementation of local bioremediation industry capable of cleaning up a high number of polluted sites, as well as to improve the decision making of entrepreneurs and consultants, and may help to trigger government-generated environmental policies, regulations and standards for contaminated soils.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su141911854/s1>, Figure S1: Dimensions of projected soil biopiles for bioremediation; Table S1: Soil volume per hectare treated during each bioremediation cycle; Table S2: Total initial capital of the different bioremediation treatments; Table S3: Cost of 130 bioremediation projects worldwide; Table S4: Products and period costs of the different bioremediation approaches; Table S5: Total machinery depreciation of the different bioremediation treatments; Table S6: Recovery assets of the bioremediation treatments after initial investment recovery. Refs. [44,78–140] are cited in supplementary materials.

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