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Environmental Impact Assessment of Remediation Strategy in an Oil Spill in the Ecuadorian Amazon Region

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Abstract: Past petroleum-extraction activities in Ecuador have contaminated its Amazon region. To assess the environmental impact attributed to remediation activities regarding the cleanup of these oil spills, two scenarios were studied according to Life Cycle Analysis methodology: (1) No-action, which means to leave the contamination in place without any further action and (2) Environmental remediation, where the environmental-load attributed to the remediation of the representative oil spill was studied. Results indicated that the no-action scenario presented a higher environmental impact for 12 out of the 16 environmental categories evaluated (climate change, ozone depletion, human toxicity non-cancer effects, particulate matter, ionizing radiation human health, ionizing radiation ecosystem, photochemical ozone formation, acidification, terrestrial eutrophication, marine eutrophication, freshwater ecotoxicity, mineral, fossil and renewable resource depletion). Moreover, the no-action scenario presented a global weighted score of contamination of 5.45 points, while the remediation scenario got a score of 3.3 points, which means that the remediation decreased by 39% of the global environmental impact due to the remediation activity applied, showing the positive influence of environmental remediation to mitigate the effects attributed to the presence of pollution sources associated to the petroleum industry in the Ecuadorian Amazon region.

Keywords: climate change; oil pollution; life cycle assessment LCA

1. Introduction

Petroleum is among the main Ecuadorian products of exportations [1], every year representing around 40% of total exportations and contributing 9% of the Gross Domestic Product in 2019 [2]. The Ecuadorian petroleum industry started in the 1970s [3], mainly in the Amazon region (east of the country) with 112 oil fields, and also in the coastal region with two oil fields [4]. However, despite the economic importance of the petroleum industry for the country, environmental damages attributable to these activities were left behind. For example, wastes resulting from the oil exploration and production activities (sludge, oil, water and drill cuttings, and others) were disposed of in the vicinity of the extraction facilities without any treatments [5,6]. As a consequence, these areas have environmental liabilities that require attention. In general, environmental liability is associated with a source of pollution and tends to increase over time [5].

On the other hand, the demographic growth had a strong influence on the appearance of new settlement, some of them in the influence area of (former) petroleum facilities [3]. Moreover, the expansion of agricultural frontiers due to the need of increasing the food production can also result in human health problems that result from the environmental liabilities of the petroleum industry. Rural populations and indigenous communities are clearly the most affected human groups. The affectation of soil, water, flora and fauna, attributable to inappropriate practices of the petroleum industry was largely studied [7–9]. In addition, several reports on the negative effects on human health due to the exposure of humans to compounds associated with petroleum extraction manifesting as skin, digestive, respiratory, pregnancy and reproductive diseases, among others, were widely reported [10–12].

In this regard, the Ecuadorian government has executed several projects for the closure and remediation of the environmental liabilities associated with the petroleum industry in the Ecuadorian Amazon region since 2005. These projects involve a variety of activities including cleaning, remediation, reshaping, and revegetation of areas polluted, mainly, in the provinces of Francisco de Orellana and Sucumbíos [5,6].

Environmental remediation is “the removal of pollutants or contaminants from groundwater, surface water, soil, and sediment” [13]. Indeed, one of the most important goals of environmental remediation is the recovery of polluted areas to improve the living conditions of their inhabitants. However, traditional remediation activities also demand the use of a considerable number of natural resources, fossil fuels, energy and human labor. Therefore, they also generate hazardous and non-hazardous wastes, as well as gaseous emissions. Consequently, a negative environmental impact can be also attributed to remediation activities [14,15] and must be taken into consideration. Therefore, a cost-benefit analysis of these activities is necessary. A quantification of the negative impacts is also required to propose improvement strategies to lower the global impact.

In this sense, life cycle assessment (LCA) is an option to evaluate the environmental behavior of products or process. In fact, LCA was previously used for the evaluation of remediation technologies in various scenarios, such as soil pollution by heavy metals, polychlorinated biphenyls and volatile organic compounds (VOC) [14,16–21]. During LCA evaluation, the identification of primary and secondary impacts in remediation technologies is important; primary impacts are those related to residual contamination left in the subsurface during and after remediation, while secondary impacts refer to the consumption of resources and generation of emissions in other stages of the remediation life cycle of the project [14].

This study assesses the environmental impact of the remediation activities of an environmental liability attributed to the petroleum industry, which contemplate clearing and solid waste collection, construction of facilities, soil washing, reshaping and revegetation. Two scenarios were compared: (1) the environmental remediation of a representative oil spill (i.e., the release of a liquid petroleum hydrocarbon into the environment) that occurred in the 90s decade, and (2) a no-action scenario, that means no execution of any action of remediation, leaving the environmental liability in its place with no anthropogenic influence in the slow degradation of pollutants. This led us to consider how to improve the current strategies of environmental remediation applied in the Amazon Region of Ecuador.

2. Materials and Methods

2.1. Study Site

Environmental remediation activities for an oil spill from the Sacha 124 well that occurred more than a decade ago were evaluated. The environmental liability was codified as SA_124_02D (total remediated area of 2701.84 m²) by the government institution. It is located at Canton Joya de los Sachas (Francisco de Orellana province) in the Ecuadorian Amazon region (Coordinates: 9,957,666.78 N, 289,612.60 E). The site is at 275 masl. It has an average annual temperature of 23 to 25 °C, relative humidity of 90% and an annual precipitation of 4500 mm. The soil in the area is shallow and has rocky outcrops with

limitations for agricultural, livestock and forestry activities [22]. This environmental liability was chosen as a case of study due to the availability of data and for representing a common scenario in the activities of remediation carried out in this region.

2.2. Environmental Remediation Activities

The remediation strategy involves the following steps (a) clearing of solid waste, (b) construction of facilities, (c) washing of soil contaminated with crude oil, (d) reshaping of the affected area and (e) revegetation. These activities require the use of heavy machinery (excavators, dump trucks), pumps and vehicles for the mobilization of people as well as for the transport of tools and equipment. Furthermore, workers wear uniforms and specific personal protective equipment (PPE) such as gloves, helmets, masks, protective suits against chemical agents and raincoats. Taking into account that these materials are considered to be hazardous waste and are incinerated at the end of their lifetime, their volume was quantified through detailed records in the waste delivery manifests.

Additionally, there are other activities included, such as the measurement of affected area with basic topographic techniques [23]; the monitoring of the concentration of Total Petroleum Hydrocarbons (TPH) in the soil before, during and after remediation [24] until the concentration of TPH is under the limits that are established in environmental regulations [25]; and the socialization of the remediation activities to owners of the affected area to obtain their authorization. However, these activities are not considered in the study because they do not demand a considerable consumption of resources. The remediation activities evaluated in this study encompass the following phases that are developed in a continuous and parallel way.

2.2.1. Clearing of Solid Waste

This consists of removing the vegetation and collecting other wastes. It involves the use of excavators and dump trucks to remove the entire surface layer from the area to be intervened. Contaminated vegetation is taken to treatment centers for composting and uncontaminated vegetation is reincorporated into the site when intervention activities are completed.

2.2.2. Construction of Facilities

Pedestrian and vehicular accesses, places where workers can take a break, waste collection sites, and other facilities are needed. They must be built, and heavy machinery is needed.

2.2.3. Soil Washing

In oil spills such as the case of the study, the predominant contaminant is crude oil, and the main affected matrix is soil. According to the experience of the government institution in charge of remediation activities, in similar scenarios, the best technique to recover the soil is in situ soil washing with water and biodegradable surfactants (e.g., limonene-based) to facilitate the removal of hydrocarbons (hydrophobic contaminants). Water is taken from nearby water bodies. The use of pressure pumps allows for the generation of turbulent conditions for the cleanup of the soil (contaminants are released from the soil). The activity is carried out until the presence of contamination is not visually distinguishable. In this stage, the crude oil is recollected and transported to a recuperation plant for its final reincorporation into national production. After soil washing, physical-chemical analyses of the used water are carried out and, if values of relevant parameters comply with the limits established in Environmental Regulations [26], it can be discharged into the environment; otherwise, the water must be treated before its discharge, for example by coagulation and flocculation [27].

2.2.4. Reshaping and Revegetation

The remediation of soil is completed when the concentrations of pollutants comply with permissible limits established in Environmental Regulations [25]. After, the facilities are dismantled and the intervened area is reshaped, taking into account the original topography, and revegetated with native species.

2.3. Life Cycle Assessment (LCA)

LCA was carried out according to the procedure of the Standards ISO 14040 (2006) and ISO 14044 (2006) [28,29]. The aspects and/or components needed to perform the LCA are briefly described in the following.

2.3.1. Scope

Environmental remediation activities carried out in the oil spill SA_124_02D were analyzed and compared with the no-action scenario. The study is descriptive, and the limits of the system are visualized in Figure 1, which represents all activities from the environmental remediation process.

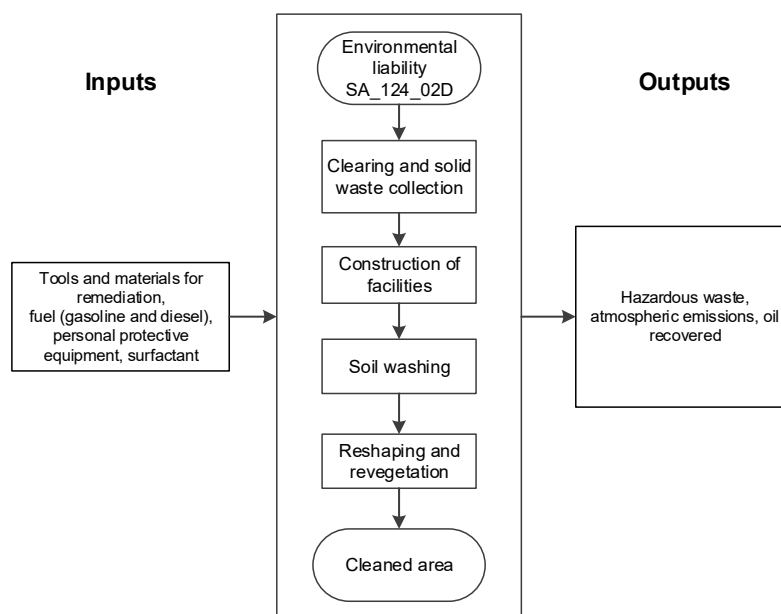


Figure 1. System boundary of remediation activities scenario.

2.3.2. Life Cycle Inventory

To quantify the inputs and outputs of the system, data were collected throughout the described remediation process. The main collected and/or calculated data were:

- Fuel consumption (diesel and gasoline) for the operation of vehicles and mobile equipment, the total mileage for the vans and the km/t for the trucks.
- The volume of the biodegradable limonene-based surfactant. The composition of this product was obtained from the technical sheets available from the distributor.
- The volume of crude oil recovered from the cleaned oil spill, which was incorporated into national production.
- Use and consumption of tools and materials for remediation and PPE were considered. Subsequently, the predominant component of each item was determined by reviewing the manufacturer's technical data sheets, as shown in Table 1.

Table 1. Main components of tools, supplies and personal protective equipment in the environmental remediation process.

Personal Protection Equipment	Weight (g)	Principal Component	Weight (g)
Sitex bib overall	800	PVC plastic	800
Gloves—PVC dotted (pair)	4	Natural cotton fibers 45%	1.8
		Polyamide 45%	1.8
		PVC 10%	0.4
Long nitrile gloves (pair)	150	Nitrile	150
Short nitrile gloves (pair)	175	Nitrile	175
Protective suit against chemical agents	42.5	High-density polyethylene	83
Clear glasses	25	Polycarbonate (66%)	16.5
		PVC plastic (34%)	8.5
Waterproof jacket	200	Polyamide with polyurethane coating	108
Disposable hearing aids	3	Hypoallergenic foam	3
Dark glasses	25	Polycarbonate (66%)	16.5
		PVC (Polyvinyl chloride) plastic (34%)	8.5
Rubber boots with steel tip (pair)	1500	Reinforcement on the toe: modified PVC: 50%	750
		Lining: polyester 5%	75
		Tip: 1.5 mm thick antistatic steel; 25%	375
		Shoe sole: nitrile 10%	150
		Shoe insole: cotton and foam rubber 10%	150
Leather boots (pair)	1260	Reinforcement on the toe: 22-gauge waterproof leather: 50%	630
		Shoe sole: polyurethane with thermoplastic polyurethane: 10%	126
		Tip 1.5 mm thick antistatic steel; 25%	315
		Shoe insole: cotton and foam rubber 10%	126
		Lining: polyester 5%	63
Aerosol and particulate respirator	15	Outer layer: polyester 40%	6
		Electrostatic filter: polypropylene microfibers with ACMB (Activate Carbon Melting Blowing) technology 15%	2.25
		Inner layer: polypropylene 30%	4.5
		Nasal pad: high-density foam, 5%	0.75
		Elastic band: synthetic rubber braided with latex-free polyester, 5%	0.75
Nappa gloves (pair)	8	Adjustment clip: polypropylene 5%	0.75
		Cowhide leather (nappa) (80%)	6.4
Gas and vapor mask (half face)	168	Natural cotton (20%)	1.6
		Silicone (60%)	100.8
Vapor filter	8.63	Nylon (40%)	67.2
		Activated carbon: 70%	6.041
		Polyethylene: 22%	1.8986
		Carbon treatment: 4%	0.3452
Helmets	360	Polyester: 4%	0.3452
		Polyethylene	360

The same area of 2701.84 m² was considered for the no-action scenario. In fact, the weight of hydrocarbons contained in this amount of soil was determined as 80,136 kg of TPH.

Specific data for the reshaping and revegetation stage was not available. Therefore, required resources for this stage were estimated. Similar requirements for the phase of access routes and facility construction were assumed. Long-lasting materials such as tools and equipment for laboratory analysis were not considered. The specific assumptions and

limitations of this study are summarized in Table S1. The complementary information needed for the usual process was taken from Ecoinvent LCI Database [30].

2.3.3. LCA Evaluation

The modeling of the flow of materials and the calculations of associated environmental impacts were carried out using SimaPro software (PRé Sustainability B.V., Amersfoort, The Netherlands) [31], together with ILCD (International Reference Life Cycle Data System) 2011 Midpoint + V1.10/EC-JRC Global methodology [32] and Ecoinvent Databases [30]. The unknown data of the process is complemented by the information of the Ecoinvent Database.

The environmental categories analyzed in this work were climate change, particulate matter, ozone layer depletion, eutrophication (terrestrial, freshwater and marine), human toxicity (carcinogenic and non-carcinogenic effects), ionizing radiation for human health, ionizing radiation for ecosystems, acidification, freshwater ecotoxicity, photochemical ozone formation, mineral, fossil and renewable resource depletion, land use and water resource depletion.

Environmental impact from the characterization stage were calculated. A weighting methodology proposed in an earlier report [33] was also applied in this work. In this regard, extractions and emissions measured worldwide were taken as reference factors for each of the values of the environmental categories evaluated, and then transformed to dimensionless values (points) [33]. In this way, the comparison of the categories affected by specific characteristics of the scenarios was possible. Furthermore, the results of some categories were grouped to show the end-point environmental effects. In this regard, the “resource depletion effect” is represented by the climate change, ozone depletion, photochemical ozone formation, land use, water resource depletion, mineral-fossil and renewable resource depletion categories. The “human health impacts” contemplate human toxicity-non cancer effects, human toxicity-cancer effects, particulate matter and ionizing radiation human health categories, while “ecosystem impacts” are formed by acidification, terrestrial-, freshwater- and marine-eutrophication and freshwater ecotoxicity.

3. Results

3.1. Life Cycle Inventory

The life cycle inventory was generated for both scenarios. The results are summarized in Table 2.

3.2. Environmental Impact in Each Environmental Category of LCA

Table 3 shows the results of the environmental impact assessment obtained by LCA in the characterization stage with the corresponding percentages for each category, thus providing a trend of the behavior of each indicator for each scenario. Also, weighted midpoint results for each category in both scenarios are included in Table 3.

Table 2. Life cycle inventory for the environmental remediation and non-action scenarios.

Inputs				Outputs			
Description	Database Ecoinvent	Amount	Unit	Description	Database Ecoinvent	Amount	Unit
Environmental Remediation Scenario							
Crudo oil recovered from the environmental liability	Petrol, low-sulfur production Cut-off, U	80,136	kg	Crude oil recollected and transported to a recuperation plant for its final reincorporation to national production	Petrol, low-sulfur {RoW} production Cut-off, U	80,136	kg
Contaminated vegetation recollected	Compost {RoW} treatment of biowaste, industrial composting Cut-off, U	3.42	t	Emissions generated in LCA related to the inputs	Electricity/heat emissions to air, emissions to water, emissions to soil, final waste flows, nonmaterial emissions, social issues, economic issues, waste to treatment	ND	ND
Use of heavy machinery (excavators, dump trucks), pumps, and vehicles for the mobilization of people as well as for the transport of tools, and equipment (vans and trucks)	Machine operation, diesel, ≥ 74.57 kW, high load factor {GLO} market for Cut-off, U	42.93	hr				
	Transport, freight, light commercial vehicle {RoW} processing Cut-off, U	3096.8	tkm				
	Transport, passenger car, large size, diesel, EURO 4 {RoW} transport, passenger car, large size, diesel, EURO 4 Cut-off, U	2746	km				
	Machine operation, diesel, < 18.64 kW, steady-state {GLO} market for Cut-off, U	1665.1	hr				
Biosurfactant used in soil washing	Biosurfactant	147.63	l				

Table 2. Cont.

Inputs				Outputs			
Description	Database Ecoinvent	Amount	Unit	Description	Database Ecoinvent	Amount	Unit
Principal componentes in PEE, tools and materials used in remediation activities	Polyvinylidenchloride, granulate {RoW} production Cut-off, U	22,135.1	g	Hazardous waste sent to incineration	Hazardous waste, for incineration {RoW} treatment of hazardous waste, hazardous waste incineration Cut-off, U	278,772.05	g
	Seal, natural rubber based {RoW} production Cut-off, U	7629.66	g				
	Nylon 6 {RoW} production Cut-off, U	9358.33	g				
	Synthetic rubber {RoW} production Cut-off, U	10,108.33	g				
	Polycarbonate {RoW} production Cut-off, U	13,141	g				
	Polyurethane, flexible foam {RoW} production Cut-off, U	153,066.7	g				
	Polyester-complexed starch biopolymer {RoW} production Cut-off, U	2564.66	g				
	Steel, low-alloyed {RoW} steel production, electric, low-alloyed Cut-off, U	9789.69	g				
	Cotton fibre {RoW} cotton production Cut-off, U	31,213.66	g				
	Polyethylene, high density, granulate {RoW} production Cut-off, U	179.92	kg				
	Polypropylene, granulate {RoW} production Cut-off, U	22,025.76	kg				
	Textile, jute {RoW} production Cut-off, U	2.37	kg				
Non-action Scenario							
Hydrocarbons spilled to the ground	Petrol, low-sulfur {RoW} production Cut-off, U	80,136	kg	Hydrocarbons recovered from the soil	Petroleum oil	80,136	kg

RoW: Global process excluding the European Union. GLO: Global process. LCA: Life Cycle Analysis. EURO: UE vehicle clasification. ND: No experimental data.

Table 3. Results of LCA for the no-action and remediation scenarios in the characterization stage.

Environmental Category	Caracterization			Percentage (%)		Points	
	Units	No-Action Scenario	Environmental Remediation Activities	No-Action Scenario	Environmental Remediation Activities	No-Action Scenario	Environmental Remediation Activities
Climate change	kg CO ₂ eq.	55,477.99	42,010.33	100	75.72	0.401	0.304
Ozone depletion	kg CFC ⁻¹¹ eq.	5.56×10^{-2}	4.35×10^{-3}	100	7.83	0.172	0.013
Human toxicity, non-cancer effects	CTUh	3.04×10^{-3}	1.40×10^{-3}	100	46.02	0.380	0.175
Human toxicity, cancer effects	CTUh	9.97×10^{-5}	5.79×10^{-4}	17.22	100	0.180	1.046
Particulate matter	kg PM _{2.5} eq.	57.45	19.75	100	34.37	1.008	0.346
Ionizing radiation human health	Bq U ₂₃₅ eq.	18,951.12	1282.53	100	6.77	1.118	0.076
Ionizing radiation ecosystem (interim)	CTUe	1.34×10^{-1}	9.20×10^{-3}	100	6.84	0.000	0.000
Photochemical ozone formation	kg NMVOC eq.	255.40	169.50	100	66.37	0.537	0.356
Acidification	molc H ⁺ eq.	610.26	171.01	100	28.02	0.860	0.241
Terrestrial eutrophication	molc N eq.	583.93	540.53	100	92.57	0.221	0.205
Freshwater eutrophication	kg P eq.	5.23×10^{-1}	7.12×10^{-1}	73.51	100	0.024	0.032
Marine eutrophication	kg N eq.	52.99	49.41	100	93.25	0.209	0.195
Freshwater ecotoxicity	CTUe	30,066.81	27,747.30	100	92.29	0.229	0.212
Land use	kg déficit de C	2544.05	4291.63	59.28	100	0.002	0.004
Water resource depletion	m ³ eq. water	52.29	65.39	79.97	100	0.043	0.054
Mineral, fossil & renewable resource depletion	kg Sb eq.	0.10	0.07	100	73.29	0.064	0.047
Total						5.448	3.305

From the 16 environmental categories subject to evaluation, 12 of the categories showed higher impact values in the no-action scenario than in the environmental remediation scenario. These categories are climate change, ozone depletion, human toxicity with non-carcinogenic effects, particulate matter, ionizing radiation for human health, ionizing radiation for ecosystems, photochemical ozone formation, acidification, terrestrial eutrophication, marine eutrophication, freshwater ecotoxicity and depletion of mineral, fossil and renewable resources. In contrast, the remaining four categories (human toxicity with carcinogenic effects, eutrophication of freshwater, land use and depletion of water resources) showed higher impact values in the environmental remediation scenario. In general, there is a greater environmental impact in the no-action scenario with 5.45 points. Furthermore, between the two scenarios there is a difference of 2.14 points. Therefore, the environmental load for the remediation scenario is lower by 39.4%.

3.3. End-Point Results of LCA Categorized by Type of Final Affection

Figure 2 shows the impacts for the final affected groups. In all the groups, a lower environmental impact is observed for the remediation scenario. Impacts on ecosystems decreased by 43% and impacts on human health decreased by 39%. Also, it is important to highlight that impacts on the availability of resources decreased by 36%.

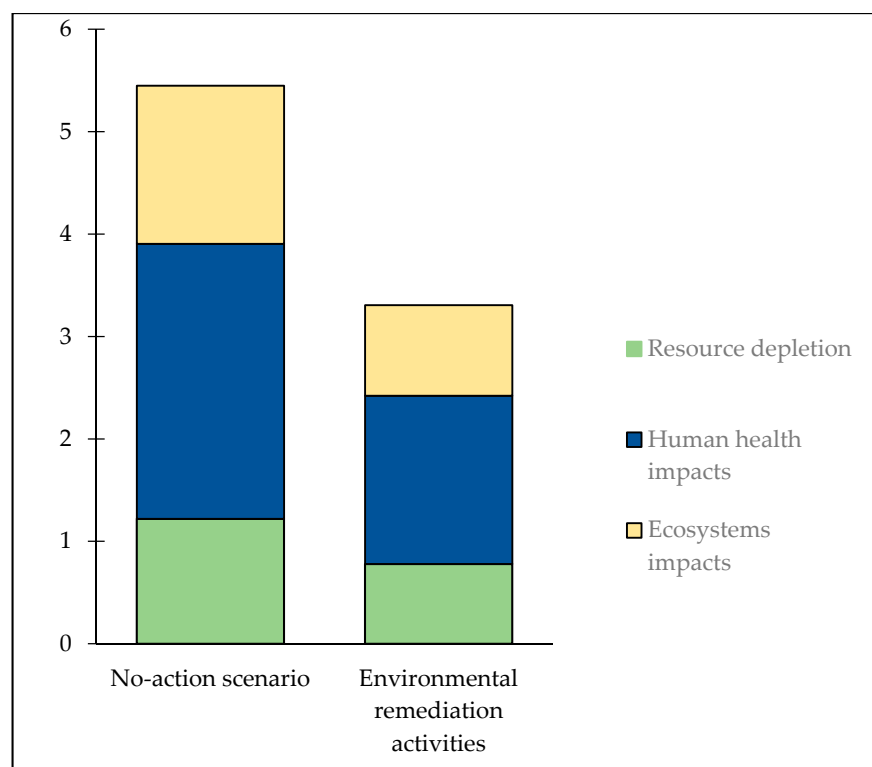


Figure 2. End-point results of LCA (Life Cycle Analysis) categorized by type of final affection.

4. Discussion

The interpretation of the results requires an evaluation in terms of activities included in each scenario that can produce a potential environmental impact. These activities were identified and related to the environmental categories considered for the LCA.

4.1. Environmental Remediation Scenario

4.1.1. Consumption of Fossil Fuels by Heavy Machinery, Vehicles, and Pressure Pumps

The use of vehicles, heavy machinery and mobile equipment is crucial in all stages of the environmental remediation under consideration. The mobilization of people, the transport of tools and equipment, as well as the removal (and transport) of soil for ex situ

treatments and the movement of recovered crude oil, require the consumption of fossil fuels. Gasoline and diesel, which have a fossil origin, generate gaseous emissions that are released into the atmosphere. The resulting environmental impacts are related to the following environmental categories:

- Climate change, since the emissions include carbon dioxide (CO₂), the most known greenhouse gas. However, CO₂ is not the only greenhouse gas and other gases such as methane (CH₄), nitrous oxide (N₂O) and ozone-depleting substances (ODS) also contribute to global warming [34]. Combustion processes can produce nitrogen oxides (NO_x) [35] and N₂O [36]. Despite the natural bacterial breakdown of nitrogen in soils and in the oceans is considered to be the main source of N₂O in the atmosphere, it is recognized that the combustion of fossil fuels and biomass are also contributors that cannot be underestimated [37]. The transport of contaminated soil is responsible for the environmental impacts related to the category of climate change; some authors found that, for distances larger than 200 km between the remediation site and the soil treatment site, the impact associated with gaseous emissions was significant [38]. Other studies have also reported a significant contribution to the impact in this category due to the use of fossil fuels [17,39,40]. In this study the environmental remediation implied a total path traveled by a truck of 6194 km, while the van traveled 2744 km. It is undeniable that impacts associated to the vehicles are considerable and alternatives with less mobilization should be explored.
- Stratospheric ozone depletion, since, as explained before, N₂O is produced by the combustion of fossil fuels.
- Particulate matter, since it is produced by the incomplete combustion of fossil fuels. The main component of particulate matter that results from the combustion of fossil fuels is black carbon, which absorbs solar radiation and therefore is an important source of global warming [39], together with the health effects mainly impacting the respiratory system. In fact, some authors suggested that black carbon could be the second strongest contributor to global warming after CO₂ [40,41].
- Formation of photochemical ozone, since NO_x and VOC resulting from vaporization of fuels are precursors of tropospheric O₃ and pernitrate species (the most abundant is Peroxyacetyl nitrate, PAN) [35]. Additionally, tropospheric ozone (O₃) is another gas that contributes to global warming; however, O₃ is not regulated by the Kyoto and Paris Protocols likely because it is a secondary pollutant [42].
- Acidification and terrestrial eutrophication, since NO_x and sulfur dioxide (SO₂) are emitted due to the combustion of fossil fuels. The emission of NO_x and SO₂ can be explained by taking into account that fossil fuels contain variable amounts of sulfur and nitrogen compounds [43,44]. In addition, a high temperature combustion of a fuel in contact with atmospheric nitrogen (N₂) results also in the formation of NO_x [45].
- Human toxicity with non-carcinogenic effects, since populations can be exposed to primary and secondary pollutants resulting from the combustion of fuels. Primary pollutants include CO₂, CO, particulate matter, NO_x (fundamentally NO and NO₂) and SO₂. Secondary pollutants are a variety of photochemically produced gases such as tropospheric O₃, particulate matter derived from atmospheric chemical reactions, PAN and other organic compounds occurring in the photochemical smog. Short-term effects of the exposition to these air pollutants can range from slight temporal discomfort, irritation of the eyes, nose, skin and the respiratory tract, coughing, chest tightness, breathing difficulties, headaches, nausea and dizziness, to more serious conditions such as asthma, pneumonia, bronchitis, and lung and heart problems [46].

4.1.2. Gaseous Emissions and Discharges Generated by the Incineration of Hazardous Waste

PPE and other tools that reached to the end of their lifetime are incinerated to ensure a proper elimination of these wastes. According to some authors [47,48], the incineration of hazardous waste contributes to the following categories: climate change, human toxicity

with non-carcinogenic and carcinogenic effects, particulate matter, photochemical ozone formation, marine and soil eutrophication, and depletion of mineral, fossil and renewable resources.

Special importance is given to the category of human toxicity with non-carcinogenic and carcinogenic effects due to implications to human health. There are many chemical species that can be produced, and therefore released due to incineration; the most problematic are polycyclic aromatic hydrocarbon (PAH), polychlorinated biphenyls (PCBs), dioxins and furans. Also, flue gas can contain variable concentrations of (heavy) metals, which is usually associated to particulate matter [49]. The generation of carbon monoxide is an inevitable consequence of incomplete combustion and, together with acid gases (e.g., HCl, SO₂), is a notable contributor to the hazardous nature of gaseous emissions from incinerators.

4.1.3. Gaseous Emissions and Discharges Related to the Manufacture of Tools and Materials for Remediation Activities and PPE

PPE and tools are used in the remediation process and, at the end of their lifetime, are wastes. In all stages, the processes involved in the environmental remediation requires the use of PPE for the protection of workers since they are in contact with hazardous chemical compounds. The life cycle assessment of the predominant components of PPE is showed in Table S2 (Supplementary Material). The manufacture and use of PPE impacts the environment in all evaluated categories, and, to a lesser extent, leads to ionizing radiation in ecosystems and land use.

4.1.4. Transfer of Crude Oil and Other Chemical Compounds Present in Contaminated Soil and Sediment

In the soil washing phase, turbulent conditions are created to separate crude oil from the soil. This increases the contact of contaminants with the aqueous washing solution, and thus increases the availability of contaminants [50]. Contaminants are transferred to water and a remainder of those substances will be present even in the treated water; therefore, there is an affectation in the category of freshwater toxicity and depletion of water resources. Surfactants are used in soil washing procedures and these substances affect the content of oxygen in the water. The biodegradation of chemical compounds in water requires oxygen and this oxygen is obtained from the dissolved oxygen. Moreover, common surfactants used for remediation purposes [51] contain nitrogen in their structure (e.g., cetrimonium bromide, CTAB and cocamidopropyl betaine, CAPB) and could promote eutrophication.

4.1.5. Remediation Activities

Since remediation activities are carried out in many cases manually, mainly in the clearing phase, workers have direct exposure to contaminants. Despite the rigorous use of PPE, the exposure to carcinogenic and non-carcinogenic substances cannot be ruled out. The contribution of the remediation scenario to the categories of ionizing radiation for ecosystems and human health is of particular importance. Crude oil, production sludge, formation waters and gas, among others, are a considerable source of Technologically Natural Radioactive Materials (TENORM). TENORM are accumulated by the high content of radionuclides in rocks (for example: Uranium, Thorium and Radium and their decay products, and Potassium-40) that have existed since the formation of the earth, which are also characterized by the accumulation over time, so they can put human health at risk and damage the environment. Despite being significantly lower compared to no-action, the consequences to human health are a concern for its exposure to radioactive material hydrocarbon compounds [52]. The presence of TENORM in Ecuador has been previously reported, especially in the production of crude oil [53].

4.1.6. Emissions and Discharges Resulting from the Reincorporation of Crude Oil Recovered from Environmental Liabilities to National Production

Crude oil recovered from the environmental liability is reincorporated into national production. Its generation of gaseous emissions and discharges when it is finally used would contribute to the category of freshwater ecotoxicity and human toxicity with carcinogenic and non-carcinogenic effects, as verified in previous studies of the life cycle study of crude oil production [54].

4.1.7. Impact on the Landscape and Soil by the Environmental Remediation Activities

According to the Simapro software, there are three causes that affect the landscape and land use [55]. This software analyzes the impact on land use based on the Organic Matter Deficit in the soil, which has direct impacts on the fertility and physical-chemical conditions of the soil (infiltration, stability, habitats, and morphology of the site), generating midpoint impacts related to the impact on the production of biotics and biomass, and as a final impact the potential damage to ecosystem services [56]:

- Drainage/irrigation: when the activities of clearing, construction of accesses and surface reshaping are carried out, the natural drainage courses of the bodies of water are modified for the construction of dams to control the effluents during soil washing. Although surface reshaping is carried out based on the initial topography of the site, at the end of the operations, the area of the remediated environmental liability is not exactly equal to the initial area and natural restoration will take a significant amount of time.
- Compaction: surface reshaping affects soil compaction.
- Modification of the vegetation layer: when the revegetation activities of the remediated area are carried out, pioneer plant species are used in the first instance and, since the environmental liabilities are generally located in private properties, plant species of interest of the owner are also planted, changing the species found before the remediation activities and therefore the ecosystem is modified.

4.2. No-Action Scenario

By analyzing the no-action scenario, it was determined that environmental impacts may be related to the contamination of natural resources. The study area where remediation activities were carried out has an average annual rainfall greater than 3000 mm reaching 6000 mm, a relative humidity of 90%, and an average temperature of 23 to 25 °C [57]. Based on the mentioned climatic conditions, it is highly probable that the pollutants have migrated, following the natural course of the nearby bodies of water. Furthermore, the greater contact of the pollutants with air favors the evaporation of volatile fractions and gaseous emissions.

According to the final disposal routes for hydrocarbons from oil spills [58], the following environmental impacts are identified.

4.2.1. Water Contamination

The composition of hydrocarbons in crude oil is diverse, with densities between 0.85–1.04 g/cm³. In freshwater bodies, the dispersion of pollutants will depend on various factors, such as their density (<1 float; >1 sink), the ability to interact with sediments and the intensity of water flows. The contamination of bodies of water by hydrocarbons represents an impact on aquatic life, causing toxic effects at all levels of the trophic chain, affecting phytoplankton, zooplankton, fishes, aquatic birds, mammals and benthic organisms [59]. Water contamination in this scenario would be related to the following environmental categories:

- Human toxicity with carcinogenic and non-carcinogenic effects: compounds classified as carcinogenic by the Agency for Toxic Substances and Disease Registry (ATSDR) that are present in crude oil could include benzene, benzopyrene, benzoanthracene, dibenzoanthracene, chrysene, benzo (b) fluoranthene and benzo (k) fluoranthene.

These compounds are lipophilic and are transported by the lipoproteins of cell membranes, and are then accumulated in the fatty tissues of living organisms, thus entering the trophic chain, and causing serious disorders such as cancer, malformations and genetic mutations [58]. Furthermore, toxic effects related to PAHs have been found to cause cancer of the bladder, breast, esophagus, larynx, lung, liver, skin, pancreas and prostate [60].

- The toxic compounds found in the oil, but which are without carcinogenic effects used by the SimaPro software [61], are aromatic compounds such as toluene, ethylbenzene, xylene; aromatic compounds such as naphthalene, isopropyl benzene and biphenyl; aliphatic compounds such as hexane; and aliphatic compounds such as kerosene and fuel oil.
- Freshwater ecotoxicity: depending on the characteristics of the crude oil, it will form a complex with the surrounding soil, sediments, vegetation and water. When crude oil is mixed with water, it interacts with sediments forming Crude Oil Aggregate Particles (OPA). According to [62] (pp. 145–156), based on models of crude-sediment interactions, up to 65% of the volume of spilled crude is linked as OPA and the rest is partitioned directly in the water; this fraction is highly bioavailable, so its toxicity increases, affecting to aquatic ecosystems. It should be considered that for the case study, the water from estuaries is commonly used by the surrounding human population for the fulfillment of their vital functions; therefore, this contamination could affect their health.
- Eutrophication of freshwater: when crude oil is in contact with water, forms an oily layer on the surface that hinders gas exchange, increasing the amount of oxygen required by the biota in the water, favoring eutrophication [63].
- Depletion of water resources: it would represent the equivalent volume of water that cannot be used because is contaminated.

4.2.2. Air Pollution

Mainly, due to the generation of permanent gaseous emissions over time for the presence of crude oil and other pollutants in the environmental liability [58], semi-volatile VOCs are important precursors of organic secondary aerosols [64,65]. If the size of the aerosols is smaller than 100 nm, they are considered ultra-fine particles and may travel very far distances from the oil spill site, with long residence times in the atmosphere thus increasing the radius of contamination. However, the final disposal and environmental impact of hydrocarbons in the atmosphere will be specific to the type of hydrocarbon and its physical state (dissolved or evaporated) is dependent on its initial partitioning by solubility or volatility [58].

Air pollution from oil spills would contribute to the following environmental categories:

- Climate change: CO₂ contribution may be related to the area of contaminated soil without vegetation that stops sequestering carbon from the environment. Other studies have also shown that the presence of residual hydrocarbons, originated by oil extraction in soils with high levels of organic matter in anaerobic environments, promotes their decomposition and the formation of methane. In the context of climate change, the warming potential of methane is 25 times higher than CO₂ [66]. In global terms, the environmental remediation of this liability prevented the release of 13.5 kg CO₂ eq. to the environment per the LCA functional unit.
- Formation of photochemical smog and acidification: this is due to the interaction of hydrocarbons from the oil spill with nitrogen-oxides in the presence of light that would later return to the surface as acids [58].

4.2.3. Soil Contamination

Soil is affected by oil spills, and is where degradation routes such as bioaccumulation, volatilization, filtration, adsorption, and other chemical and physical-chemical processes take place [58]. This contamination is related to the following categories:

- Soil use: oil contamination affects in soil could cause damage to infiltration, stability and use of habitats. In turn, these generate midpoint impacts in the filtration and purification of water, regulation of the water flow, resistance and stability of the soil, functional diversity, diversity of species, and aesthetic and cultural values [56].
- Particulate matter: a possible cause of the higher concentration of particulate matter in this scenario would be the formation of stable pavements or structures on the soil surface or sediments contaminated with hydrocarbons that are not very soluble in water. Since they are combustible compounds, a considerable amount of black smoke with particulate matter is generated in the natural ignition process of the hydrocarbons, which despite containing minimal amounts of residual hydrocarbons, presents a potential risk to human health [58].
- Ionizing radiation for human health and ionizing radiation for ecosystems: the environmental impact would be related to the presence of radioactive waste in the environmental liability, because in the presumed date that the spill at well Sacha 124 occurred, environmental considerations for crude oil production did not meet adequate technical standards. According to [52], crude oil, sludge, formation waters and gas, among others, are a considerable source of TENORM, due to the high content of radionuclides in the rocks that have existed since the formation of the earth, which also accumulates over time [52,67–69]. A predominant factor is its characteristic of being bioaccumulative. It is necessary to emphasize that this category is “provisional”, which means that the method used is the most appropriate compared to others, but that it requires even more development, so its results require validation before issuing a recommendation [70].

4.2.4. Air, Soil and Water Pollution Caused by Emissions, and Discharges Generated in the Production of Crude Oil

In the no-action scenario, 80,136 kg of oil crude were present in the oil spill. Therefore, the environmental loads associated to production of crude were considered by analyzing previous studies of the life cycle analysis of the production and refining process of petroleum [54,71,72]. Here, CO₂ and CH₄ are identified as predominant emissions that contribute mainly to climate change and the photochemical ozone formation. In addition, an important contribution is observed in the category of human toxicity, with carcinogenic and non-carcinogenic effects, freshwater ecotoxicity, acidification, eutrophication of freshwater and resource depletion. On the other hand, the refining process of petroleum shows that approximately 20% of the total contribution associated with ozone depletion and the significant generation of particulate matter is related to crude oil production [54].

4.3. Weighted Results Analysis

A greater impact was observed in the no-action scenario. This would be related mainly to the environmental loads corresponding to acidification. Regarding the impact on human health, where the impact of environmental strategy scenario is lower by 39%, this decrease would be mainly related to the category of ionizing radiation, according to the difference of 1.04 points between both scenarios. In the group corresponding to the impact on the availability of resources, an environmental contribution lower by 36% was determined in the remediation scenario, mainly related to the category of photochemical ozone formation with a difference of 0.18 points between the two scenarios evaluated.

Our results are consistent with previous studies where the impact of executing remediation activities was compared with no-action. In the study carried out by [73], the application of bioremediation through biopiles to soils contaminated with diesel was evaluated. It was observed that the presence of contamination in soils constituted the most

important contribution to global environmental impacts in an order of 1 to 10 if is compared with soils that were remediated. Likewise, in similar studies developed by [38], it was determined that remediation technologies have a positive impact on the environment and health of people. In other words, the environmental cost of carrying out environmental remediation is lower than the environmental cost of leaving the contamination in the soil.

4.4. Improvement Strategies in Environmental Remediation Processes

Based on the environmental categories that presented the highest values in the environmental remediation scenario, the following improvement opportunities were identified.

Regarding the use of vehicles and heavy machinery, it would be useful to review the routes used by vehicles and heavy machinery to optimize distances and reduce mileage, preventative and corrective maintenance programs that ensure optimal working conditions cannot be neglected. Sharing vehicles for activities in nearby places must be considered.

Concerning the use of PPE, it is advisable to review the technical specifications involved in looking for alternatives for materials that both meet the safety requirements and have a longer durability than the current ones, to reduce the generation of hazardous waste when incinerated. If it is not possible to find materials with longer durability, would be necessary to choose materials with less hazardous effects once incinerated. It is advisable to carry out the associated risk analysis in the workers directly involved in the remediation to evaluate the best PPE they should use.

Another aspect of improvement is the evaluation of alternative surfactants used in soil washing and the selection of the options with higher biodegradability.

5. Conclusions

The remediation process of spill-type pollution sources carried out in this study was environmentally evaluated using LCA methodology, followed the procedure stated at ISO 14040 and ISO 14044 standards and was then compared with the scenario of no-action. The environmental characterization indicates a greater positive environmental impact in the environmental remediation scenario in 12 out of the 16 environmental categories evaluated, with a global score of 5.45 points for no-action and 3.3 points for the environmental strategy carried out. This fact reflects that the execution of remediation on environmental liabilities reduces the global environmental impact, indeed approximately 39.4% for our case of study. Regarding the groups of categories of the final affectation, a reduction of 43% in the environmental impact was reach to the ecosystem impacts, followed by 39% for the affectation to human health impacts and 36% for resources depletion. Therefore, evaluated remediation activities on this study contributed positively to mitigate the environmental effects generated by the presence of sources of pollution associated with wastes from hydrocarbon activity in the Ecuadorian Amazon. However, improvements of the process have not been ruled out.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/pollutants1040019/s1>. Table S1: Assumptions and limitations considered in the life cycle assessment of remediation activities of the environmental liability SA_124_02D, Table S2: Environmental impacts related to the manufacture of supplies and personal protection equipment in remediation activities.

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