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Analysis of Environmental Sustainability through a Weighting Matrix in the Oil and Gas Industry

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Abstract: In the oil sector, various strategies are applied to mitigate harmful effects on the environment. These strategies include, among others, compensation plans, the measurement and control of the carbon footprint and/or water footprint, the recovery of waste from activities and processes, and Environmental Management Systems (EMS). An EMS provides a formal framework that enables more efficient work on environmental issues, thereby improving performance. It aims to raise awareness of the environmental impacts associated with the oil industry in different areas through the use of weighting matrices. Additionally, it seeks to conduct sustainable studies and optimize the direct activities involved in the exploitation of hydrocarbons as a natural resource. Factors considered in decision making include ensuring that the strategy does not compromise the well-being of future generations, has economic viability, and does not hinder any oil sector activities such as exploration, drilling, production, or processing of derivatives. The purpose of this is that it allows for the creation of decision matrices based on weighting methodologies that outline possible correlations between specific activities of the oil sector such as water use, effects on soils and landscapes, greenhouse gas emissions, solid waste, liquid effluents, hazardous waste, and toxic waste, among others. The decision matrices can also help elucidate the relationship of these activities with mitigation strategies to provide a decision-making tool for environmental management plans so that activities are implemented in a way that can mitigate impacts on water, soil, and air resources. The results of this study were classified using a traffic light matrix, based on the level of technical congruence, using an optimal (green), regular (yellow), medium (orange), and at-risk (red) scale. The environmental impact of "alteration of the geoform of the land" was positioned in the at-risk category due to its assessment by experts in relation to the activity of "land adaptation". In the medium category, a total of 23 impacts were identified, while 10 impacts fell into the regular category. These results were evaluated in the context of the environmental, social, and economic sustainability of the oil industry.

Keywords: activities; industry; environment; optimization; risk

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Citation: Guerrero-Martin, C.A.; Ortega-Ramírez, A.T.; Rodríguez, P.A.P.; López, S.J.R.; Guerrero-Martin, L.E.; Salinas-Silva, R.; Camacho-Galindo, S. Analysis of Environmental Sustainability through a Weighting Matrix in the Oil and Gas Industry. *Sustainability* **2023**, *15*, 9063. https://doi.org/10.3390/su15119063

Academic Editor: Grigorios L. Kyriakopoulos

Received: 17 April 2023
Revised: 19 May 2023
Accepted: 21 May 2023
Published: 3 June 2023

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1. Introduction

In the oil and gas industry, various activities involve the extraction and utilization of organic compounds. This exploitation process entails significant technical aspects that play a crucial role in specific processes. Failure to manage these processes effectively can have severe consequences. Within the oil and gas industry, there are four main operations that will be discussed in greater detail in the following sections.

One definition of environmental sustainability is a social, economic, and environmental balance to ensure, as far as possible, continuity in the future [1]. For Colombia, the 2012 United Nations Conference on Sustainable Development in Rio de Janeiro created awareness of the need to continue striving toward fulfilling the Millennium Development Goals (MDGs). The MDGs paved the way for the Sustainable Development Goals, with the idea to reaffirm commitments and actions of nations to eliminate poverty and ensure peace, prosperity, and natural resources for the planet and humanity [2]. The economy encourages oil activity due to its weight in the international market, not because this would not be limited to the sector per se but rather because of its size and scope. As with the issue of sustainability at a multidimensional level, this phenomenon in the field extends to consideration for the social and cultural sectors.

Taking these parameters into consideration, it is crucial to consider both the economic and social aspects of the oil industry. This study aims to estimate the environmental degradation caused by the oil industry, considering its impact on both the economy and society. Deforestation resulting from oil extraction creates an environmental impact that can be quantified through the loss of ecosystem services. To assign an economic value to the emitted CO_2, which is a byproduct of hydrocarbon exploitation, the annual CO_2 emissions from refining the extracted oil were multiplied by the price per ton of CO_2. According to a report by the World Bank and *Ecofys*, carbon pricing initiatives implemented worldwide value 1 ton of CO_2 ranging from below USD$1 to a maximum price of $139 [3].

The first operation in the oil industry is exploration, which involves utilizing various techniques to locate sites with significant oil reservoirs. This process encompasses multiple steps, including the acquisition of seismic data to establish numerical and stratigraphic criteria for identifying areas rich in oil [4]. Additionally, there are complementary sub-activities that enhance well and seismic records, such as well testing, land adaptation, the creation of exploratory wells, and the assessment of formation types. These activities collectively contribute to gathering information to identify potential areas for oil extraction. The primary objective of exploratory wells is to confirm the geological model of previously identified structures, utilize geophysical models, discover oil, and evaluate the potential of target formations [5].

The second significant operation is known as drilling, which involves various sub-activities related to the production well which is supported by a drilling column. These activities include the use of drilling fluids, such as water-based mud (WBM) or oil-based mud (OBM), to facilitate the drilling process in the oil-bearing area [6]. Downhole motors are utilized in drilling and are categorized based on their base components. They serve as tools that provide additional power to the drilling string, especially in challenging conditions, and enable adjustments to the well's trajectory for more efficient outcomes [7]. It is important to emphasize the interdependence of these operations within the industry as they contribute to optimizing processes and achieving the best possible outcomes. The third operation is production. In this process, there is a phase during which oil and gas are extracted from a reservoir to a well and from there to the surface, where the oil and gas are separated, treated, stored, measured, and transported for their subsequent use [8]. Similar to the other operations, this process is composed of different sub-activities such as recovery systems, which consider the recovery factor. The recovery factor, one of the most important variables in the recovery process, is the percentage of the original crude that can be recovered from a reservoir. This process has three types of recovery, one of which is primary recovery, which consists of the techniques applied to light crudes where a displacement caused by the natural energy of the reservoir is generated. In last place is tertiary recovery, also known as enhanced recovery techniques, which are used for crude oils whose API gravity is less than 10° (extra-heavy). These techniques are used to increase the recovery of a reservoir that has been previously exploited by secondary techniques and are generally classified into thermal methods, gas injection, and chemical and microbiological methods [9]. Further activities include pipeline implementation, operation phases, treatment plants, and artificial lift systems, which is a mechanism external to the producing formation [10].

The final operation is known as teardown and installation. Production facilities, including transportation lines and equipment used in the crude oil treatment process, play a crucial role in oil production. These facilities need to be assessed to determine their operational state and whether any changes or maintenance are required [11].

These operations, along with their respective activities, have significant environmental impacts. In this environmental risk study, the magnitude and probability of occurrence of these consequences are taken into consideration [12].

When discussing the exploration operation, it is important to consider the potential environmental risks involved. Some risks associated with exploration operations include deforestation and air pollution resulting from micro-leaks of methane, butane, and propane. There can also be risks of water contamination and damage to formations during controlled explosions and the use of drilling mud, which may contain additives that pose a threat to local flora. Different methodologies may be employed for these processes depending on whether the oil extraction is conducted onshore or offshore.

During offshore extraction, there is a risk of contaminating marine fauna and microbiological species on the seabed. This contamination can be detected using radars or by following a three-step process: identifying dark areas with low backscatter, characterizing these areas using satellite imagery, and classifying potential oil spills using statistical methods [13]. Considering these risks, the adoption of a matrix system could provide valuable support to decision-makers in the oil and gas sector.

2. Materials and Methods

During the development of this study, the social, environmental, and economic aspects of oil exploitation were carefully considered. A key outcome of this study is the creation of an environmental risk matrix, which could potentially contribute to better regulation and management of sustainability within the industry. To evaluate the environmental impacts, a weighting matrix was developed, where these impacts are assigned numerical values based on the environmental impact index set by the regulations of the Colombian Ministry of the Environment.

A dynamic weighting system was adopted to assess the sensitivity of the proposed framework. This allows for the adaptation of the weighting matrices to specific contexts. The study aims to examine the interrelationships among decision factors that are essential for strategic analysis when determining the location of a new productive zone. Furthermore, the study seeks to generate specific data that can be utilized through practical exercises to enhance society and the environment. The goal is to determine the different types of oil activities and their respective magnitudes of impact.

By utilizing the matrix, a clearer understanding can be obtained regarding which activities pose higher risks and the economic implications of either continuing or improving them for optimal quality of hydrocarbon exploitation.

This methodology is utilized in decision-making processes as it offers a swift and efficient approach to categorizing the direct factors that give rise to environmental risks within the oil industry. Furthermore, its simplicity enhances comprehension, thanks to the clear categorization and color-coded system reflecting the severity of activities and their environmental impacts. This enables the identification of various risk-generating conditions.

The weighting matrix emerges as a highly effective tool for making informed decisions that promote environmental sustainability within the oil and gas industry. To ensure its continued usefulness, it is advisable to regularly update the data, ideally every 3–6 months. This approach allows for a comprehensive and in-depth study, facilitating the determination of the quality of oil activities and enabling the effective and efficient mitigation of risks. By adopting such measures, superior sustainable management practices can be implemented in the realm of hydrocarbon exploitation.

The constantly evolving and uncertain context emphasizes the necessity of conducting a meticulous study to determine the most optimal locations for productive operations. When considering the ideal choice of location, a thorough analysis of key criteria becomes imperative [14–16]. These criteria encompass a diverse range of indicators including air quality, physical properties of the atmosphere, sound pressure levels, radiation levels, geological conditions, topographical characteristics of the terrain, geotechnical aspects, groundwater quality, availability of groundwater resources, fluvial dynamics, sedimentation patterns, surface water quality, availability of surface water resources, oceanographic conditions, coastal morphology, soil quality, visual perception alterations, land use changes, terrestrial ecosystems, vegetation, flora, terrestrial fauna, aquatic ecosystems, aquatic biota, landscape, and various others. Furthermore, potential indicators may also include the presence of unpleasant odors and fluctuations in demographic variables [17,18].

The assessment of environmental indicators plays a pivotal role in evaluating the potential environmental risks associated with various activities within the oil industry. In this regard, it is essential to consider five key activities in petroleum production: seismic logging, site preparation, exploration well drilling, well testing, and well type sampling. Each of these activities carries its own set of environmental implications that need to be carefully examined. For instance, drilling involves crucial sub-activities such as bit drilling, the utilization of drilling motors, and the application of drilling fluids such as mud and cement, which can have significant environmental consequences. Additionally, the production of hydrocarbons encompasses the implementation of recovery systems (primary, secondary, and tertiary), artificial lift systems, pipeline installations, operational phases, and treatment facilities. Lastly, in the final stage of the industry's operations, namely dismantling and installation, critical sub-activities include equipment dismantling, clarifier application, management of tanks and pumps, as well as the supervision of hydrocarbon transportation stations. To establish meaningful correlations between these activities and their corresponding environmental indices, the expertise, and insights of petroleum engineers with direct experience in the oil industry have been enlisted. Their valuable knowledge helps ensure a comprehensive assessment of the environmental risks involved.

The weighting matrix, developed by industry experts, utilizes a scale ranging from 1 to 4 to assess the environmental risks associated with different factors. A rating of 1 signifies a low environmental risk, 2 represents a moderate risk, 3 indicates a medium risk, and 4 denotes a high risk. The matrix incorporates indices and their corresponding definitions, enabling the evaluation process (refer to Figure 1) to consider the specific environmental risk indices. This systematic approach allows for a comprehensive assessment of the environmental risks involved in the oil industry operations.

The initial step involves presenting a form where specialists can provide their pertinent personal information. This form includes fields for the specialist's full name, a signature for approval of participation in the matrix development, a signature for a confidentiality agreement, profession, field of expertise, and years of experience (refer to Table 1). Additionally, the form requests the experts' consent to create the matrix and assures them that the provided data will be made fully accessible to the evaluators. The table also encompasses crucial aspects and professional experience in the industry for the purpose of this study.

Based on data collected by the experts, a statistical table was created showing their areas of expertise and number of years of experience. (Figure 2).

The following table summarises the environmental risk indices provided by the Colombian Ministry of the Environment and Sustainable Development so that the expert, when filling out the matrix, has clarity on the factors' importance and specific definitions (Table 2).

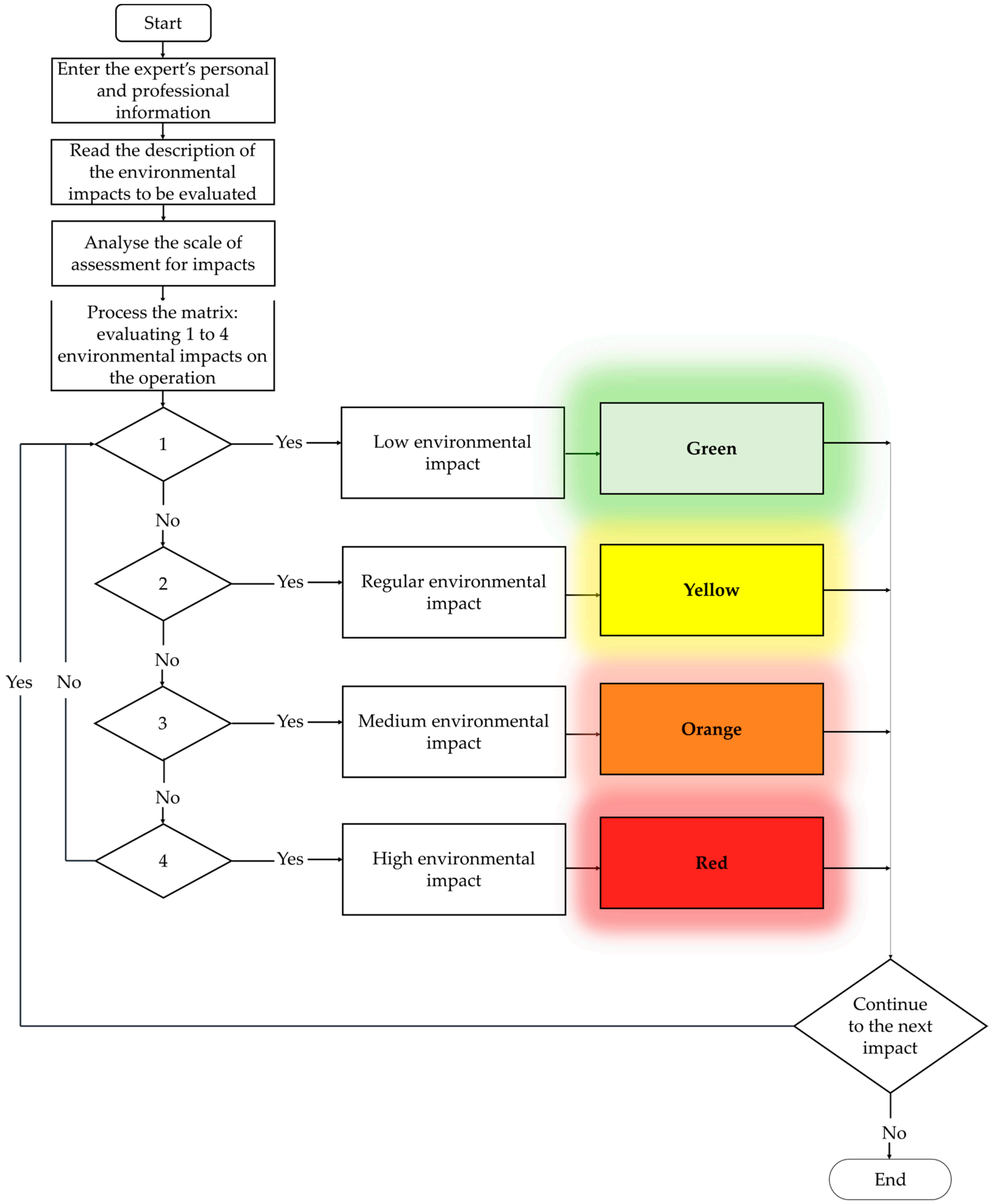

Figure 1. Flowchart, methodology. (Note: made using EdrawMax by authors, 2022).

Table 1. Data collection example.

Names	**Last Names**
Field of expertise	Perforation
Years of experience	1–5 6–10 11–15 16–20 21–25 26–30 31–35 36–40 41–45 +45
Expert signature for confidentiality Expert signature for matrix creation approval	

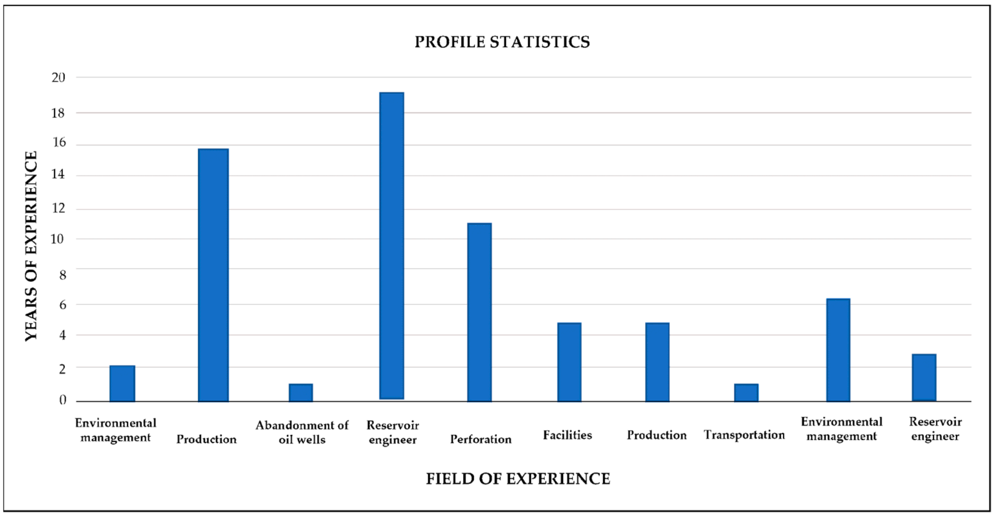

Figure 2. Industry expert profile information.

Table 2. Summary of the environmental risk indices provided by the Colombian Ministry of Environment and Sustainable Development.

Impact	Description
Alteration to air quality	Increase or decrease in the concentration of ammonia, arsenic, benzene, polychlorinated biphenyls, bioaerosols, BTEX, butane, cadmium, elemental carbon, total organic carbon, inorganic chlorine, hydrogen chloride, copper, chlorofluorocarbon compounds, inorganic chlorine, inorganic fluorine, halocarbons, volatile organics, persistent organics, and hazardous air burns.
Alteration to soil quality	Change in soil biological characteristics, physical characteristics, microbiological characteristics, and chemical characteristics.
Alteration in radiation levels	Change in ionizing radiation levels and non-ionizing radiation levels; interference in telecommunication services; increase or decrease in incident light intensity, microwave radiation levels, infrared radiation, light radiation, thermal radiation, ultraviolet radiation, gamma rays, X-rays, radioactive particles, and solar radiation incidence.
Alteration in the supply and availability of surface water resources	Change in water supply, surface water body flow rates, surface water body volumes; increase or decrease in water supply for human consumption, transport, navigation, fishing, aquaculture, preservation of flora and fauna, agriculture, domestic use, aesthetics, industrial use, mining, livestock, recreational use, environmental and ecological purposes, volumetric purposes, water consumption, and water volume.
Alteration to the geoform of the land	Change in the dynamics in continental and/or coastal marine landforms of geomorphic, erosional, morphodynamic, and sedimentary processes; terrain slopes, stability, morphology, morphostructure, and topography; and geomorphological units.
Modification of accessibility, mobility, and local connection	Change in community access to nucleated centers; travel frequency, times, and flows; road safety; and types of mobility.
Alteration to flora communities	Change in plant species composition, structure, and function; fragmentation of ecosystems; increase or decrease of individuals of one or more species; and modification of populations.
Alteration to groundwater resource quality	Change in physical, microbiological, and chemical groundwater characteristics.

The Ministry of Environment and Sustainable Development of Colombia has provided eight environmental impact indicators that serve as the foundation for evaluating the weighting matrix of the 34 environmental impacts [17]. These indicators are used to derive the various environmental impacts associated with the aspects under consideration. The present study focuses on the potential environmental impacts of the oil industry's sub-activities in relation to air, water, soil, and radiation. The weighting matrix includes a table of values with color-coded ratings, ranging from lowest to highest (refer to Figure 3), which serves as a reference for experts to assign a numerical rating from 1 to 4 to each sub-activity based on its level of environmental risk.

Figure 3. Numerical and color scale of environmental risk.

The final step involves the completion of the matrix, where the environmental risk levels are assigned to the sub-activities within the four key operations of the oil industry. This process yields a comprehensive weighting matrix that evaluates the environmental impact risks associated with the industry. As an illustration, Table 3 presents an example of the weighting matrix, focusing on the exploration operation and its five activities, in relation to the six identified environmental risks.

Table 3. Matrix example of exploration activities versus six environmental risks.

	Activity	Alteration to Air Quality	Alteration to the Geoform of the Terrain	Alteration in the Supply and Availability of Surface Water Resources	Alteration to Groundwater Resource Quality	Alteration in Radiation Levels	Alteration to Flora Communities
Exploration	Seismic	1	3	3	2	1	2
	Adequacy of land	1	3	3	2	1	2
	Well testing	1	3	3	2	1	2
	Well drilling	1	3	3	2	1	2
	Sample type of training	1	3	3	2	1	2

An example visualization of the weighting matrix, along with the corresponding values used to create the traffic light system, is presented in Table 3. The complete matrix encompasses a total of 34 impacts for each operation within the oil industry, including exploration, drilling, production, dismantling, and installation. By gathering such data, a more comprehensive understanding of environmental risks associated with oil industry activities is facilitated, particularly when supported by experts who possess firsthand experience in the oil exploitation process.

The purpose of this weighting matrix is to establish a consensus on data representation through a traffic light system, effectively organizing and highlighting actions with the greatest impact. To collect the necessary data, two weighting matrices were considered: one involving experts specialized in abandoned wells and another involving experts with experience in drilling wells, with a focus on higher occurrence rates and sample collection for analysis and interpretation within the oil industry.

3. Results

The table presented below (Table 4) highlights the primary activities within the oil industry that yield higher environmental risk indices, as determined by the Colombian Ministry of Environment and Sustainable Development. These activities predominantly fall under the medium impact classification, except for the land suitability component in the exploration operation, which exhibits a significant level of impact on the alteration of land reforms. It is important to note, however, that there are more activities classified as regular impact than medium or high impact. These activities primarily pertain to exploration and drilling operations, which play a crucial role in understanding soil composition and distribution.

Table 4. Numerical scale and activities with respective environmental impact.

Environmental Impact	Activities That Generate the Greatest Environmental Impact	Value Impact	Classification
Alteration to air quality.	Exploratory well drilling, production well drilling, recovery systems, artificial lift systems, treatment plant, separator application, scrubber application, tanks and pumps, flow station management.	2	Regular
Alteration to air physical properties.	Producer well drilling, scrubber application, flow station management.	3	Medium
Alteration in sound pressure levels.	Land development, drilling of exploratory wells, drilling of production wells.	3	Medium
Alteration in radiation levels.	Well testing, seismic.	3	Medium
Generation of offensive odors.	Drilling fluids, treatment plant.	3	Medium
Alteration of geological conditions	Seismic, land suitability, exploratory well drilling, formation type sample, drilling of the production well.	3	Medium
Alteration of the geoform of the land	Adequacy of land.	4	High
Alteration in the supply and/or availability of groundwater resources	Drilling fluids, drilling of production wells, drilling of exploratory wells.	3	Medium
Alteration of geotechnical conditions	Seismic, land suitability, exploratory well drilling, production well drilling, drilling column, downhole motors.	3	Medium
Groundwater resource quality	Drilling of producing wells, drilling of exploratory wells.	3	Medium
Hydrogeomorphological alteration of the fluid dynamics and/or sedimentological regime	Drilling column, drilling fluids, drilling of production wells, formation type sampling, drilling of exploratory wells, well testing, land suitability, seismic, recovery systems, operation phases, tanks and pumps, flow station management.	2	Regular
Alteration in the quality of surface water resources	Drilling fluids.	3	Medium
Alteration to flora communities	Drilling of production well, land preparation.	3	Medium
Alteration in the supply and availability of surface water resources.	Drilling column, drilling fluids, drilling of production wells, formation type sampling, drilling of exploratory wells, well testing, land suitability, well completion, recovery systems, operation phases, flow station management, scrubber application, artificial lift systems, pipeline implementation, separator application, tanks and pumps.	2	Regular
Alteration in oceanographic conditions	Formation type sampling, exploratory well drilling, well testing, land suitability, seismic, production well drilling, well completion, separator application, scrubber application, tanks and pumps, flow station management, equipment abandonment.	3	Medium
Alteration of the morphological conditions of the coastline	Formation type sampling, exploratory well drilling, well testing, land suitability, seismic, production well drilling, well completion, separator application, scrubber application, tanks and pumps, flow station management, equipment abandonment.	2	Regular
Alteration to terrestrial fauna communities	Adequacy of land, drilling of exploratory wells, drilling of production wells.	3	Medium
Alteration to aquatic ecosystems	Land suitability, drilling fluids.	3	Medium
Alteration to the hydrobiota	Land suitability, exploratory well drilling, production well drilling, drilling fluids, drilling column, well completion, recovery systems.	2	Regular

Table 4. *Cont.*

Environmental Impact	Activities That Generate the Greatest Environmental Impact	Value Impact	Classification
Change in demographic variables	Land suitability, exploratory well drilling, production well drilling, recovery systems, pipeline implementation, operation phases, treatment plant, separator application, scrubber application, tanks and pumps, equipment abandonment.	2	Regular
Alteration in the visual perception of the landscape	Land suitability, well testing, exploratory well drilling, production well drilling, separator application, flow station management, equipment abandonment.	3	Medium
Generation and/or alteration of social conflicts	Seismic, land suitability, well testing, exploratory well drilling, production well drilling, drilling fluids, drill string, recovery systems, artificial lift systems, pipeline implementation, operation phases, treatment plant, separator application, scrubber application, tanks and pumps, equipment abandonment.	3	Medium
Alteration of water and marine sediment quality	Flow station management, tanks, and pumps, scrubber application, separator application, operation phases, well completion, drill string, drilling fluids, production well drilling, exploratory well drilling.	3	Medium
Modification of accessibility, mobility, and local connectivity	Seismic, land suitability, well testing, exploratory well drilling, production well drilling, well completion, recovery systems, artificial lift systems, pipeline implementation, operation phases, treatment plant, tanks and pumps, equipment abandonment.	2	Regular
Modification of physical and social infrastructure, and public and social services	Land suitability, well testing, exploratory well drilling, production well drilling, well completion, recovery systems, artificial lift systems, pipeline implementation, operation phases, treatment plant, tanks and pumps, equipment abandonment, formation type sampling, drilling fluids, drill string, downhole motors, separator application, scrubber application, flow station management.	2	Regular
Involuntary population transfer	Land suitability, well testing, exploratory well drilling, production well drilling, well completion, recovery systems, artificial lift systems, pipeline implementation, operation phases, treatment plant, tanks and pumps, equipment abandonment, formation type sampling, drilling fluids, drill string, downhole motors, separator application, scrubber application, flow station management.	2	Regular
Alteration of land cover	Drilling of production wells.	3	Medium
Microbiological alteration	Drilling of producing wells, drilling fluids, drill string, tanks and pumps, flow station management.	2	Regular
Alteration of archaeological heritage	Abandonment of equipment.	3	Medium
Alteration to soil quality	Drilling fluids.	3	Medium
Change in land use	Land suitability, well testing, exploratory well drilling, formation type sampling, production well drilling, pipeline implementation, and operation phases.	3	Medium
Alteration to terrestrial ecosystems	Adequacy of land, drilling of production wells.	3	Medium
Alteration of vegetation cover	Equipment abandonment, land suitability, well testing, formation type sampling, and drilling of production wells.	3	Medium
Modification of economic activities in the area	Exploratory well drilling, land preparation.	3	Medium

Activities classified as medium impact include well drilling and utilization of drilling fluids, among others. To mitigate potential adverse effects on water sources, subsoil, and microbial life, it is imperative to implement coating and sealing systems to prevent leaks. Additionally, the implementation of control safety systems and adherence to equipment operation protocols are vital in preventing environmental catastrophes resulting from mechanical or electrical failures.

Figure 4 provides a visual representation of the results obtained from the weighting matrix using a traffic light table. This graphical display enhances the visibility and management of the data derived from the matrix, allowing for a clear understanding of the numerical scale of environmental risks associated with the different activities within the oil industry.

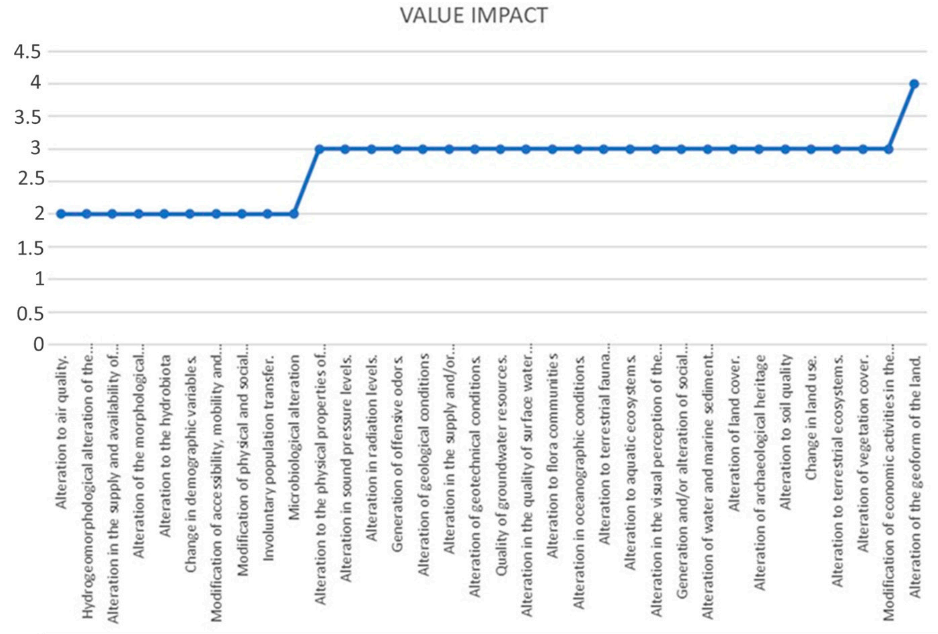

Figure 4. Numerical categorization of environmental impacts.

Decree 1076 of 2015 in Colombia establishes that alterations in the biotic, abiotic, and socioeconomic environment, whether adverse or beneficial, total or partial, corresponding to the development of a work, project, and activity, are defined as environmental impacts. Impacts in the biotic environment correspond to the flora (vegetation cover), fauna, and hydro biota (aquatic ecosystems). The abiotic environment includes impacts on geology, geomorphology, soils, water resources, geotechnics, and the atmosphere. The socioeconomic environment corresponding to impacts of the demographic, spatial, economic, cultural, archaeological, and political organizational dimensions are the main environmental impacts generated by the oil industry in Colombia.

The results suggest that the activity with the greatest impact on air quality is the operation of the treatment plant because the processing of crude oil in these plants to obtain its derivatives contaminates the air to a great extent. In the alteration of surface water quality, the activity with the greatest impact is the drilling of fluids, with a medium level of impact. For the alteration of the form of the land, dismantling is the activity that generates the greatest impact, with a medium result, because the dismantling of the oil and gas infrastructure is a high source of chemical pollutants that are introduced into the environment. In the alteration of radiation levels, results suggested that well testing is the activity generating the greatest impact, with a medium result, because such radiation is used for electrical logs in the wells.

The process of land reclamation carries a significant environmental impact and, therefore, necessitates the implementation of effective environmental measures, protocols, and strategies for remediation and restoration. These measures aim to address the changes in land morphology, chemical composition, and physical–chemical characteristics resulting from the activity. Additionally, it is crucial to consider the impact on the various animal species inhabiting the area, as their behavior, distribution patterns, and population structure can be affected.

Achieving successful land reclamation requires fostering a harmonious relationship with the environment. This entails the adoption of sustainable strategies to mitigate the impact and promote long-term environmental stewardship.

Regardless of the level of impact, all activities associated with land reclamation should be accompanied by preventive measures and comprehensive environmental management plans. These plans enable the identification, description, collection, and analysis of relevant data to assess the overall environmental impact of the production process. By doing so, it becomes possible to manage and address any potential environmental issues and implement suitable solutions.

The study's findings reveal medium and regular environmental impacts as a result of oil well abandonment. Experts have identified instances of equipment abandonment, such as drills, containers, tanks, and camps [19]. To address these concerns, it is recommended to establish dedicated structures for housing the abandoned equipment and implement safety protocols, including the installation of electrical systems and pipelines.

To mitigate the environmental impacts and restore the affected areas, it is crucial to carry out comprehensive measures. This includes dismantling the equipment, conducting a thorough cleaning of the site, removing cemented areas and debris, and implementing appropriate treatment methods for liquid waste [19]. By undertaking these actions, the disturbed environment can be effectively restored and improved.

Visual representations using color-coded indicators are employed to illustrate the activity levels. Generally, darker colors indicate lower activity levels, while lighter colors represent higher activity levels (Figure 5). Various color schemes can be utilized to create heat maps, each offering its advantages and disadvantages. Rainbow color maps are commonly used as they allow for a broader range of color perception compared to grayscale, enabling better visualization of detail within an image [20].

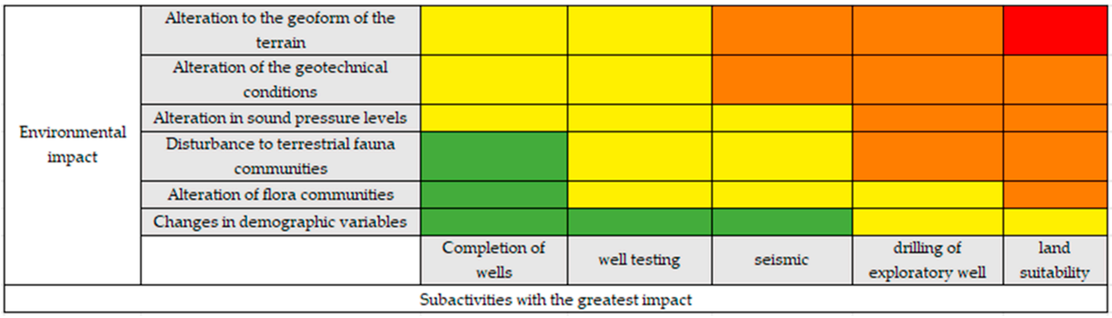

Figure 5. Heat map of environmental impacts vs. activities. (Note: made using Microsoft Excel by authors, 2022).

The heat map provides a visual representation of the environmental alterations based on the color-coded numerical results. It clearly illustrates that these alterations vary depending on the specific activities within the oil industry, highlighting the distinct repercussions of each activity. For instance, there are notable variations in the impacts on fauna and flora between exploration and drilling activities. Within these aspects, exploration and drilling activities appear to have more significant implications for these environmental impacts compared to production and facilities, as well as dismantling. All activities exhibit either low or high levels of impact by expert assessments of the most crucial impacts.

The Triple Bottom Line (TBL) diagram (Figure 6) outlines the project approach and the strategy to be implemented. Its primary objective is to assess and mitigate the level of impact generated, thereby achieving an economically, socially, and environmentally sustainable project.

In the TBL (Triple Bottom Line) methodology, the evaluation of technical–economic, social, and environmental aspects is essential to ensure the proper development of a project and achieve sustainable outcomes. Each factor plays a critical role in shaping the project approach and strategy. The following description provides insights into the following three factors.

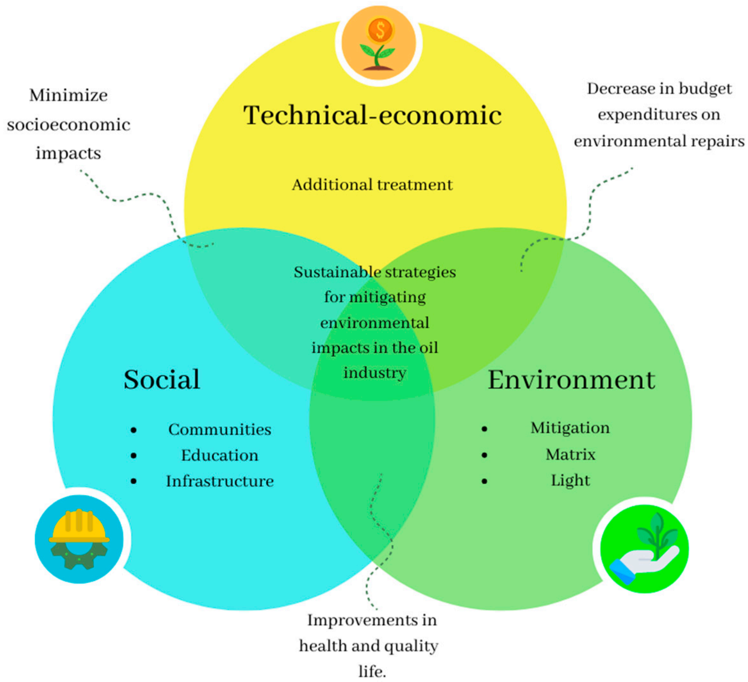

Figure 6. A triple bottom line diagram showing how technical-economic, social, and environmental aspects are related. (Note: made using Canva by authors, 2022).

Technical–economic factors: The oil industry's activities have direct environmental impacts that can also affect the economic viability of the sector. This study examines the environmental impacts associated with each process, prioritizing them for mitigation. By doing so, it aims to prevent the economic burden of environmental remediation. Additionally, it is important to assess the effects of oil industry activities on local communities and the overall economy. This evaluation helps identify potential issues such as corruption or job reductions, enabling the proposal of solutions to minimize negative impacts on nearby communities.

Social factors: Consideration should be given to the effects on communities located in oil-producing areas. Exploration and land adaptation activities often lead to infrastructure and educational challenges for residents living near extraction sites or treatment facilities. In this study, land adaptation, which significantly alters the land's morphology, directly affects the social fabric of communities. Consequently, it becomes a priority to plan and execute mitigation strategies effectively, aiming to minimize both environmental and social impacts.

Environmental factors: The environmental impacts have been identified and evaluated through the matrix. This assessment allows for the establishment of a prioritization framework using the traffic light system. The focus is on implementing strategies that effectively reduce the most significant impacts to a low level. The goal is to address environmental concerns without compromising the project's economic viability, social well-being, and overall environmental sustainability.

By incorporating these three factors into the TBL methodology, a comprehensive and sustainable approach can be developed for oil industry projects. This approach ensures the consideration of technical–economic aspects, social implications, and environmental preservation, leading to responsible and balanced project outcomes.

4. Discussion

Based on the parameters provided by experts, the study examines the potential effects of oil exploitation not only on the environment but also on the local population. It acknowledges that societal setbacks occur when exploitation is necessary but lacks human-centric considerations, which directly impacts the well-being of communities relying on this resource. The study investigates whether adverse effects on growth, fiscal resources, and public investment align with the theories of the "resource curse" and fiscal "laziness". It also explores the hypothesis that the quality of institutions and regional/local political dynamics determine the positive or negative impact of these exploitations and royalties on economic growth and fiscal performance [21].

Oil has been a focal point of social and political conflicts in Colombia's recent history. Throughout the twentieth century, the different stages of oil activities in occupied territories have led to migration, the establishment of new towns, displacement, and the marginalization of local cultures. Unfortunately, regions with oil discoveries or existing fields often coincide with areas experiencing violence [22]. Furthermore, there are health risks for the local population due to harmful components of hydrocarbons, which pose dangers to individuals who meet these substances.

These aspects underscore the complex and multifaceted nature of oil exploitation, emphasizing the need for thorough analysis and consideration of its social and environmental implications. By understanding the challenges and potential risks associated with oil activities, policymakers and stakeholders can strive for more sustainable and equitable approaches that prioritize the well-being of both the environment and affected communities.

Polycyclic aromatic hydrocarbons (PAHs) are a group of harmful components commonly associated with hydrocarbons. An incident of the extensive oil spill in Brazil in 2019 resulted in acute contamination of PAHs in the edible tissues of 34 fish and shellfish species. During that time, only 3% of marine products sold in nearby markets showed evidence of this contamination, indicating a minor risk to the human population. However, due to the lack of knowledge surrounding this piece of information, concerns arose, leading to the withdrawal of these products from the market as they were no longer deemed suitable for consumption [23]. PAHs pose a threat to food security when present in fish species intended for human consumption, as they can cause both short-term and long-term health issues. In the long term, PAHs can negatively impact various bodily systems, including the respiratory, digestive, reproductive, cardiovascular, renal, and nervous systems. Symptoms of exposure may include headache, hypertension, depression, dizziness, sore throat, infertility, blurred vision, and nasal discomfort. Prolonged exposure to PAHs can also contribute to miscarriages and kidney damage.

Volatile organic compounds (VOCs), another byproduct of the oil and gas industry, are derivatives emitted through the reaction of crude oil with temperature and other meteorological factors. VOCs can be classified into non-carcinogenic and carcinogenic compounds. Exposure to VOCs can result in weakened immune systems, increased metabolic rates, and disturbances in the nervous, respiratory, and endocrine systems. This occurs due to the accumulation of these compounds in the lipid portions of organs such as the liver, kidneys, or gonads [23–26].

The sustainability of the organizations within the Colombian oil sector is assessed based on the main impacts generated by the changes implemented. Processes that incorporate technological components into the administrative structure demonstrate higher flexibility and improved management, leading to increased dynamism and shorter response times. These impacts primarily manifest in the restructuring of functions, positions, and work processes [27].

Since the 1920s, oil, commonly referred to as Black Gold, has emerged as the primary energy source for global industries. In the Latin American context, Caribbean Petroleum, an oil company, initiated the exploitation of Lake Maracaibo fields in Venezuela. Subsequently, various multinational companies entered Latin American countries, resulting in increased oil production and profits. This situation necessitated governments to develop policies that would protect the resource while ensuring adequate economic and social development. However, the formulation of national legislation about environmental regulations, economic norms, exploitation rates, and other aspects was heavily influenced by the oil companies. Some countries chose to nationalize their oil industry, while others opted for privatization [28].

During the 1920s, the United States of America expanded its search for oil in the region, leading to political consequences. These factors contributed to the initial generosity of Latin American governments towards multinational oil companies when signing the first oil concessions. The oil policy in the region is inherently dynamic, undergoing various structural and ordinary changes. These changes often revolve around objectives such as increased production, enhanced development levels, expansion of the hydrocarbon frontier, incorporation of new crude reserves, energy self-sufficiency, surpluses in direct foreign investment, and a significant increase in government tax revenue due to the rise in oil income [29].

The TBL diagram provides a comprehensive visual representation of the environmental, economic, and social factors incorporated into the weighting matrix. It offers a broader perspective on the conditions and impacts of the oil industry, allowing for a better understanding of the sustainable outcomes desired in the industry. The diagram takes into account expert opinions on the quality and riskiness of hydrocarbon exploitation practices, considering the specific aspects outlined in the project. By doing so, it helps identify economic challenges related to society and the environment. The diagram highlights the interrelationship among these three components, crucial for assessing the feasibility of a sustainability project. The qualitative results obtained from the study of oil industry operations in Colombia, where the project was implemented, contribute to a clearer understanding of the project's sustainability outcomes and their potential for environmental improvement in oil exploitation practices.

5. Conclusions

Most environmental disasters in the oil sector result from failures in regulatory and safety measures during production processes [30]. An illustrative example is the impact of oil spills in the municipality of Tumaco, Colombia, where the loss of ecosystem services has been observed due to the decline in support and regulatory functions [31]. This case exemplifies the significant impacts on local ecosystems caused by "medium" level risks, such as alterations to geological conditions, flora communities, and vegetation cover.

Water contamination also poses a risk associated with the oil industry [31]. In this study, specific impacts were assessed, including changes in the quality of surface water resources, groundwater resources, water, and marine sediment quality, as well as disruptions in the supply and availability of surface water resources. These categories generally received a medium rating, except for the last one, which was classified as regular. These impacts have prompted a demand for environmental improvement, compelling companies in the oil industry to adopt sustainable strategies and efficient technologies to reduce and treat contaminants in the environment. This shift also involves embracing new socioeconomic values and transforming challenges into opportunities to enhance market conditions [27].

The extraction and exposure to oil have been associated with potential health impacts, such as cancer, liver damage, immunodeficiency, and neurological symptoms. Adverse effects on soil, air, and water quality have also been identified, as evidenced by the results of the traffic light matrix, with alterations to air quality and physical properties of the air classified as regular and medium, respectively. A more comprehensive characterization of exposures related to oil drilling is necessary to fully understand the range of health risks for communities residing near drilling sites [32].

The environmental impact analysis methodology, employing high, medium, regular, and low categorizations, serves as a valuable tool to assess and compare the effects of activities within a specific scope, sector, or the entire industry. By identifying and classifying environmental impacts in different oil sector activities, effective management strategies can be developed, prioritizing solutions to the most critical environmental issues followed by those with lesser impacts. This approach facilitates informed decision making and prompt action.

The domestic energy context, characterized by economic dependence on extractive activities and the goal of achieving energy self-sufficiency, presents a contrast with climate objectives and commitments. While there is an intention to adhere to international emission reduction targets, it often overlooks solutions concerning the production and sale of fossil fuels, posing challenges for systemic transformation [33–36].

Author Contributions: Conceptualization, A.T.O.-R., P.A.P.R., S.J.R.L. and R.S.-S.; Data curation, C.A.G.-M. and P.A.P.R.; Formal analysis, L.E.G.-M. and S.C.-G.; Funding acquisition, C.A.G.-M., A.T.O.-R., S.J.R.L., L.E.G.-M., R.S.-S. and S.C.-G.; Investigation, C.A.G.-M., S.J.R.L. and L.E.G.-M.; Methodology, C.A.G.-M., L.E.G.-M. and R.S.-S.; Project administration, A.T.O.-R., P.A.P.R., S.J.R.L., L.E.G.-M. and R.S.-S.; Resources, A.T.O.-R. and S.C.-G.; Software, S.J.R.L., L.E.G.-M. and S.C.-G.; Supervision, S.J.R.L. and R.S.-S.; Visualization, A.T.O.-R.; Writing—original draft, P.A.P.R. and S.C.-G.; Writing—review & editing, C.A.G.-M., L.E.G.-M. and R.S.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request.

Acknowledgments: This work was supported for publication by PROPESP/UFPA (PAPQ).

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

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