

Environmental Life Cycle Assessment of Gasoline Production Process in Khuzestan Using an Ecosystem Approach in Environmental Planning

Eghbal. Sekhavati¹, Mehdi. Esmaeili Bidhendi^{2*}, Reza. Jalilzadeh-Yengejeh³, Farhad. Baqi-Asl⁴

¹ Ph.D. Candidate, Department of Environment, Alborz Campus, University of Tehran, Tehran, Iran.

² Faculty of Environment, University of Tehran, Tehran, Iran

³ Department of Environmental Engineering, Ahv.C, Islamic Azad University, Ahvaz, Iran

⁴ Karoon Petroleum Development & Production Company, South Oilfield Company of Iran, Ahvaz, Iran.

* Corresponding author email address: esmaeilb@ut.ac.ir

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ABSTRACT

In the present study, a comprehensive investigation and analysis of the environmental impacts of the gasoline production process in Khuzestan province were conducted using the Life Cycle Assessment (LCA) method and an ecosystem approach. The system boundary included all stages from exploration and drilling to refining and transportation, and the analyses were performed utilizing SimaPro software and the Ecoinvent database. In the Life Cycle Inventory (LCI) phase, data concerning resource consumption and pollutant emissions for each stage were collected. Subsequently, in the Life Cycle Impact Assessment (LCIA) phase, indicators such as Global Warming Potential (GWP), human toxicity, acidification, ozone layer depletion, water pollution, and photochemical air pollution were examined. The results indicated that the refining and drilling stages account for the largest share in creating negative environmental impacts. The GWP indicator, with a value of 3.62kg CO₂equivalent per liter of gasoline, assigned the highest weight to itself. Furthermore, the weighting and normalization phase was carried out using the EPM method, which determined the priority of the indicators with an emphasis on ecosystem importance. Sensitivity analysis also revealed that substituting the refinery's fossil-fuel electricity with solar energy, utilizing recycled drilling mud, and monitoring methane leakage can significantly reduce the total environmental burden.

Keywords: *Life Cycle Assessment (LCA), Gasoline, Ecosystem approach, Environment, Khuzestan*

1. Introduction

The escalating global demand for energy, predominantly driven by rapid industrialization and population growth, has positioned fossil fuels at the center of the global economic infrastructure. Gasoline, as a primary derivative of crude oil, remains a fundamental energy source for the transportation sector and various industrial applications worldwide. However, the pervasive extraction, processing, and combustion of conventional gasoline have precipitated severe environmental crises, most notably anthropogenic climate change, widespread atmospheric pollution, and long-term ecosystem degradation. The extensive reliance on internal combustion engines has catalyzed a transition toward alternative paradigms, prompting rigorous environmental evaluations of electric vehicles and other clean fuel technologies as potential mitigators of these adverse ecological impacts (Cui et al., 2023; Idris et al., 2025; Vasquez et al., 2025). Despite the accelerated development and deployment of alternative transportation modes, including hydrogen-based vehicular systems and electric mobility solutions, the current infrastructural inertia dictates that conventional gasoline will persist as a dominant fuel for the foreseeable future, necessitating an urgent reevaluation of its production processes to minimize its environmental footprint (Burchart et al., 2022).

The life cycle of gasoline—encompassing early-stage seismic exploration, complex well drilling, crude oil exploitation, expansive transportation networks, and advanced refining—constitutes a highly intricate industrial network characterized by massive material and energy flows. Among these operational stages, primary hydrocarbon production and the specific mechanics of deep-well drilling have been continuously identified as highly energy-intensive operations that release substantial quantities of greenhouse gases, such as CO₂ and CH₄, alongside toxic volatile organic compounds into the biosphere (Ghasemi et al., 2025; Rajaoalison et al., 2022). Analogous to other heavy extractive industries such as underground coal mining, the broader fossil fuel sector faces mounting scientific and societal pressure to adopt greener operational frameworks and optimize both small-scale and large-scale extraction modalities (Tao et al., 2024).

To comprehensively quantify and subsequently mitigate these widespread environmental burdens, Life Cycle Assessment (LCA) has emerged as the premier methodological framework in environmental science and

engineering. LCA provides a systematic, cradle-to-grave or cradle-to-cradle analytical structure that enables the holistic evaluation of resource consumption, energy utilization, and emission profiles across all stages of a product's life cycle (Gaffey et al., 2024; Tamoor et al., 2022). The versatility, precision, and robustness of the LCA methodology have been extensively demonstrated across a vast array of industrial and environmental sectors. For instance, LCA has been pivotal in evaluating the environmental impacts of heavy industrial manufacturing processes, such as Portland cement production (Tun et al., 2020), as well as the intricate synthesis of complex chemical intermediates like propylene oxide (Ghannadzadeh & Tarighaleslami, 2022). Furthermore, LCA frameworks are increasingly applied to civil and infrastructural developments, including slope treatment technologies, to ensure that large-scale engineering practices remain sustainable (Yao et al., 2024).

The scope of LCA extends significantly into agricultural and biological systems, underscoring its universal applicability in tracking environmental degradation. Researchers have successfully utilized LCA to conduct eco-energy evaluations of diverse agricultural commodities, such as cantaloupe production, revealing the critical nexus between conventional farming practices and environmental depletion (Azizpanah et al., 2023). Similarly, the LCA approach has been thoroughly employed to assess the impacts of silviculture and timber harvesting, highlighting the profound ecological footprints associated with active forest management and land use changes (Hájek et al., 2024). In the rapidly expanding realm of biotechnology and bioconversion, ecological perspectives integrated with advanced LCA frameworks provide profound quantitative insights into the true sustainability of biomass conversion processes and microalgae-based biological optimization methods (Kazemi et al., 2023; Longati et al., 2022).

Waste management and circular economy initiatives also heavily rely on life cycle modeling to determine optimal, scientifically sound environmental strategies. The life cycle evaluation of municipal waste management methods (Shahivand, 2021), the critical recycling of agricultural waste (Sumiyati et al., 2024), and the localized treatment systems for animal byproducts such as pig manure (Ferreira et al., 2024) all utilize LCA to identify specific pathways that minimize eutrophication, acidification, and global warming potentials. These extensive studies collectively demonstrate that effective waste management and the systematic recovery of materials—principles that are equally applicable to hazardous industrial byproducts like drilling mud in the

oil sector—are paramount for maintaining long-term ecosystem health.

As the global energy sector actively seeks to decarbonize, LCA plays an indispensable role in assessing the realistic viability of renewable energy installations and alternative fuel systems. The technical parameters and environmental capabilities of geothermal energy systems have been rigorously evaluated using LCA, confirming their substantial potential to displace fossil-based energy generation while minimizing peripheral toxic emissions (Milousi et al., 2022). Additionally, advanced energy storage and thermochemical conversion technologies, such as Power-to-Gas (PtG) configurations for renewable hydrogen and synthetic methane production, rely strictly on LCA methodologies to validate their systemic environmental benefits before large-scale commercialization (Litheko et al., 2023).

The specific geographical locus of the present study is Khuzestan Province, Iran, a region of paramount importance to the global and national petrochemical landscape. Khuzestan hosts a vast, deeply integrated network of oil extraction and refining infrastructures, which have historically imposed severe ecological stresses on local air quality, scarce water resources, and overall soil integrity. The visible environmental degradation in this region has recently prompted urgent scientific inquiries into local alternative energy potentials, such as the localized production of liquid biofuels derived from regional agricultural residues and animal fats (Ardebili & Khademalrasoul, 2018). To accurately assess the complex, multi-layered interplay between concentrated industrial emissions and regional ecology, it is essential to integrate an ecosystem services approach directly into the LCA framework. This specialized integrated approach allows researchers to determine the local ecosystem's precise capacity to absorb severe environmental burdens, a methodology that has been successfully applied to other carbon-intensive, large-scale systems such as carbon capture and storage technologies (Morales Mora et al., 2020).

While numerous contemporary studies have independently investigated the isolated life cycle impacts of specific agricultural systems, alternative fuels, and broad municipal waste management strategies, there remains a critical and noticeable lacuna in the comprehensive, multi-stage life cycle assessment of the entire gasoline production chain within the highly industrialized context of Khuzestan Province. The refining stage alone frequently dictates the majority of the environmental burden due to its immense

electrical and thermal demands, while drilling operations introduce highly toxic variables through diesel combustion and chemical leakages. Furthermore, there is an exigent need to transition beyond traditional, static environmental assessments by incorporating dynamic sensitivity analyses that evaluate pragmatic, localized optimization scenarios designed for immediate industrial application. Specific operational interventions, such as the direct integration of renewable electricity into energy-intensive refinery operations, the systematic recycling of toxic drilling muds, and the phased displacement of diesel in operational generators, must be quantitatively analyzed to determine their actual efficacy in reducing the Global Warming Potential (GWP) and mitigating severe human toxicity.

Therefore, the aim of this study is to perform a comprehensive life cycle assessment of the gasoline production process in Khuzestan Province to identify critical environmental bottlenecks and to evaluate the effectiveness of targeted optimization scenarios in reducing global warming potential and total environmental pollution.

2. Methods and Materials

The present study was conducted with the aim of a comprehensive environmental assessment of the gasoline production process in Khuzestan province, utilizing the Life Cycle Assessment (LCA) approach and integrating it with an ecosystem perspective. This research is of an applied and analytical-descriptive type and, using a quantitative method, systematically analyzes the environmental impacts across all stages of gasoline production. Since the subject of the research necessitates the investigation of the entire production chain from the exploration stage to refining, the research methodology design in the framework of LCA was carried out in accordance with ISO 14040 and ISO 14044 standards, and the system boundary was defined based on the “cradle-to-gate” concept.

In this research, the statistical population encompasses all activities and processes involved in the gasoline production chain in Khuzestan province, from the crude oil exploration stage to the refining process. These processes are categorized into five main phases, which are: 1) Geophysics, including the Lali-Karun 3D seismic operations; 2) Drilling, including the “Sahar” offshore drilling rig and the onshore drilling rig of Persia Oil and Gas Company; 3) Exploitation, including Ahvaz Exploitation Unit No. 2; 4) Crude oil transportation through the Shahid Chamran Oil Transportation Center in Ahvaz; and finally, 5) Refining at

the Abadan Oil Refinery. These five sectors are considered as the main functional units under study, and each was entered separately into the life cycle modeling process.

The statistical sample of the research includes specific and representative data from each of these phases. In the geophysics phase, data related to energy consumption, seismic equipment, pollutant emissions, and ecological impacts were extracted from the Lali-Karun 3D seismic project. In the drilling phase, field data concerning fuel consumption, lubricants, drilling waste, and the emission rates of gases and air pollutants were collected from two types of onshore and offshore rigs. In the exploitation stage, operational and environmental information related to Ahvaz Unit No. 2 was utilized. For the transportation stage, data on the amount of energy consumed at the pumping station, leakage rates, emissions, and impacts on soil and surface water at the Shahid Chamran Transportation Center were gathered. In the final phase, data associated with energy consumption, chemical reactions, pollutant generation, wastewater management, and greenhouse gases at the Abadan Oil Refinery were analyzed as the final data of the refining process.

Data collection was conducted using two methods: 1) Utilizing field data and technical reports from operating and contracting companies in the aforementioned projects; 2) Utilizing secondary data, including standard environmental databases such as Ecoinvent, SimaPro software, and similar studies in the field of gasoline production in Iran and the Middle East. The data were organized in the form of a Life Cycle Inventory (LCI), and in the Life Cycle Impact Assessment (LCIA) phase, environmental impact identification methods such as ReCiPe and CML were employed. In the final step, using specialized LCA software such as SimaPro or GaBi, process modeling was performed, and quantitative outputs were extracted in the form of key indicators such as Global Warming Potential (GWP), acidification, human toxicity, ozone layer depletion, and water and energy resource consumption. Subsequently, relying on the ecosystem approach, the results obtained from the modeling were interpreted and analyzed in the form of regional consequence analysis, ecological resilience, and ecosystem services. Ultimately, the analyses were presented with the aim of identifying critical points, proposing optimization pathways, and designing environmental policies for the sustainable management of the gasoline production process in Khuzestan.

In this stage, the goal of the study, system boundaries, functional unit, theoretical approach, and expected level of

precision were determined. Information for this section was collected by reviewing environmental policies, environmental organization reports, technical documents of oil companies, and consulting with energy experts in Khuzestan. Based on the ISO 14040 standard, the functional unit was considered equivalent to 1 liter of produced gasoline so that all stages of the process could be normalized and made comparable based on this quantity.

3. Findings and Results

In implementing the Life Cycle Assessment (LCA) for the gasoline production process in Khuzestan province, the precise determination of key components such as the study's goal, functional unit, system boundary, and analysis approach is of high importance. The primary objective of this research is the comprehensive and quantitative assessment of the environmental impacts of various stages of gasoline production; an objective that holds special significance given the strategic position of Khuzestan province as the country's oil industry hub, as well as the ecological sensitivities and high vulnerability of the ecosystems and human communities in this region. In this regard, the functional unit was selected as the production of 1 liter of gasoline. The standardization of this unit in international studies and its compatibility with specialized life cycle modeling software, such as SimaPro and GaBi, provides the possibility of accurate comparison and in-depth analysis of environmental impacts. The system boundary of the research is defined as "cradle-to-gate" and includes all effective processes from the crude oil exploration stage (Lali-Karun 3D seismic) to final refining (Abadan Oil Refinery), while the stages after the gasoline leaves the refinery and its final consumption are excluded from the scope of the study. This comprehensive boundary allows for the accurate identification of sources of environmental impacts and focuses on the production processes, preventing the dispersion of the study's scope. On the other hand, the adopted ecosystem approach moves beyond a mere focus on greenhouse gas emissions and, in addition to indicators such as global warming, incorporates human toxicity, soil and water acidification, biodiversity loss, and natural resource pollution into the analyses. Considering the ecological sensitivities of Khuzestan province, particularly the important Hoor al-Azim and Shadegan wetlands and the health challenges of oil-rich communities, this multidimensional approach contributes to a comprehensive and realistic understanding of the environmental impacts of

the gasoline production process and provides a suitable platform for adopting sustainable environmental policies. Overall, by defining a precise and scientific framework, this study has taken a significant step toward understanding

environmental impacts and providing optimization strategies for the gasoline production process in a sensitive region, which can play a key role in environmental decision-making and sustainable development planning.

Table 1

Determination of goal, functional unit, and system boundary in the life cycle assessment of gasoline production in Khuzestan.

Component	Description
Goal	Environmental assessment of the gasoline production process in Khuzestan
Functional Unit	1 liter of produced gasoline
System Boundary	From seismic surveying to refining at the Abadan Refinery
Approach	Ecosystem-based, focusing on impacts on humans and the environment

In the second step of the life cycle assessment, the system boundary was divided from a technical and statistical perspective into five macro stages: geophysics, drilling, exploitation, transportation, and refining. The precise identification of these stages, acting as the backbone of LCA modeling, was accomplished through field analyses, review of actual data from active projects in Khuzestan province, and collaboration with specialized oil institutions. Information for this stage was primarily extracted from three key sources: field performance reports of oil projects, internal databases of the Ministry of Petroleum, and direct site visits to related facilities such as the Abadan Refinery, Shahid Chamran Oil Transportation Center, and Ahvaz exploitation units. In the geophysics stage, which initiates the production chain, data were obtained from the “Lali-Karun” 3D seismic project. In this stage, the fuel consumption of high-power generators to supply the data recording devices was recorded at an average of 18,900 liters of diesel, which is considered the primary source of carbon dioxide and particulate matter emissions into the air.

In the next step, the drilling phase was carried out using offshore and onshore rigs (Sahar and Persia). The obtained data indicate that an average of 21,500 liters of diesel is consumed for each well, which illustrates the high intensity of energy consumption and, consequently, the high potential for generating gaseous pollutants in this sector. This significant amount has a notable environmental impact,

particularly in regions that do not utilize renewable energies. In the exploitation phase, data were extracted from Ahvaz Exploitation Unit No. 2. The energy consumption in this phase was recorded equivalent to 9500 MJ per day for one production unit. This energy is mainly used for phase separation processes, oil stabilization, and pumping to transmission lines. In the crude oil transportation phase, data were extracted from the Shahid Chamran Oil Transportation Center. Investigations showed that 0.34 MJ of energy is consumed to transport each liter of crude oil. This figure is considered an energy efficiency indicator in the transmission network and directly affects the indirect emission rate of greenhouse gases. In the refining phase at the Abadan Refinery, 1.42 kWh of electricity is consumed to produce each liter of gasoline. This figure, especially considering the Iranian power grid’s reliance on fossil-fuel power plants, demonstrates the refinery’s high share in CO₂ equivalent emissions. Furthermore, this stage accounts for the greatest variety of environmental impacts; including water consumption, industrial waste generation, and the emission of nitrogen oxide and sulfur dioxide gases. Therefore, it can be concluded that the drilling and refining stages are at the top in terms of energy consumption intensity and pollution potential. The data in this table were entered as direct inputs into the LCI (Life Cycle Inventory analysis) modeling phase and play an important role in the precise determination of environmental flows.

Table 2

Technical and statistical information related to the five stages of the gasoline production process in Khuzestan province.

Stage	Statistical Sample	Activity	Key Data
Geophysics	Lali-Karun seismic	Generator fuel	18,900 liters of diesel
Drilling	Sahar and Persia rigs	Well drilling	21,500 liters of diesel/well
Exploitation	Ahvaz Unit 2	Oil production	9500 MJ/day energy
Transportation	Shahid Chamran Center	Oil pumping	0.34 MJ/l
Refining	Abadan Refinery	Gasoline production	1.42 kWh/electricity

In this stage of the life cycle assessment, namely the Life Cycle Inventory (LCI) analysis phase, environmental data related to gasoline production were extracted from field sources, official reports, and credible databases, and were modeled using SimaPro software and the Ecoinvent database. The objective of this phase was the quantification of inputs (such as energy, water, and raw materials) and outputs (including pollutants and waste) for the defined functional unit, which is 1 liter of produced gasoline. Primary data were collected from drilling rigs (Sahar and Persia), the Ahvaz exploitation unit, the Shahid Chamran oil transportation center, and the Abadan oil refinery, and after conversion into the software's standard format, they were subjected to normalization. The results indicated that the amount of energy consumed to produce each liter of gasoline is 5.85 MJ. This energy is mostly consumed in the drilling (due to the diesel fuel of generators) and refining (electricity consumed by complex equipment such as distillation columns and reforming units) stages. Considering that the majority of this energy is supplied from fossil sources, it carries a high environmental burden.

In the greenhouse gas emissions sector, carbon dioxide (CO₂) accounts for the largest share with a value of 3.62 kg CO₂ eq per liter of gasoline. The main source of this gas is diesel combustion and the use of electricity generated

in thermal power plants. Methane (CH₄) also ranks second with a value of 0.021 kg CO₂ eq, which, although lower in quantity, has a significant impact due to its higher global warming potential. This gas is primarily released from the leakage of associated petroleum gases and vapor processes during exploitation and transportation. In addition to greenhouse gases, the emission of other pollutant gases such as NO_x (0.0061 kg) and SO₂ equivalent to 0.013 kg SO₂ eq was also recorded. These gases play a direct role in phenomena such as acid rain and soil acidification, and their source is the incomplete combustion of fuel in heavy engines and industrial flares. Regarding resource consumption, the amount of water consumed in the production process of each liter of gasoline was reported as 4.2 liters, most of which is consumed in the refinery's cooling systems and a portion in drilling. Given the critical condition of water resources in Khuzestan, this figure is considered a serious environmental challenge. The amount of solid waste generated is estimated at 0.15 kg per liter of gasoline. These wastes include drilling mud, used filters in refining units, sedimented materials, and industrial sludges, which, if not properly managed, can lead to the pollution of soil and water resources.

Table 3

Environmental flows related to the production of 1 liter of gasoline in Khuzestan province based on LCI modeling.

Environmental Flow	Value for 1 liter of gasoline	Unit
Total energy consumption	5.85	MJ
CO ₂ emission	3.62	kg CO ₂ eq
CH ₄ emission	0.021	kg CH ₄ eq
NO _x emission	0.0061	kg NO _x
SO ₂ emission	0.013	kg SO ₂ eq
Water consumption	4.2	Liters
Solid waste	0.15	kg

In the "Life Cycle Impact Assessment" (LCIA) phase of the LCA model, the quantitative data extracted from the inventory analysis (LCI) phase were examined with the aim of converting environmental inputs and outputs into analyzable and decision-making indicators. This phase was conducted using SimaPro software and the Ecoinvent database, focusing on the analysis of impacts associated with the production of each liter of gasoline in Khuzestan province. The ultimate goal was to quantify the intensity of environmental impacts across different stages of the gasoline

production life cycle and to identify critical points from an ecological perspective.

Modeling results demonstrated that the Global Warming Potential (GWP) indicator, with a value of 3.62 kg CO₂ eq per liter of gasoline, accounts for the highest share of the total impacts. This impact primarily originates from the drilling and refining stages, where the combustion of fossil fuels in drilling equipment and the refinery's electricity consumption were identified as the main sources of carbon dioxide and methane emissions. The high

significance of GWP in this analysis emphasizes the necessity of employing mitigation strategies in the domain of energy and fuel consumption.

Ranking second is the Human Toxicity Potential indicator with a value of 1.83 kg 1,4-DCB eq. This indicator is formed by a combination of Volatile Organic Compound (VOC) emissions during the drilling stage and chemical leaks resulting from refining, indicating substantial risks to human health upon exposure to these compounds. Control policies and the enhancement of industrial safety at this stage play a crucial role in mitigating this impact. The Acidification Potential, with a value of 0.019 kg SO₂ eq, also demonstrates that the refining process has a significant share in the emission of sulfurous gases. Through acid rain, these gases exert a negative impact on soil and surface waters, causing the acidification of ecosystems.

Table 4

Environmental impact categories resulting from the production of 1liter of gasoline based on the LCIA model.

Environmental Indicator	Value for 1liter of gasoline	Unit	Main Source
Global Warming (GWP)	3.62	kg CO ₂ eq	Drilling, Refining
Acidification	0.019	kg SO ₂ eq	Refining
Human Toxicity	1.83	kg 1,4-DCB eq	Drilling, VOC
Ozone Depletion	1.60E-06	kg CFC-11 eq	Generator
Water Pollution (Eutrophication)	0.0081	kg P eq	Drilling
Photochemical Air Pollution	0.006	kg NMVOC eq	Refining

In the final step of the Life Cycle Impact Assessment (LCIA) phase, the normalization and weighting process of environmental indicators was performed utilizing the Environmental Priority Model (EPM). The primary objective of this stage is the standardization and scaling of quantitative LCIA results to enable the comparability of indicators and determine their relative importance within the framework of the ecosystem approach. Since the raw values of the indicators are not comparable due to differences in units, dimensions, and scope of impact, data normalization serves as an essential step for accurate and scientific prioritization. Subsequently, by assigning normalized weights to each indicator, the possibility of a comprehensive assessment and decision-making based on multi-indicator analysis is provided. Based on the results obtained from the EPM analysis, the Global Warming Potential (GWP) indicator, with a normalized weight of 0.3, achieved the highest level of significance among other indicators and was classified in the “very high” category. This finding indicates the key role of greenhouse gas emissions in the environmental impact of the gasoline production process,

Furthermore, Eutrophication Potential, with a value of 0.0081 kg P eq, is predominantly observed in the drilling stage. The entry of nutrients such as nitrogen and phosphorus into water resources leads to excessive algae growth and, consequently, the disruption of aquatic ecosystems. Additionally, the Photochemical Ozone Creation Potential indicator, with a value of 0.006 kg NMVOC eq, mainly stems from the refining stage; the reaction of these compounds with sunlight leads to the generation of ground-level ozone, which poses risks to human health and air quality. Although the Ozone Depletion Potential value is reported to be relatively low, equal to 1.60×10^{-6} kg CFC-11 eq, its source has been the generators used in the operational stages, and considering the long-term and cumulative consequences of these types of compounds, even this small amount is of significance.

which is directly linked to the climate change crisis and global warming. The Human Toxicity indicator also ranked second with a weight of 0.25 and was evaluated from an ecosystem perspective as a component of “high importance”. This indicator represents the direct and indirect impacts of chemicals and toxic pollutants emitted during the drilling and refining stages on human health and local communities. In subsequent ranks, the Acidification and Eutrophication indicators, with weights of 0.2 and 0.15 respectively, were classified in the moderate importance group. These values demonstrate the impact of the gasoline production process on the degradation of soil quality, acidification of aquatic ecosystems, and biological anomalies in the region’s water resources. At the end of the spectrum, the Resource Use indicator holds the lowest relative importance with a weight of 0.1. Although this indicator is numerically lower, from a systemic and long-term perspective, attention to the sustainable exploitation of natural resources is considered essential for maintaining the ecological dynamics of the Khuzestan region.

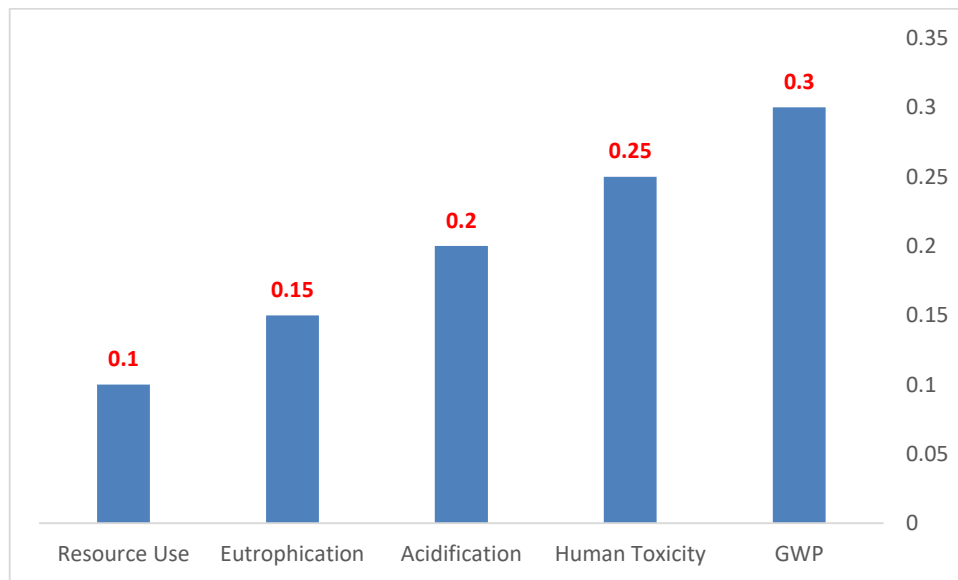
Table 5

Results of normalization and weighting of environmental indicators for the gasoline production process using an ecosystem approach via the EPM method.

Impact Indicator	Normalized Weight	Relative Importance (Ecosystem Analysis)
GWP	0.3	Very High
Human Toxicity	0.25	High
Acidification	0.2	Moderate
Eutrophication	0.15	Moderate
Resource Use	0.1	Low

Figure 1

Comparison of the normalization and weighting results of environmental indicators for the gasoline production process using an ecosystem approach via the EPM method.



In this stage, with the aim of examining the sustainability and effectiveness of the proposed solutions for reducing environmental impacts in the gasoline production process, a sensitivity analysis was conducted based on three environmental optimization scenarios. This analysis was performed to measure the extent of reduction in key indicators such as Global Warming Potential (GWP) and total pollution reduction, in order to evaluate the effectiveness of each scenario in improving the environmental status of the Khuzestan region. The results of the sensitivity analysis indicated that the use of “renewable electricity for the refinery” had the most significant impact on reducing environmental effects, leading to a 21%reduction in the GWP indicator and a 17%reduction in total pollution. This highlights the critical role of replacing fossil energy sources with clean energies in refining

processes, which can significantly contribute to reducing greenhouse gas emissions and other pollutants. The second scenario, “drilling mud recycling,” resulted in a 13%reduction in GWP and an 8%reduction in total pollution, demonstrating the importance of waste management and material recycling in the production cycle. This action not only reduces the consumption of new resources but also prevents pollution arising from improper waste disposal and helps maintain ecosystem health. “Eliminating diesel from generators” had a lesser impact, causing only a 3%reduction in GWP and a 2%reduction in total pollution. Although the effect of this scenario is less than the other two options, it is still recognized as a complementary and cost-effective solution for reducing pollutants resulting from heavy fuel combustion in energy production units.

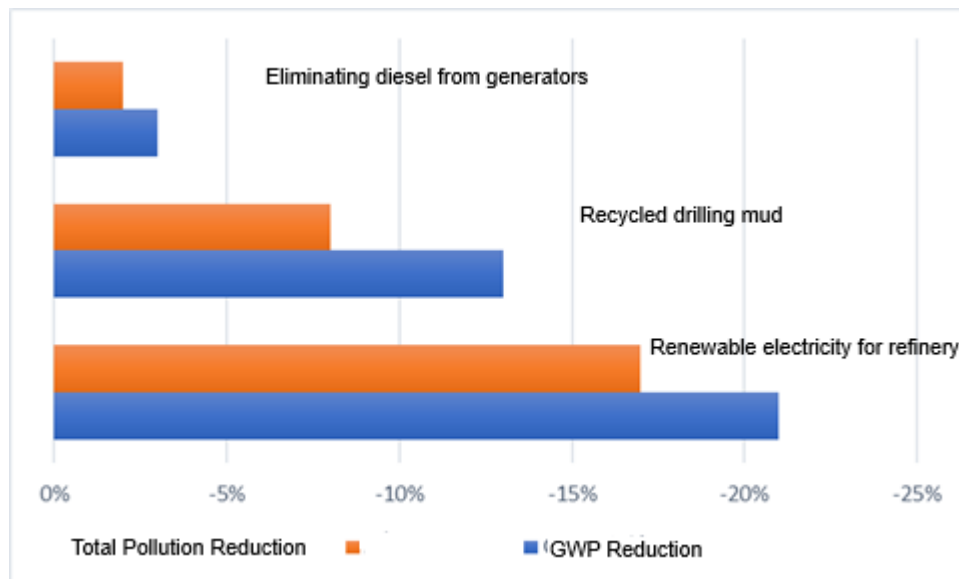
Table 6

Sensitivity analysis of environmental optimization scenarios in the gasoline production process in Khuzestan

Scenario	GWP Reduction	Total Pollution Reduction
Renewable electricity for refinery	-21%	-17%
Recycled drilling mud	-13%	-8%
Eliminating diesel from generators	-3%	-2%

Figure 2

Comparison of the sensitivity analysis of environmental optimization scenarios in the gasoline production process in Khuzestan



In this stage of the life cycle assessment of the gasoline production process, the focus was on analyzing the relative contribution of each stage of the production chain to key environmental impact indicators such as Global Warming Potential (GWP), human toxicity, and the overall contribution to total environmental impacts. The aim of this analysis was to identify environmental bottlenecks and focus on critical stages to design optimization scenarios and reduce adverse environmental effects.

The results indicate that the refining stage, with a contribution of 49.7% to GWP, 52.8% to human toxicity, and 49% of the total environmental burden, is the most significant and critical stage in the entire gasoline production cycle. This is primarily due to the high energy consumption in advanced process units such as distillation columns, reforming, and catalytic cracking, which are often powered by electricity and steam produced from fossil fuels. Furthermore, a large amount of air pollutants, including CO₂, NO_x, and volatile organic compounds, are released during this stage, directly impacting human health and the climate.

The drilling stage ranks second in terms of impact contribution, with a 28% share in GWP, 31% in human toxicity, and 30% of total environmental impacts, playing a significant role. These results reflect the extensive consumption of diesel in generators, pollution from drilling mud, oil leaks, and methane emissions from drilling wells, all of which have high global warming potential and human toxicity. The exploitation stage, with shares of 12% in GWP, 9% in human toxicity, and 11% of total impacts, ranks third. In this stage, reservoir pressure maintenance operations, crude oil extraction, and the use of turbines and pumps cause pollutant emissions and energy consumption, but their intensity is lower compared to the refining and drilling stages.

The transportation stage, which includes pipeline activities and pumping stations, has a lower impact with a 7.5% share in GWP and a 6% share in human toxicity. However, due to the risks of crude oil leaks, water and soil pollution, and the energy required for pumping, it still requires close environmental monitoring. The geophysics stage, involving seismic studies and exploration operations, is considered the least impactful stage from an

environmental perspective, with shares of 2.8% in GWP, 1.2% in human toxicity, and 2.5% of total impacts. This is

mainly related to energy consumption in seismic equipment and the limited use of chemicals.

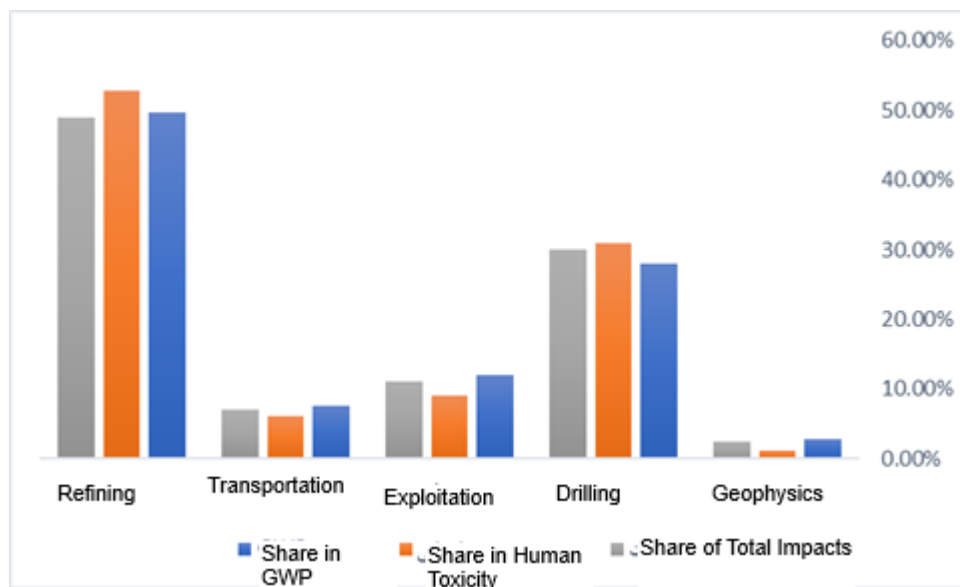
Table 7

Relative contribution of different stages of gasoline production to key environmental impact indicators.

Stage	Share in GWP	Share in Human Toxicity	Share of Total Impacts
Geophysics	2.80%	1.20%	2.50%
Drilling	28%	31%	30%
Exploitation	12%	9%	11%
Transportation	7.50%	6%	7%
Refining	49.70%	52.80%	49%

Figure 3

Comparison of the relative contribution of different stages of gasoline production to key environmental impact indicators.



4. Discussion and Conclusion

The comprehensive environmental life cycle assessment (LCA) of the gasoline production process in Khuzestan Province reveals significant ecological burdens associated with the fossil fuel supply chain, quantifying the global warming potential (GWP) at 3.62 kg CO₂ eq per liter of produced gasoline. The systematic cradle-to-gate analysis successfully identified the distinct environmental contributions of the five primary operational stages: geophysics, drilling, exploitation, transportation, and refining. Consistent with the foundational principles of environmental impact assessment in the hydrocarbon sector, the results unequivocally demonstrate that the refining and drilling stages constitute the most critical environmental bottlenecks in the regional oil industry (Rajaoalison et al.,

2022). By applying a highly localized ecosystem approach that integrates the specific vulnerabilities of Khuzestan's biosphere, this study provides a precise quantification of the anthropogenic pressures exerted on the region, underscoring the necessity of targeted optimization interventions to mitigate severe human toxicity and long-term climate impacts (Morales Mora et al., 2020).

A detailed examination of the relative contributions of each production phase indicates that the refining stage at the Abadan Oil Refinery is the dominant source of environmental degradation, accounting for 49.7% of the total GWP, 52.8% of human toxicity, and 49% of the overall environmental burden. This disproportionate impact is primarily driven by the massive electricity and thermal energy requirements inherent in complex refining operations, such as atmospheric distillation, catalytic reforming, and fluid catalytic cracking. The high energy

intensity of these advanced chemical conversions relies heavily on the combustion of fossil fuels, resulting in substantial emissions of carbon dioxide, nitrogen oxides (NO_x), sulfur dioxide (SO₂), and volatile organic compounds (VOCs). These findings closely align with life cycle assessments of other complex chemical synthesis processes, which similarly identify thermal energy consumption and fossil-based electricity grids as the primary drivers of greenhouse gas emissions and photochemical ozone creation (Ghannadzadeh & Tarighaleslami, 2022). Furthermore, the overwhelming environmental footprint of the refining stage highlights the persistent ecological deficit of conventional clean fuel vehicle systems when relying on fossil-derived energy carriers, as the upstream processing of gasoline fundamentally limits the overall sustainability of the transportation sector (Cui et al., 2023).

The drilling stage, utilizing both offshore and onshore rigs, emerged as the second most critical phase, contributing 28% to the GWP, 31% to human toxicity, and 30% of the total environmental impacts. The rigorous demands of deep-well drilling necessitate continuous, high-volume diesel consumption by industrial generators, coupled with the systemic generation of hazardous drilling muds and the fugitive emission of potent greenhouse gases such as methane (CH₄). This finding is strongly supported by recent critical reviews focusing specifically on the life cycle impacts of well drilling processes, which confirm that the localized combustion of heavy diesel fuels and the mismanagement of drilling fluids are paramount contributors to terrestrial ecotoxicity and atmospheric degradation (Ghasemi et al., 2025). The environmental dynamics observed in the Khuzestan drilling operations mirror the sustainability challenges faced by other heavy extractive industries, such as underground coal mining, where intense mechanization and reliance on decentralized fossil energy sources inherently elevate the life cycle environmental costs of resource extraction (Tao et al., 2024).

To evaluate actionable pathways for mitigating these identified bottlenecks, the study conducted a sensitivity analysis based on three distinct environmental optimization scenarios. The implementation of “renewable electricity for the refinery” yielded the most substantial environmental benefits, projecting a 21% reduction in the GWP indicator and a 17% decrease in total pollution. The efficacy of decarbonizing industrial electricity inputs is well-documented in LCA literature across various sectors. The integration of renewable energy sources, such as solar or geothermal power, into highly centralized industrial nodes

fundamentally decouples production from fossil-based grid emissions, a strategy that has proven highly effective in evaluating the technical and environmental capabilities of sustainable systems (Miloussi et al., 2022). Moreover, the transition toward renewable electricity in refining processes parallels the required systemic shifts in advanced energy frameworks, such as Power-to-Gas (PtG) technologies, where the environmental viability of producing alternative fuels is entirely dependent on the utilization of renewable energy inputs (Litheko et al., 2023).

The second optimization scenario, focusing on “drilling mud recycling,” demonstrated a highly commendable 13% reduction in GWP and an 8% reduction in total environmental pollution. This scenario emphasizes the critical importance of circular economy principles and advanced waste management within the hydrocarbon extraction sector. The substantial reduction in toxicity and climate impacts achieved through material recovery is consistent with the broader scientific consensus on waste optimization. Life cycle assessments of various waste management systems, ranging from municipal solid waste (Shahivand, 2021) to the localized treatment of agricultural residues (Sumiyati et al., 2024) and animal byproducts (Ferreira et al., 2024), consistently demonstrate that recycling and the prevention of toxic leakage into soil and water matrices are essential for minimizing eutrophication and acidification potentials. By recycling drilling mud, the industry not only curtails the demand for virgin chemical inputs but also mitigates the severe localized ecotoxicity associated with offshore and onshore disposal.

The third scenario, “eliminating diesel from generators,” resulted in a 3% reduction in GWP and a 2% reduction in total pollution. While the relative magnitude of this mitigation is smaller compared to refinery electrification and mud recycling, it remains a vital complementary strategy. The localized reduction of diesel combustion directly translates to a decrease in the emission of particulate matter and sulfur compounds, which are key contributors to human toxicity and respiratory ailments in the immediate vicinity of drilling rigs. The necessity of phasing out internal combustion engines—even in stationary industrial applications—is increasingly emphasized in comparative life cycle assessments evaluating the environmental performance of conventional combustion technologies against electrified alternatives (Idris et al., 2025). As the global transportation sector gradually transitions toward electric and alternative fuel vehicles to reduce urban emissions (Vasquez et al., 2025), it is imperative that the

upstream fuel production infrastructure simultaneously adopts cleaner localized energy generation to ensure a holistic reduction in environmental burdens.

Ultimately, comparing the staggering life cycle impacts of conventional gasoline production in Khuzestan to the potential of alternative energy pathways reinforces the urgency of regional energy transitions. Exploring alternative fuel production, such as hydrogen derived from coal gasification or renewable biomass, offers valuable comparative metrics for assessing the true cost of fossil fuel dependency (Burchart et al., 2022). Furthermore, Khuzestan Province possesses significant untapped potential for liquid biofuel production utilizing agricultural residues, which could serve as a regionally appropriate, lower-carbon substitute for conventional gasoline (Ardebili & Khademalrasoul, 2018). The methodical application of LCA methodologies, as refined by recent reviews (Gaffey et al., 2024), ensures that policymakers and industrial stakeholders possess the rigorous quantitative data required to navigate the complex trade-offs between sustaining current energy supplies and protecting vulnerable ecosystems.

While this study provides a robust evaluation of the environmental impacts of gasoline production, several methodological and practical limitations must be acknowledged. First, the reliance on secondary data from the Ecoinvent database for certain background processes may introduce geographical and temporal uncertainties, as these datasets are predominantly modeled on European industrial averages and may not perfectly reflect the specific technological efficiencies or aging infrastructure of the Iranian oil and gas sector. Second, the system boundary was restricted to a “cradle-to-gate” scope, thereby excluding the environmental impacts associated with the final distribution of gasoline to regional fueling stations and its subsequent combustion in vehicle engines, which represents a massive portion of the fuel’s total life cycle emissions. Third, the localized ecosystem approach, while beneficial for assessing specific regional vulnerabilities such as the Hoor al-Azim and Shadegan wetlands, faced limitations regarding the availability of high-resolution, empirical ecotoxicity data, forcing the reliance on generalized impact assessment models that may underrepresent or overrepresent acute, short-term localized pollution events such as minor, undocumented oil spills.

To address current gaps and expand upon the findings of this study, future research should prioritize a full “cradle-to-grave” life cycle assessment that incorporates the tailpipe emissions of various regional vehicle fleets utilizing the

locally produced gasoline, thereby providing a complete picture of the fuel’s environmental footprint. Additionally, researchers should focus on developing highly localized life cycle inventory databases specific to the Middle Eastern and Iranian petrochemical sectors, utilizing direct, real-time emission monitoring at extraction and refining sites rather than relying on global averages. Future studies could also conduct complex, multi-criteria decision analyses to compare the environmental and economic feasibility of the proposed optimization scenarios against entirely different energy paradigms, such as transitioning regional infrastructure to support bioethanol blends, large-scale solar-to-hydrogen facilities, or the widespread implementation of carbon capture and storage technologies at existing refineries.

For industrial stakeholders, policymakers, and environmental regulatory bodies in Khuzestan Province, immediate practical steps must be taken to operationalize the findings of this study. Refinery management should urgently prioritize capital investments in upgrading outdated thermal equipment and aggressively pursue power purchase agreements or direct installations of solar infrastructure to systematically replace fossil-fueled electricity, which has been proven to yield the highest environmental dividend. For drilling operations, regulatory agencies must enforce stricter mandates and provide technical support for the closed-loop management and mandatory recycling of drilling muds, heavily penalizing the improper disposal of toxic effluents in sensitive ecological zones. Finally, oil extraction companies should initiate phased replacement programs for aging diesel generators, transitioning to natural gas-fired generators utilizing captured flare gas or mobile battery storage systems, thereby simultaneously reducing localized human toxicity and mitigating the wasteful flaring of valuable hydrocarbon resources.

Authors’ Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

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