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Sustainable Construction of Deep-Water Injection Wells: A Life Cycle Assessment Approach

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Abstract

The study evaluates the environmental sustainability of constructing deep-water injection well systems for waste management. As the use of these systems is developing in Qatar, there is no research on their impacts from a sustainability point of view. The research aims to provide useful insights through a comprehensive life cycle assessment of constructing such wells. The analysis examines key construction stages: mobilization, drilling and casing, geophysical surveying, well development, wellhead assembly, and data logger installation for ground-term monitoring. Each stage is evaluated for its environmental and socio-economic effects. Initial findings show that while construction poses some environmental challenges, particularly regarding drilling and material use, the long-term environmental and social benefits may outweigh these concerns. The paper sheds light on the environmental implications of constructing deep-water injection wells and identifies initial opportunities to enhance their sustainability. The findings can serve as an important reference for the future development and sustainable operation of these waste management systems.

Keywords
Deep-water injection Wells, Life Cycle Assessment (LCA), Environmental Sustainability, Waste Management and Construction Impact Analysis.

1. Introduction
The concept of sustainability in the construction industry has become increasingly significant, as evidenced by various papers and reports emphasizing the improvement of the environment, economy, and social sustainability - the three bottom lines in the industry. The construction industry is known for its substantial environmental impact, consuming vast resources, materials, and energy throughout the lifecycle of any project. These impacts include but are not limited to, global greenhouse gas (GHG) emissions, high energy use, air and water pollution, deterioration of the ecological system, and poor waste management.

Deep Injection Wells (DIW) have gained significance as a key method to manage treated sewage effluent (TSE) in areas where wastewater disposal is challenging. These wells, reaching depths of approximately 400m, are crucial in managing excess TSE, offering a reliable mechanism for both seasonal and emergency disposal needs. However, the construction of these systems, consisting of deep injection wells (DIWs), deep monitoring wells (DMWs), and shallow monitoring wells (SMWs) as can be seen in Figure 1, involves complicated procedures that consume significant resources and materials that have large environmental impacts.

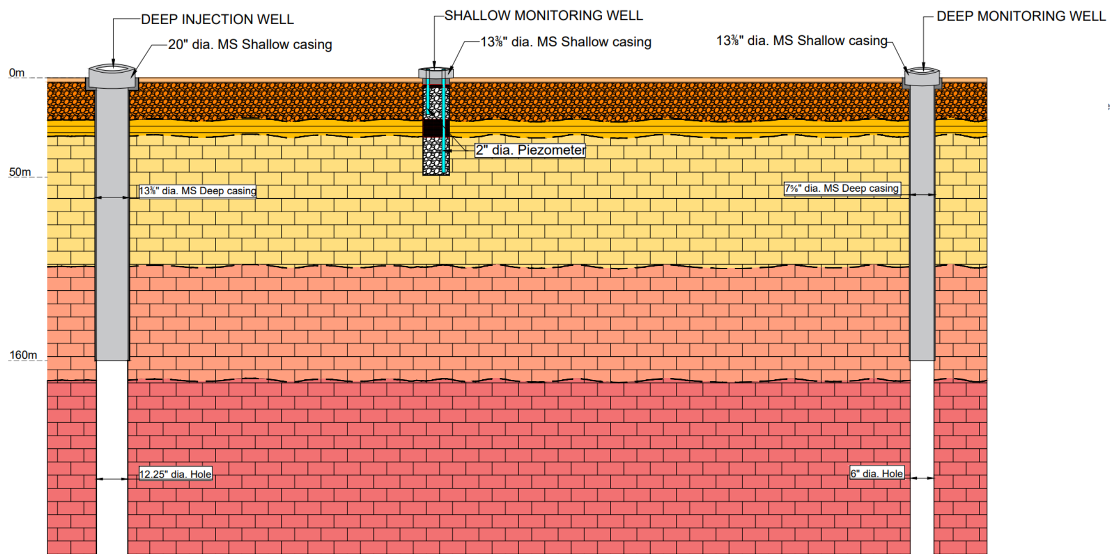

Figure 1. Well system component

While DIW systems offer a viable solution for TSE management, it is essential to examine the environmental impacts arising from the materials and processes used during their construction phase. This study aims to outline the life cycle assessment from material production to system construction, focusing on environmental conservation and sustainability. And To identify and quantify the materials and emissions involved throughout the construction phase. by utilizing the OPENLCA software to ascertain the outputs, thereby facilitating the development of a life cycle inventory.

1.1 Objectives

The primary objectives of this study on the holistic sustainability life cycle assessment of the construction phase of DIW systems are as follows:

1. **Conduct a Comprehensive Sustainability Life Cycle Assessment:** This involves performing an in-depth life cycle assessment of the construction phase of the DIW systems, focusing on sustainability aspects.
2. **Identify and Quantify Materials and Emissions:** The study aims to identify and quantify the various materials and emissions involved throughout the construction phase of the DIW systems.
3. **Utilize OPENLCA Software:** The research utilizes OPENLCA software to ascertain the outputs, which will facilitate the development of a comprehensive life cycle inventory.
4. **Implement a Life Cycle Impact Assessment Using the TRACI Method:** The study will implement a life cycle impact assessment using the TRACI method and explore potential alternative technologies and processes that could mitigate environmental impacts.

2. Literature Revie

This part of the paper provides a comprehensive examination of Life Cycle Assessment (LCA) with a focus on the construction phase of a deep-water injection well system. It begins by introducing the concept of Life Cycle Assessment (LCA) and its four fundamental stages: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. This introduction offers a foundational understanding of the methodological approach used in the subsequent chapters, illustrated by Figure 2, which depicts the LCA framework based on ISO 14040 (2006).

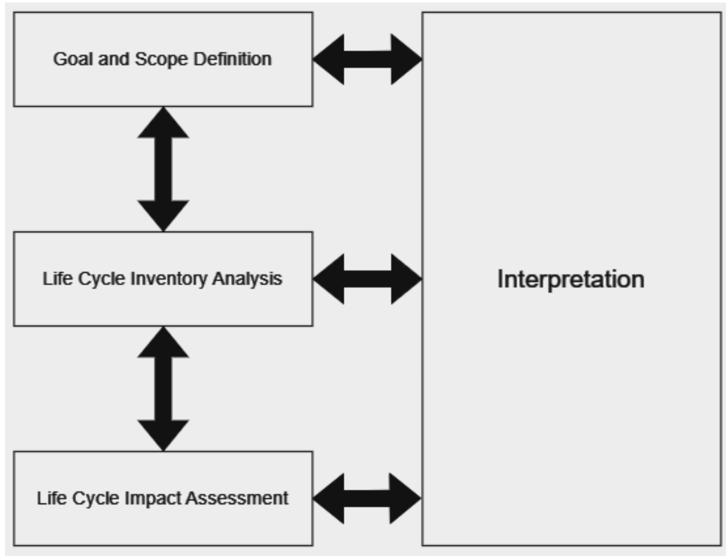

Figure 2. LCA framework based on (ISO, 2006)

2.1 Life Cycle Assessment (LCA):

Recognized for its "cradle to grave" approach as can be shown, LCA assesses environmental impacts from raw material extraction to end-of-life phases. The Goal and Scope definition is crucial in LCA and involves the precise identification of functional units and demarcation of system boundaries (Marceau et al., 2012) as can be seen in Table 1 below. This is followed by life cycle impact Analysis (LCIA) (Figure 3), where data is accumulated and quantified (Atmaca, 2016).

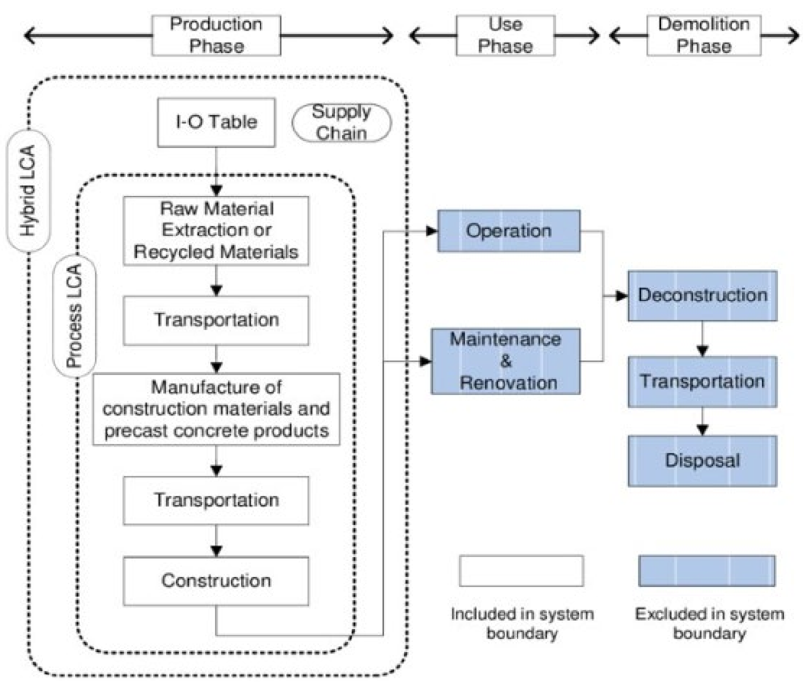

Figure 3. Flow diagram of a system boundary in typical construction projects (Omar et al., 2014).

Table 1. Goals, Objectives, and Scope of the Research

Category	Description
Goals	Environmental implications and sustainable practices associated with the construction of DIW systems.
Objectives	To study and evaluate the environmental and sustainability aspects of DIW systems for waste management.
Scope	The research focuses on the assessment of the construction of DIW systems and their environmental outcomes.

The LCIA and Interpretation stages are then discussed. LCIA attributes potential environmental impacts based on LCI data, and the Interpretation phase consolidates these results for analysis and recommendations, utilizing modeling platforms like OPENLCA.

The LCA for a DIW well system requires consideration of distinct factors due to the specialized nature of the infrastructure as detailed in Figure 4. Whereas typical system LCAs may evaluate material sourcing, transport, and emissions, an assessment of this system must incorporate:

- Material procurement and manufacturing for construction elements such as steel casing, cement grout, and bentonite polymer.
- Construction processes involving rotary drilling, installation of casings, cement grouting, and well development.
- Transportation of workers, materials, and equipment to and from the site.
- Air emissions like carbon dioxide, sulfur dioxide, and carbon monoxide especially during drilling and development.

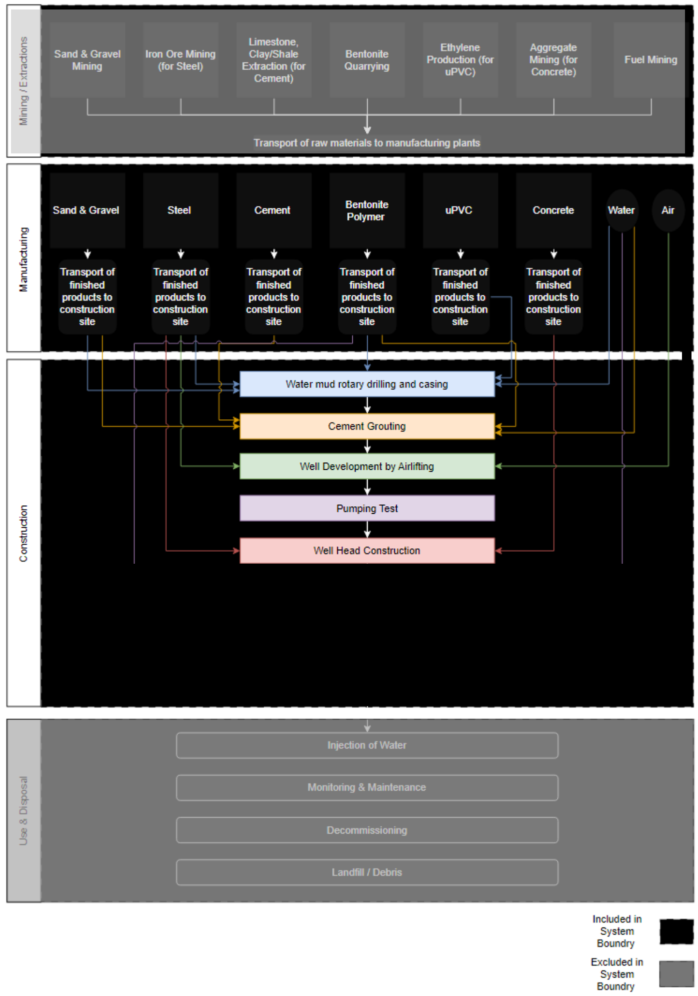

Figure 4. System boundary for Deep Water Injection Wells Projects

3. Methods

In this study, an assessment of the effects linked to the construction of DIW was conducted using a systematic Life Cycle Assessment (LCA) approach. To do so we divided our methodology into stages each focusing on aspects of the LCA process;

1. Defining Goals and Scope; The study aimed to gain insights, into the implications and sustainable practices associated with constructing DIW systems for waste management. During this stage, objectives defining the scope of the research and determining the unit for analysis were established.

2. Establishing System Boundaries; a "cradle to gate" approach was adopted to comprehensively assess the construction process. This means that the system boundary encompassed all processes and inputs from raw material manufacturing through to well completion.

3. Specifying Functional Units; For a representation of the objective in wastewater disposal the unit was defined as "the construction of a single DIW system."

4. Analyzing Life Cycle Inventory (LCI); In this phase, the data was collected, and the energy inputs and outputs associated with constructing these systems. This helped to understand the burden posed by the process in the predefined system boundaries.

5. Conducting Life Cycle Impact Assessment (LCIA); Utilizing methods for environmental impact assessment based on LCI data that was collected such as the use on OPENLCA software.

By following this approach, the impacts were assessed and evaluated throughout the life cycle of DIW construction.

4. Data Collection

The data collection process for this study was many-sided, drawing information from various sources to ensure a comprehensive LCA:

1. Raw Materials and Manufacturing Data: Information regarding the production and procurement of key construction materials like cement, steel, and drilling fluids was gathered from different literature and using LCI databases. This included data on the manufacturing processes, resources used, and associated environmental costs.

2. Transportation Data: Data about the transportation of materials from manufacturing or processing plants to the well construction site was collected, considering the environmental impact of logistics and vehicle emissions.

3. Construction Phase Data: On-site material and energy usage data were obtained, primarily from the databases of construction companies. This covered the consumption of resources like electricity and fuel during drilling and related construction activities.

4. Software and Database Utilization: The OpenLCA software was employed for a full LCI analysis, with data adapted from Ecoinvent and Exiobase databases. Adjustments were made to this data to fit the specific context of the well systems being studied.

5. Results and Discussion

5.1 Numerical Results

This section presents the Life Cycle Assessment (LCA) results for each phase of the deep-water injection well construction process.

• Mobilization

The LCA results for the mobilization phase reveal the environmental impacts associated with the transportation and delivery of equipment and materials (Table 2).

Table 3. LCIA Results – Mobilization

		Delivery							
Impact Category	**Reference Unit**	**Rig**	**Excavator**	**Drilling Materials**	**Site Facilities**	**Generators**	**Mud Pump**	**Water Tankers**	**Total Mobilization**
Environmental Impact - Acidification	moles of H+-Eq	7.96E+01	7.96E+01	3.98E+01	3.98E+01	2.65E+01	2.65E+01	2.65E+01	**3.18E+02**
Environmental Impact - Ecotoxicity	kg 2,4-D-Eq	1.13E+02	1.13E+02	5.65E+01	5.65E+01	3.77E+01	3.77E+01	3.77E+01	**4.52E+02**
Environmental Impact - Eutrophication	kg N	2.46E-02	2.46E-02	1.23E-02	1.23E-02	8.21E-03	8.21E-03	8.21E-03	**9.86E-02**
Environmental Impact - Global Warming	kg CO2-Eq	7.65E+00	7.65E+00	3.83E+00	3.83E+00	2.55E+00	2.55E+00	2.55E+00	**3.06E+01**
Environmental Impact - Ozone Depletion	kg CFC-11-Eq	4.93E-06	4.93E-06	2.47E-06	2.47E-06	1.64E-06	1.64E-06	1.64E-06	**1.97E-05**
Environmental Impact - Photochemical Oxidation	kg NOx-Eq	1.41E-01	1.41E-01	7.06E-02	7.06E-02	4.71E-02	4.71E-02	4.71E-02	**5.65E-01**
Human Health - Carcinogenics	kg benzene-Eq	1.75E+00	1.75E+00	8.74E-01	8.74E-01	5.82E-01	5.82E-01	5.82E-01	**6.99E+00**
Human Health - Non-Carcinogenics	kg toluene-Eq	5.15E+04	5.15E+04	2.57E+04	2.57E+04	1.72E+04	1.72E+04	1.72E+04	**2.06E+05**
Human Health - Respiratory Effects, Average	kg PM2.5-Eq	2.78E-01	2.78E-01	1.39E-01	1.39E-01	9.26E-02	9.26E-02	9.26E-02	**1.11E+00**

• Pre-Site Works
This subsection details the environmental impacts of activities conducted during the pre-site works phase, including site preparation and initial setup (Table 3).

Table 4. LCIA Results – Pre-Site Works

Impact category	**Reference unit**	**Diesel for Excavator**	**Diesel for Transportation**	**Materials of Manual Inspection Pit**	**Total Pre-Site Works**
environmental impact - acidification	moles of H+-Eq	1.66E+03	1.76E+02	5.49E+02	**2.39E+03**
environmental impact - ecotoxicity	kg 2,4-D-Eq	2.36E+03	2.50E+02	1.15E+03	**3.76E+03**
environmental impact - eutrophication	kg N	5.15E-01	5.45E-02	2.47E-01	**8.17E-01**
environmental impact - global warming	kg CO2-Eq	1.60E+02	1.69E+01	5.01E+01	**2.27E+02**
environmental impact - ozone depletion	kg CFC-11-Eq	1.03E-04	1.09E-05	7.75E-05	**1.91E-04**
environmental impact - photochemical oxidation	kg NOx-Eq	2.95E+00	3.13E-01	1.66E+00	**4.93E+00**
human health - Carcinogenics	kg benzene-Eq	3.65E+01	3.87E+00	1.81E+01	**5.84E+01**
human health - non-Carcinogenics	kg toluene-Eq	1.08E+06	1.14E+05	5.24E+05	**1.71E+06**
human health - respiratory effects, average	kg PM2.5-Eq	5.80E+00	6.14E-01	1.43E+00	**7.84E+00**

4.2.3 Drilling

Here, we explore the LCA results for the drilling phase, focusing on the environmental footprint of operations like rig and mud pump usage (Table 4).
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Table 5. LCIA Results – Drilling Works

Impact Category	**Reference Unit**	**Diesel for Mud Pump**	**Diesel for The Rig.**	**Water Mud**	**Samples Transportation**	**Workers Transportation**	**Total Drilling Works**
environmental impact - acidification	moles of H+-Eq	9.00E+01	2.77E+03	1.30E+03	7.05E+01	1.76E+02	**4.40E+03**
environmental impact - ecotoxicity	kg 2,4-D-Eq	1.28E+02	3.93E+03	3.81E+02	1.00E+02	2.50E+02	**4.79E+03**
environmental impact - eutrophication	kg N	2.78E-02	8.57E-01	9.33E-02	2.18E-02	5.45E-02	**1.05E+00**
environmental impact - global warming	kg CO2-Eq	8.65E+00	2.66E+02	1.28E+02	6.77E+00	1.69E+01	**4.26E+02**
environmental impact - ozone depletion	kg CFC-11-Eq	5.57E-06	1.71E-04	3.13E-05	4.37E-06	1.09E-05	**2.24E-04**
environmental impact - photochemical oxidation	kg NOx-Eq	1.60E-01	4.91E+00	3.51E-01	1.25E-01	3.13E-01	**5.86E+00**
human health - Carcinogenics	kg benzene-Eq	1.97E+00	6.08E+01	5.30E+00	1.55E+00	3.87E+00	**7.34E+01**
human health - non-Carcinogenics	kg toluene-Eq	5.82E+04	1.79E+06	1.70E+05	4.56E+04	1.14E+05	**2.18E+06**
human health - respiratory effects, average	kg PM2.5-Eq	3.14E-01	9.65E+00	6.45E+00	2.46E-01	6.14E-01	**1.73E+01**

4.2.4 Steel Casing

The LCA outcomes for the steel casing phase are discussed, highlighting the environmental implications of casing installation and associated activities (Table 5).
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Table 6. LCIA Results – Casing Works

Impact Category	Reference Unit	Operation of Mobile Crane to Install Casing	Diesel for Workers Transportation	Steel	Total Casing Works
environmental impact - acidification	moles of H+-Eq	1.42E+04	1.76E+02	4.27E+03	**1.86E+04**
environmental impact - ecotoxicity	kg 2,4-D-Eq	2.02E+04	2.50E+02	8.90E+03	**2.93E+04**
environmental impact - eutrophication	kg N	4.39E+00	5.45E-02	1.92E+00	**6.37E+00**
environmental impact - global warming	kg CO2-Eq	1.36E+03	1.69E+01	3.90E+02	**1.77E+03**
environmental impact - ozone depletion	kg CFC-11-Eq	8.79E-04	1.09E-05	5.97E-04	**1.49E-03**
environmental impact - photochemical oxidation	kg NOx-Eq	2.52E+01	3.13E-01	1.29E+01	**3.84E+01**
human health - Carcinogenics	kg benzene-Eq	3.12E+02	3.87E+00	1.40E+02	**4.55E+02**
human health - non-Carcinogenics	kg toluene-Eq	9.18E+06	1.14E+05	4.06E+06	**1.33E+07**
human health - respiratory effects, average	kg PM2.5-Eq	4.95E+01	6.14E-01	1.11E+01	**6.13E+01**

4.2.5 Grouting

This section quantifies the environmental impacts of the grouting process, including material usage and pump operation (Table 6).

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Table 7. LCIA Results – Grouting Works

Impact Category	Reference Unit	Materials	Cement Mixer Operation	Grouting Pump Operation	Worker Transportation	Total Grouting Works
environmental impact - acidification	moles of H+-Eq	5.71E+04	4.15E+03	9.00E+01	1.76E+02	**6.15E+04**
environmental impact - ecotoxicity	kg 2,4-D-Eq	1.70E+04	5.90E+03	1.28E+02	2.50E+02	**2.33E+04**
environmental impact - eutrophication	kg N	4.16E+00	1.29E+00	2.78E-02	5.45E-02	**5.53E+00**
environmental impact - global warming	kg CO2-Eq	5.62E+03	3.99E+02	8.65E+00	1.69E+01	**6.05E+03**
environmental impact - ozone depletion	kg CFC-11-Eq	1.35E-03	2.57E-04	5.57E-06	1.09E-05	**1.62E-03**
environmental impact - photochemical oxidation	kg NOx-Eq	1.49E+01	7.37E+00	1.60E-01	3.13E-01	**2.27E+01**
human health - Carcinogenics	kg benzene-Eq	2.37E+02	9.11E+01	1.97E+00	3.87E+00	**3.34E+02**
human health - non-Carcinogenics	kg toluene-Eq	7.60E+06	2.68E+06	5.82E+04	1.14E+05	**1.05E+07**
human health - respiratory effects, average	kg PM2.5-Eq	2.83E+02	1.45E+01	3.14E-01	6.14E-01	**2.98E+02**

4.2.6 Well Assembly

Finally, the LCA results for the well assembly phase are presented, encompassing the comprehensive impacts of assembling the well structure (Table 7).

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Table 8. LCIA Results – Well Assembly Works

Impact Category	**Reference Unit**	Cement Mixer Operation	Grouting Pump Operation	Worker Transportation	**Total Grouting Works**
environmental impact - acidification	moles of H+-Eq	4.15E+03	9.00E+01	1.76E+02	**6.15E+04**
environmental impact - ecotoxicity	kg 2,4-D-Eq	5.90E+03	1.28E+02	2.50E+02	**2.33E+04**
environmental impact - eutrophication	kg N	1.29E+00	2.78E-02	5.45E-02	**5.53E+00**
environmental impact - global warming	kg CO2-Eq	3.99E+02	8.65E+00	1.69E+01	**6.05E+03**
environmental impact - ozone depletion	kg CFC-11-Eq	2.57E-04	5.57E-06	1.09E-05	**1.62E-03**
environmental impact - photochemical oxidation	kg NOx-Eq	7.37E+00	1.60E-01	3.13E-01	**2.27E+01**
human health - Carcinogenics	kg benzene-Eq	9.11E+01	1.97E+00	3.87E+00	**3.34E+02**
human health - non-Carcinogenics	kg toluene-Eq	2.68E+06	5.82E+04	1.14E+05	**1.05E+07**
human health - respiratory effects, average	kg PM2.5-Eq	1.45E+01	3.14E-01	6.14E-01	**2.98E+02**

Each table provides a detailed analysis of the respective phase, ensuring a comprehensive understanding of the environmental impacts associated with the construction of a DIW.

5.2 Graphical Results

This section visually represents the Life Cycle Assessment (LCA) results for each phase of the deep-water injection well construction project. Through a series of bar charts, we provide an intuitive and clear understanding of the environmental impacts associated with the Mobilization, Pre-Site Works, Drilling, Steel Casing, and Grouting phases. These graphical interpretations are designed to complement the numerical data, offering an accessible and straightforward way to comprehend the complex environmental implications of each construction activity (Figure 5**-** Figure 10).

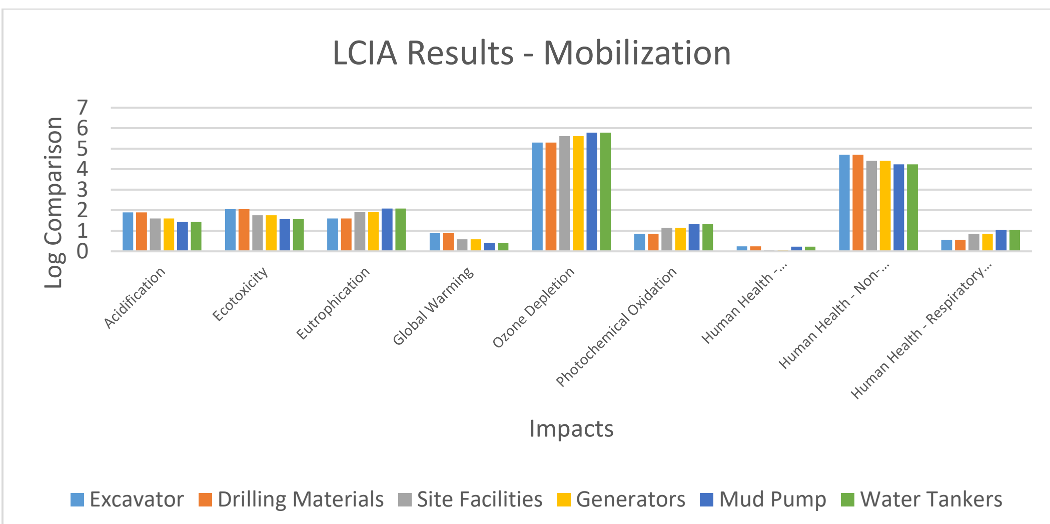

Figure 6. LCIA Results – Mobilization Works

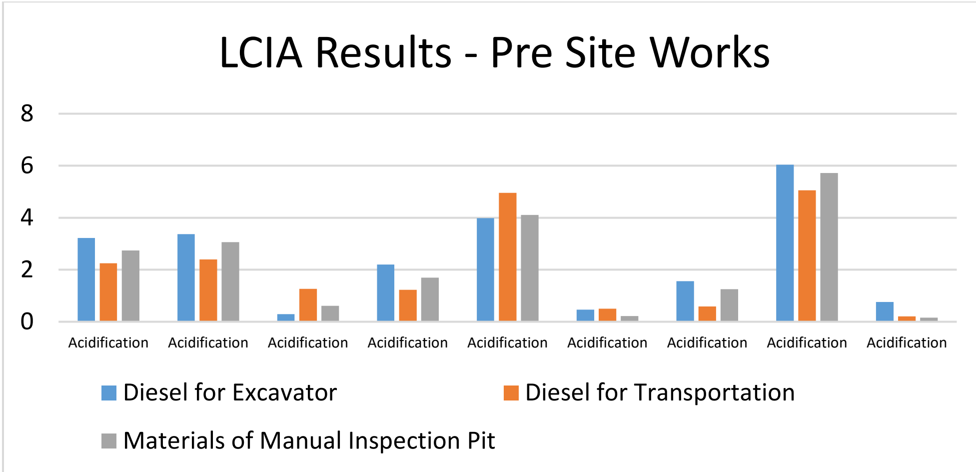

Figure 7. LCIA Results – Pre-site Works

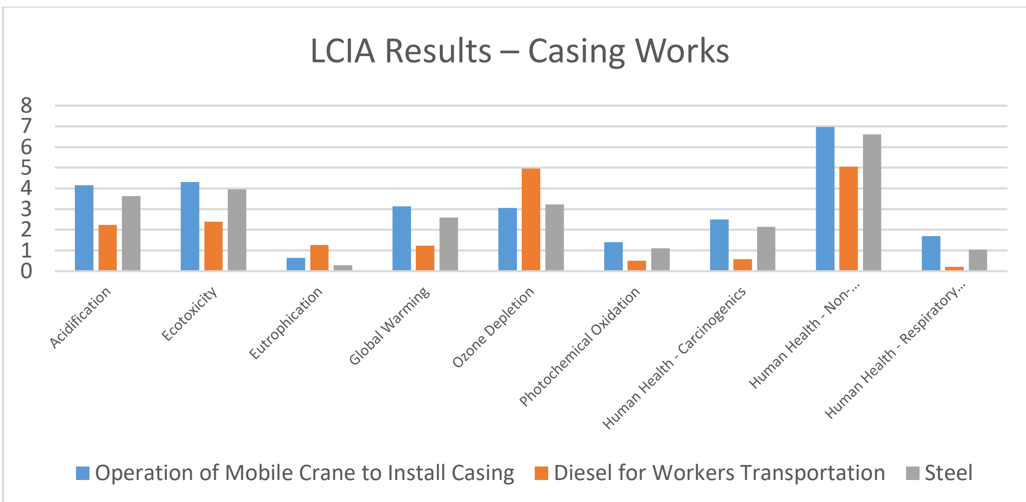

Figure 8. LCIA Results – Drilling Works

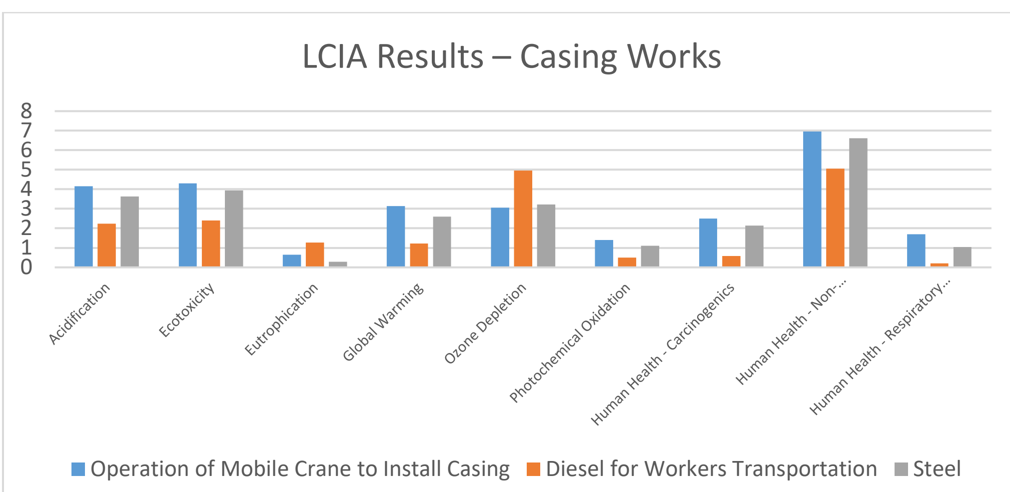

Figure 9. LCIA Results – Casing Works

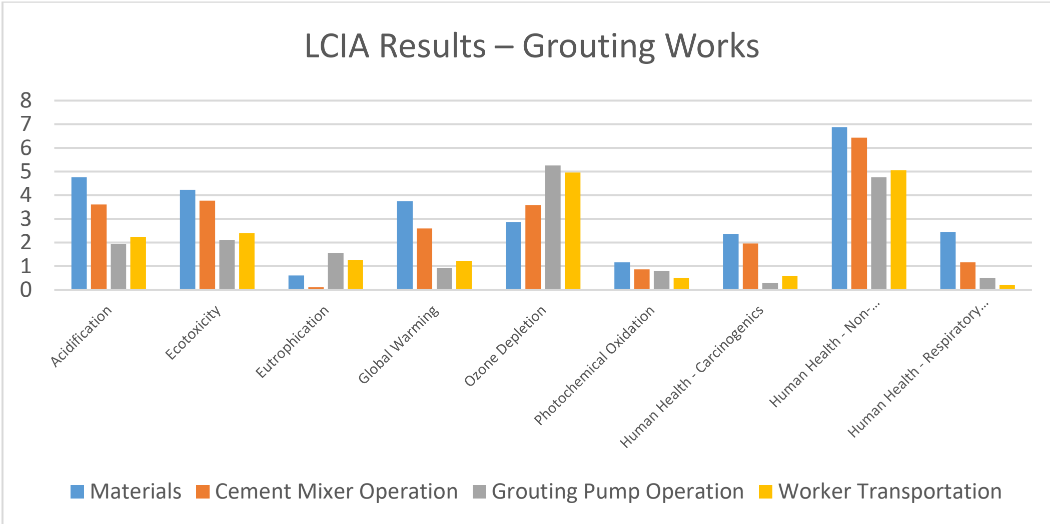

Figure 10. LCIA Results – Grouting Works

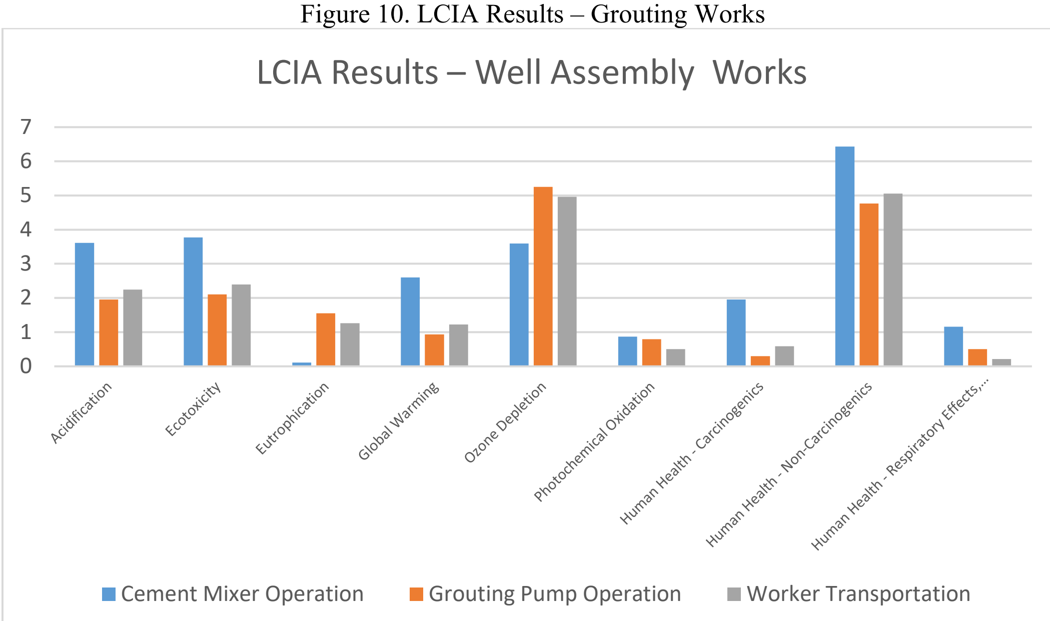

Figure 11. LCIA Results – Well Assembly Works

6. Conclusion

This section proposes potential improvements and identifies areas for future research, particularly focusing on the environmental benefits of replacing diesel-powered vehicles and heavy equipment with electric alternatives in the construction of deep-water injection wells.

Replacement of Diesel Vehicles with Electric Models: We suggest a shift towards electric vehicles for transportation and site activities. This change could significantly reduce the carbon footprint associated with diesel consumption, as highlighted in our LCA results.

Electrification of Heavy Equipment: The adoption of electrically powered drilling rigs, excavators, and other heavy machinery is proposed. This shift not only promises a reduction in direct emissions but also aligns with global trends towards sustainable construction practices.

Future Research Opportunities: This section opens avenues for further research into the feasibility, cost implications, and long-term environmental benefits of such electrification. Future studies could explore the integration of renewable energy sources to power these electric vehicles and equipment, further enhancing the sustainability of well-construction projects.

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Biographies

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