Title

Life Cycle Assessment of Bio-mediated and Bio-inspired Geotechnical Systems for Geologic Hazard Mitigation

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Life Cycle Assessment of Bio-mediated and Bio-inspired Geotechnical Systems for Geologic Hazard Mitigation

By

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DISSERTATION

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ABSTRACT

Recently, bio-mediated and bio-inspired solutions in the field of geotechnical engineering have been proposed as sustainable alternatives to traditional, cement-intensive business-as-usual technologies for infrastructure resiliency through geologic hazard mitigation. As these biogeotechnologies develop, it is imperative that quantitative sustainability assessment, such as life cycle sustainability assessment (LCSA), is employed to assess and guide their sustainable development. This can ensure that they produce both technological and sustainability advantages compared to traditional technologies considering social, environmental, and economic impacts. This dissertation addresses these needs for improved environmental assessment across biogeotechnologies by presenting a framework to evaluate the environmental impacts and cost across the whole life cycle of a geologic hazard mitigation project.

Chapter 1 introduces bio-mediated and bio-inspired geologic hazard mitigation techniques as potentially sustainable alternatives to existing technologies and life cycle sustainability assessment (LCSA) as a method to evaluate them. Chapter 2 then presents a systematic literature review of emerging bio-mediated and bio-inspired ground improvement LCSA studies, including those focused on enzyme induced carbonate precipitation (EICP), microbially induced carbonate precipitation (MICP) and microbially induced desaturation and precipitation (MIDP). The review demonstrates that environmental impacts such as global warming and eutrophication are the most assessed and that inconsistencies in methodology limit the application of the reviewed assessments.

Chapter 3 of this dissertation presents a framework for the evaluation of the environmental impacts and costs incurred across the whole life cycle of geotechnical earthquake mitigation

projects. This chapter also provides clear guidance for completion of a whole life cycle assessment following the ISO 14040 and 14044 life cycle assessment standards. Permeation grouting is evaluated as a liquefaction mitigation technique to provide an example implementation of the proposed framework and guidance. This case study shows that the construction stage of the permeation grouting project, specifically raw material supply for the microfine cement grout, contributes greatly to the whole life cycle impacts. Site investigation activities account for less than 1% of whole life cycle impacts suggesting that an increased scope site investigation program could provide a better understanding of the subsurface, reducing design uncertainties, without significantly impacting project sustainability.

Finally, a life cycle assessment of EICP columns for ground improvement is completed in Chapter 4 to determine the environmental sustainability of EICP columns as compared to permeation grouting. The study finds that EICP columns impacts are primarily due to calcium chloride and urea production and transportation, with EICP biogeochemical process emissions (i.e., ammonium production) accounting for the high eutrophication potential of EICP columns. Other than when considering eutrophication potential, EICP columns present as a more environmentally sustainable alternative to cement-based ground improvement.

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1. INTRODUCTION

Resilience is crucial when planning and designing infrastructure projects that holistically reduce geologic disaster risk, including effects exacerbated by climate change (Risken et al., 2015; Chang et al., 2019). Mitigating geologic hazards in our built environment (e.g., earthquake-induced liquefaction, landslides, coastal erosion, and subsidence) via geotechnical engineering techniques can improve infrastructure resiliency. Ground improvement techniques are one category of hazard mitigation technologies that have seen increased adoption. Ground improvement methods such as jet grouting (subsurface application of pressurized cement grout) and vibro compaction (vibrations to physically densify soil) can mitigate earthquake-induced soil liquefaction and landslides through soil reinforcement and densification mechanisms, respectively (Mitchell, 2012; Raymond et al., 2021a). However, hazard mitigation techniques impact social, environmental, and economic dimensions. Traditional ground improvement techniques can be resource-intensive and often lead to high life cycle greenhouse gas (GHG) emissions due to their high rates of cement use and fuel consumption (Jefferis, 2008; Basu et al., 2015; Raymond et al., 2021a). However, ground improvement plays a significant role in improving the resilience of critical lifelines such as electricity and transportation systems which are crucial in providing support to communities after a geologic event and throughout potential evacuation procedures (Andrus and Chung, 1995).

The need to continue investing in civil infrastructure coupled with the need to mitigate GHG emissions and other environmental impacts has led to development of a number of sustainability rating systems and benchmarks for use across civil design, but to date, they lack guidance for geotechnical engineering applications such as geologic hazard mitigation (Kendall et al., 2018a; Raymond et al., 2021a). In addition, these rating systems and benchmarks do not require evaluation of projects from a life-cycle standpoint. Previous research has concluded that life cycle-based methods, including life cycle sustainability assessment (LCSA), can improve both the sustainability and technical feasibility of geotechnical projects (Shillaber et al., 2016a; Kendall et al., 2018a; Lee and Basu, 2018). LCSA evaluates the social, environmental, and economic impacts of a system or project over its entire supply chain and life cycle and can be used to guide the development of more sustainable geotechnical solutions (Kendall et al., 2018b; Raymond et al., 2021a).

LCSA builds on existing life cycle assessment (LCA) and life cycle cost assessment (LCCA) frameworks—two methods with long histories and broad acceptance in civil engineering (Harvey et al., 2011; Cabeza et al., 2014; Parrish and Chester, 2014). Traditional LCSAs of civil infrastructure projects typically assess only life cycle environmental impacts through LCA and life cycle economic impacts through LCCA, excluding social impacts such as human rights, working conditions, or impacts on cultural heritage (Jørgensen et al., 2007; United Nations Environment Programme, 2020). However, a complete LCSA should include a social life cycle assessment (S-LCA) to understand the sometimes competing social, environmental, and economic impacts of a project. Throughout this dissertation, we use the term LCSA to describe any study which includes at least LCA, and may also include LCCA, but recognize that a true LCSA must include all three (LCA, LCCA, and S-LCA). The term LCA implies only an environmental assessment is completed.

LCSA has previously been applied to evaluate geotechnical engineering projects (e.g., Raymond et al., 2021), but it remains in its nascent stages for the geotechnical community. Previous reviews of geotechnical LCSAs have shown that the methods used to perform geotechnical LCSA vary, producing data that are not harmonized and that cannot be used in project or technology comparisons across studies (Kendall et al., 2018b; Song et al., 2020; Samuelsson et al., 2021).

Biogeotechnics has emerged as a promising solution to improve the sustainability of geotechnical infrastructure for geologic hazard mitigation, by reducing the environmental impacts and cost of ground improvement (Dejong et al., 2014; Wang et al., 2017; Sharma et al., 2021). Biogeotechnics are typically classified in two ways, as bio-mediated technologies and bio-inspired technologies. Bio-mediated technologies rely on microbial activity to achieve geologic hazard mitigation while bio-inspired technologies mimic natural systems to reduce geologic risks (Khodadadi et al., 2017). Bio-mediated and bio-inspired technologies often replace cement-intensive traditional grouting methods, which have high costs associated with them (Jefferis, 2008; Basu et al., 2015; Raymond et al., 2021a).

Biogrouting, or biocementation, is a group of methods currently under development for ground improvement applications, such as foundational support and earthquake-induced liquefaction mitigation (DeJong et al., 2010; Khodadadi et al., 2017). Biogrouting techniques include enzyme-induced carbonate precipitation (EICP), microbially induced carbonate precipitation (MICP), and microbially induced desaturation and precipitation (MID and MIDP) (van Paassen et al., 2010a; Almajed et al., 2018; Moug et al., 2022). MICP and MIDP rely on microbial activity to produce carbonate precipitates, whereas EICP relies on enzymatic activity to produce these precipitates (Khodadadi et al., 2017). Carbonate precipitation improves the strength and dilatancy of soil. MIDP also involves another mechanism, microbially induced desaturation, through which microbial activity produces nitrogen gas desaturating the soil thereby providing liquefaction mitigation (Dejong et al., 2014; O'Donnell et al., 2017b).

While a key driving factor behind the development of bio-mediated and bio-inspired geotechnical technologies has been their assumed environmental benefits, such as reduced cement consumption, these technologies carry their own environmental impacts (Raymond et al., 2021b). As these technologies develop, quantitative sustainability assessments can be used to verify their performance regarding social, environmental, and economic impacts and to guide sustainable bio-mediated and bio-inspired technology development (Raymond et al., 2020a). At the same time, traditional geologic hazard mitigation technologies must also be assessed so that fair comparative assessments can be made.

The core research objectives of this work, each presented as one chapter, are:

1. To determine the state of the art of sustainability assessment of bio-mediated and bio-inspired ground improvement techniques and highlight areas for improvement.

2. To develop a framework for the evaluation of the environmental impacts and costs of geotechnical earthquake hazard mitigation techniques.

3. To complete a comparative LCA of EICP columns and permeation grouting for ground improvement.

2. SUSTAINABILITY OF BIO-MEDIATED AND BIO-INSPIRED GROUND IMPROVEMENT TECHNIQUES FOR GEOLOGIC HAZARD MITIGATION: A SYSTEMATIC LITERATURE REVIEW

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2.1. Introduction

Life cycle sustainability assessment (LCSA) is steadily gaining popularity as a method to evaluate and guide the sustainability of civil infrastructure projects, including those focused on geologic hazard mitigation. While standards exist for the implementation of LCSA, particularly life cycle assessment (LCA) and life cycle cost assessment (LCCA), existing studies use varied methodologies and sometimes present conflicting results (Menzies et al., 2007). As bio-mediated and bio-inspired technologies gain popularity as sustainable alternatives to traditional geologic hazard mitigation technologies, it is imperative that the methods used to evaluate the sustainability of these technologies are well understood.

To understand the current state of practice for LCSA applied to bio-mediated and bioinspired ground improvement technologies, a systematic literature review of quantified sustainability assessments, such as LCSA, of EICP, MICP, and MIDP technologies, is undertaken. In addition to understanding the current state of practice, the literature review:

1. Investigates the frequency of bio-mediated and bio-inspired LCSA studies within broader ground improvement literature

2. Summarizes the sustainability potential of bio-mediated and bio-inspired technologies at their current stage of development

3. Recommends future directions for bio-mediated and bio-inspired technology development to achieve sustainability goals

2.2. Background

2.2.1. Life Cycle Assessment (LCA)

LCA can be used to determine the environmental and human health impacts of any product or system, over its entire life cycle. Examples of impact categories assessed include global warming, eutrophication, acidification, and human health impacts. LCA is also used to quantify the life cycle water consumption and cumulative energy demand of a product or system. LCAs are typically completed with a 'cradle-to-grave' scope, or system boundary, where each of the following life cycle stages is modeled: extraction and processing of raw materials, manufacturing, transportation of materials and equipment, construction, operation and maintenance, and end-of-life. For a geotechnical engineering project, the whole life cycle includes these stages over the entire project life including site investigation, construction, potential remedial measures in the case of a geologic event, and decommissioning.

The International Organization for Standardization (ISO) 14040 and 14044 standards are the most cited standard for LCA (ISO, 2006a, 2006b). The ISO standard is conceived in four phases. The goal and scope phase includes determining the purpose of the study, the system boundary of analysis, and the application and its function and functional unit, among other criteria. In the life cycle inventory (LCI) analysis phase, all environmental inflows, including energy and material inputs, and outflows, including water and air emissions as well as solid waste outputs, across the modeled system are quantified and aggregated. A life cycle impact assessment (LCIA) is then performed through which characterization factors are applied to relevant flows to estimate the environmental and human health impacts of the system.

Conclusions from the LCI analysis and LCIA are then drawn during the interpretation phase and possible recommendations for technology use or development, or future LCAs are provided.

2.2.2. Life Cycle Cost Assessment (LCCA)

LCCA accounts for the capital, operation and maintenance, potential replacement, and end-of-life phases of a product or system and can also include external costs associated with the system. In an LCSA, these costs are estimated for the same goal and scope outlined in the LCA. In an LCCA, all future costs are discounted to account for the change in monetary value over time. While less common, LCCA can also be used to estimate the external costs of a system such as the environmental or social cost of environmental emissions. For example, the social cost of carbon (SCC) has been applied to geotechnical projects where the economic damages that would result from 1 ton of carbon emissions are evaluated (Reddy and Kumar, 2018; Raymond et al., 2021b).

2.2.3. Social Life Cycle Assessment (S-LCA)

Social life cycle assessment is a method to assess the direct and indirect social impacts of a project. Direct impacts refer to those stemming from the project itself, such as the benefits of geologic hazard mitigation on a community, while indirect impacts refer to those that occur further up the supply chain. One method to assess the indirect social impacts of a project are through existing social hotspot databases such as the Product Social Impact Life Cycle Assessment (PSILCA) database and the Social Hotspot Database (SHDB) (Benoit-Norris et al., 2012; Maister et al., 2020). However, these databases currently do not comprehensively cover geotechnical-related construction materials or assess emerging alternative construction methods (e.g. bio-inspired and bio-mediated technologies). Tools such as Design for Freedom have also recently been developed to highlight the resource intensity and equity of building construction material supply chains predominantly across the buildings sector (Grace Farms, 2022). These supply chains are analyzed and evaluated to provide a qualitative assessment of a variety of social sustainability indicators (e.g., labor practices, resource exploitation). While the ground improvement materials can differ from conventional building construction materials, Design for Freedom presents a social and environmental sustainability framework that can be applied to understand the sustainability of materials-intensive industries. Direct impacts such as those on construction workers and the local community should similarly be assessed through qualitative means.

2.3. Overview of Bio-mediated and Bio-inspired Ground Improvement Techniques

MICP and MIDP are considered bio-mediated technologies since they directly use microbial activity in the treatment process. However, EICP is considered a bio-inspired technology because it uses a manufactured enzyme for treatment and does not involve microorganism activity (Khodadadi et al., 2017). Common benefits across each technology include the omission of carbon-emitting cement and the non-disruptive nature of treatment allowing, in many cases, ground improvement to be implemented below existing structures (Dejong et al., 2014; Khodadadi et al., 2017). Concerns across each technology include obtaining uniform treatment throughout the targeted soil volume and groundwater and soil contamination via unreacted process inputs or intermediary products resulting from the incomplete conversion of inputs (Hall, 2021). In addition, due to the novelty of each technology, the duration and durability of treatment have not been robustly tested.

The applications, process inputs, and technological and environmental concerns of EICP, MICP, MIDP, and MID are summarized in Table 1. The technical feasibility and sustainability impacts of each technology are determined by factors including:

- The bacterial and material inputs required for the biogeochemical process
- The equipment installation and treatment methods required for implementation
- The biogeochemical reaction rate
- The durability of treatment, and whether treatment needs to be repeated over the service life of the system
- Reagent utilization (ie. the efficiency of each biogeochemical reaction)
- The products and by-products of the overall biogeochemical process
- Whether each biogeochemical reaction is performed to completion

Table 1. Summary of bio-mediated and bio-inspired technologies and their environmental impacts

Technology	**Applications**	**Process Inputs**	**Technological Concerns**	**Environmental Concerns**
EICP	• Shallow soil stabilization eg. roadways • Wind erosion control • Liquefaction mitigation • Slope stability • Reduce hydraulic conductivity • Foundational support	• Free urease enzyme • Urea • Calcium chloride • Optional additives such as non-fat milk powder	• Uniformity of treatment • Precipitate clogging at injection points	• Ammonium, ammonia, and chloride production • N_2O emissions from application of fertilizers to soil surface

Technology	**Applications**	**Process Inputs**	**Technological Concerns**	**Environmental Concerns**
MICP	• Liquefaction mitigation • Foundational support • Reduce hydraulic conductivity • Slope stability	• Urea • Calcium chloride • Bacteria	• Uniformity of treatment • Precipitate clogging at injection points	• Ammonium, ammonia, and chloride production • N_2O emissions from application of fertilizers to soil surface
MID	• Liquefaction mitigation	• Calcium acetate • Calcium nitrate	• Uniformity of treatment • Longevity of gas desaturation	• Incomplete denitrification results in N_2O emissions • CO_2 emissions to air

Technology	Applications	Process Inputs	Technological Concerns	Environmental Concerns
MIDP	• Liquefaction mitigation • Foundational support	• Calcium acetate • Calcium nitrate	• Uniformity of treatment • Precipitate clogging at injection points	• Incomplete denitrification results in N_2O emissions • CO_2 emissions to air

2.3.1. *Enzyme Induced Carbonate Precipitation (EICP)*

EICP uses plant-derived (e.g., Jack beans) urease enzymes to induce urea hydrolysis, and when combined with calcium chloride. calcium carbonate precipitation occurs (Eqns [1-5]) (Khodadadi et al., 2017; Almajed et al., 2018). Non-fat milk powder can also be used as an additive in the EICP process to stabilize the enzymes (Martin et al., 2021). EICP can be applied as a treatment to the soil via three mechanisms depending on application purpose and soil properties: mechanical mixing and compaction, solution injection using traditional grouting methods, and surface spraying (Martin et al., 2020; Woolley et al., 2020a; Arab et al., 2021). EICP improves the strength of soils, such as the shear strength, by cementing soil grains together (Almajed et al., 2021).

$$CO(NH_2)_{2(aq)} + 2H_2O_{(l)} \rightarrow 2NH_{3(aq)} + H_2CO_{3(aq)} \quad (1)$$

$$NH_{3(aq)} + H_2O_{(l)} \leftrightarrow NH^{+}_{4(aq)} + OH^{-}_{(aq)} \quad (2)$$

$$H_2CO_{3(aq)} \leftrightarrow HCO^{-}_{3(aq)} + H^{+}_{(aq)} \leftrightarrow CO^{-2}_{3(aq)} + 2H^{+}_{(aq)} \quad (3)$$

$$Ca^{2+} + 2Cl^{-} \leftrightarrow CaCl_{2(aq)} \quad (4)$$

$$Ca^{+2}_{(aq)} + CO^{-2}_{3(aq)} \leftrightarrow CaCO_{3(s)} \quad (5)$$

The reaction rate of EICP is governed by the concentration of inputs, the source of the urease enzyme, which influences enzyme activity, the temperature and pH of the system and the soil type (Saif et al., 2022). These parameters must be optimized to obtain a slow reaction rate to reduce precipitate clogging near the injection points (van Paassen et al., 2010c). Experimental studies have presented varied optimal concentrations for urea and calcium chloride due to differences in urease concentration and enzymatic activity, as well as environmental conditions (Almajed et al., 2019; Ahenkorah et al., 2021).

While EICP eliminates the need for large volumes of cement, cost and environmental concerns still exist. For example, the cost of the urease enzyme has been highlighted as a concern (Khodadadi et al., 2017). Environmental concerns of EICP are the production of ammonium, which contributes to eutrophication, and chloride ions which contribute to salinization and can corrode steel (Eqns [2,4]). If the overall reaction does not occur to completion, ammonia may also be introduced as an intermediary product to the groundwater (Eqn [1]). When applied to the surface layer of the soil, the introduction of urea may result in nitrous oxide and ammonia emissions to the air (Raymond et al., 2021c). However, at depth, it is unlikely for these emissions to occur.

2.3.2. Microbially Induced Carbonate Precipitation (MICP)

MICP via urea hydrolysis has been the most widely researched MICP pathway. MICP relies on introducing cultivated microorganisms, most often Sporoscarcina pasteurii which carry the urease enzyme, urea, and calcium chloride to the soil that is to be treated through augmentation (van Paassen et al., 2010c). Stimulation of microorganisms native to the soil to be treated can also be conducted to achieve MICP (Burbank et al., 2011, 2012; Gomez et al., 2014, 2017) (Burbank et al., 2011, 2012; Gomez et al., 2014, 2017). MICP can be applied below the surface through injection of the microorganisms and substrates. MICP can improve the load-bearing capacity of soils and provide liquefaction mitigation (Whiffin et al., 2007; Montoya et al., 2013).

The MICP process via urea hydrolysis is as follows:

$$CO(NH_2)_{2(aq)} + 2H_2O_{(l)} \rightarrow 2NH_{3(aq)} + H_2CO_{3(aq)} \quad (6)$$

$$NH_{3(aq)} + H_2O_{(l)} \leftrightarrow NH^+_{4(aq)} + OH^-_{(aq)} \quad (7)$$

$$H_2CO_{3(aq)} \leftrightarrow HCO^-_{3(aq)} + H^+_{(aq)} \leftrightarrow CO^{-2}_{3(aq)} + 2H^+_{(aq)} \quad (8)$$

$$Ca^{2+} + 2Cl^- \leftrightarrow CaCl_{2(aq)} \quad (9)$$

$$Ca^{+2}_{(aq)} + CO^{-2}_{3(aq)} \leftrightarrow CaCO_{3(s)} \quad (10)$$

Like EICP, the rate of substrate injection must be controlled to avoid precipitate clogging at the injection points (Mortensen et al., 2011). The efficiency of the MICP process is dependent on the rate of ureolysis and treatment formula used (Martinez et al., 2013). This influences the applicability of MICP as a method to produce uniform treatment over large areas (van Paassen et al., 2010c).

Among the environmental concerns of MICP, ammonium chloride is produced as a by-product of the MICP process and must be removed or treated to reduce the risk of eutrophication and salinization of groundwater. Rinsing processes have been introduced to remove ammonium from the treated soil, however, this produces wastewater which must be treated (Lee et al., 2019; San Pablo et al., 2020). Regarding costs, bio-stimulation of native organisms may be favored over bio-augmentation as this requires the construction and maintenance of on-site bioreactors (Sharma et al., 2022).

2.3.3. Microbially Induced Carbonate Precipitation and Desaturation (MIDP)

MIDP is a two-mechanism hazard mitigation process that relies on microbial denitrification to produce biogenic gas for desaturation and calcium carbonate precipitation for biocementation. MIDP uses the user-supplied substrate recipe of calcium acetate and calcium nitrate. Acetate acts as the electron donor (provides energy to the microbes) to facilitate microbial reduction of the nitrate to inert nitrogen gas through denitrification. Dissolved inorganic carbon (i.e., CO_2, CO_3^{2-}, HCO_3^-, and H_2CO_3) is also produced during denitrification, which when combined with the provided calcium leads to calcium carbonate precipitation. Biogenic gasses desaturate the soil, thereby reducing the liquefaction potential of soil by dampening pore pressure build-up during a cyclic shaking event (Eqns [11-16]) (Dejong et al., 2014; O'Donnell et al., 2017b). The precipitation of calcium carbonate mitigates liquefaction through the same hazard mitigation method as MICP, by improving the strength and dilatancy of soil (Eqn [17]) (O'Donnell et al., 2017a; Hall, 2021).

When aiming to mitigate liquefaction, MID may be preferred over MIDP since treatment via desaturation is reached before sufficient carbonate precipitation occurs to provide liquefaction mitigation (Hall et al., 2022b). Additionally, a greater amount of calcium acetate and calcium nitrate are required for carbonate precipitation, increasing costs and environmental impacts.

An advantage of MID and MIDP is that microorganisms do not need to be cultivated and injected into the soil since denitrifying microorganisms are widely found across various soil types, reducing costs (Hall et al., 2018). Another advantage of the processes is that users extract groundwater from the treatment site to dissolve and mix the substrates then, this water is re-introduced to the ground in a closed system with no external input of water. Existing groundwater technology, including injection and extraction wells, can be used to implement MID and MIDP (Moug et al., 2022).

Ongoing field trials of MID have demonstrated a desaturation persistence of at least 92 days, the length of the experiment when monitoring ceased (Moug et al., 2022). While longer-term trials of MID have not been conducted yet and the durability of desaturation has not been robustly tested, previous studies have indicated that abiotic desaturation can persist for up to 26 years (Okamura et al., 2006).

Benefits of MID and MIDP are the lack of waste products generated. For example, when the MID and MIDP reactions occur to completion, the products, nitrogen gas and carbon dioxide, do not need to be removed as is with EICP and MICP. It is unlikely that a significant amount of carbon dioxide will be released to the atmosphere through this process because of the typical pH levels of application sites and the high solubility of CO_2, leading the majority of produced CO2 to remain in solution (Hall, 2021).

Complications of MID and MIDP include the impact that the primary and intermediary products can have on technical feasibility and environmental impacts. For example, the hydraulic conductivity of the soil may be reduced by the production of nitrogen gas and carbon dioxide gas and this may impact flow of the substrates through the soil (Stallings Young et al., 2021). Further, if the reaction is incomplete, process intermediates (primarily nitrite, but potentially nitrous and nitric oxide) may accumulate (Hall, 2021). The accumulation of these intermediates are potentially toxic and harmful to the environment. Intermediates also inhibit denitrification and can lead to reduced precipitation and desaturation (Eqns [13,15]) (van Paassen et al., 2010b; Hall, 2021).

$$Ca(CH_3COO)_{2(aq)} \leftrightarrow Ca^{+2}_{(aq)} + 2CH_3COO^-_{(aq)} \quad (11)$$

$$Ca(NO_3)_{2(aq)} \leftrightarrow Ca^{+2}_{(aq)} + 2NO^-_{3(aq)} \quad (12)$$

$$\frac{1}{2}NO^-_{3(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \rightarrow \frac{1}{2}NO^-_{2(aq)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (13)$$

$$NO^-_{2(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + H^+_{(aq)} \rightarrow NO_{(aq)} + \frac{5}{8}H_2O_{(l)} + \frac{1}{8}CO_{2(aq)} + \frac{1}{8}HCO^-_{3(aq)} \quad (14)$$

$$NO_{(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \rightarrow \frac{1}{2}N_2O_{(aq)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (15)$$

$$\frac{1}{2}N_2O_{(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \rightarrow \frac{1}{2}N_{2(g)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (16)$$

$$Ca^{+2}_{(aq)} + CO^{-2}_{3(aq)} \leftrightarrow CaCO_{3(s)} \quad (17)$$

2.4. Systematic Literature Review Protocol

We conducted a systematic literature review of published ground improvement studies, including journal articles, conference papers, book chapters and industry reports. We completed a literature search following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021). The databases utilized for the literature search were Web of Science, Scopus, and the American Society of Civil Engineers (ASCE) databases. We identified articles by searching abstracts using the search term: (“sustainability” OR “life cycle” OR “cost” OR “economic” OR “carbon” OR “energy”) AND (“EICP” OR “MICP” OR “carbonate precipitation” OR “microbially induced desaturation” OR “biocement” OR “biogrout” OR “bio-grout” OR “bio-mediated” OR “bio-mediated” OR “bioinspired” OR “bio-inspired”) AND (“assessment” OR “analysis” OR ”footprint”). The resulting studies were then reviewed for relevance and duplication to arrive at a final set of studies that met our review criteria. We further sought to identify studies that may have been overlooked in the database searches by screening the references cited in the relevant studies that were found via database.

2.4.1. Process for Identifying Relevant Literature

To respond to the research goals of this study, which include an assessment of the relative frequency of sustainability assessment of bio-mediated and bio-inspired ground improvement technologies compared to conventional methods, we also conducted a literature review of quantitative sustainability assessments applied to conventional ground improvement techniques. The flow chart for this literature search is presented in Figure S- 1 in the Supplementary Information.

We reviewed each of the identified sustainability assessment studies with specific focus on the following parameters:

- Application (e.g., EICP, MICP, MIDP)
- Functional unit
- System boundary
- Life cycle inventory
- Biogeochemical reactions
- Life cycle impact assessment

- Results
- Uncertainty assessment

The goal of examining these parameters is to examine variability across the methods and modeling choices in existing studies, which determines the comparability and comprehensiveness of studies that reflect the current state of practice. The greater the variability in methods and key assumptions, the less comparable study findings are likely to be.

We also document the findings of the reviewed studies, with the goal of making recommendations for reducing the environmental impacts and cost of bio-mediated applications.

2.4.2. Methods for Systematic Review

Scopus returned 21 references, Web of Science returned 18 references, and the ASCE database returned two references. As shown in Figure 1, we screened these references for relevance to identify ground improvement related EICP, MICP, MID or MIDP studies such as those that reference soil stabilization or liquefaction mitigation. Only studies that completed a quantitative sustainability assessment, such as an LCA, an LCCA, S-LCA were chosen for this review. One study identified is a techno-economic analysis (TEA), however, this is considered as an LCCA in this review since the methods followed align with those of an LCCA. Studies that assessed bio-mediated or bio-inspired methods that can be applied to ground improvement even when they were not used in ground improvement applications were also included; however, those applied to structures, such as carbonate precipitation within concrete, were not included since the function of these technologies differs to ground improvement. After screening relevant studies for duplicates, five unique studies remained. After screening the citations of these studies, an additional two studies were identified that met the search criteria, one of which was an industry report. An additional paper was identified outside of the systematic review via knowledge of the authors. We identified eight sustainability assessment studies in total. Seven of these studies are life cycle assessments, two of which also include a life cycle cost assessment, and one is the TEA considered as an LCCA.

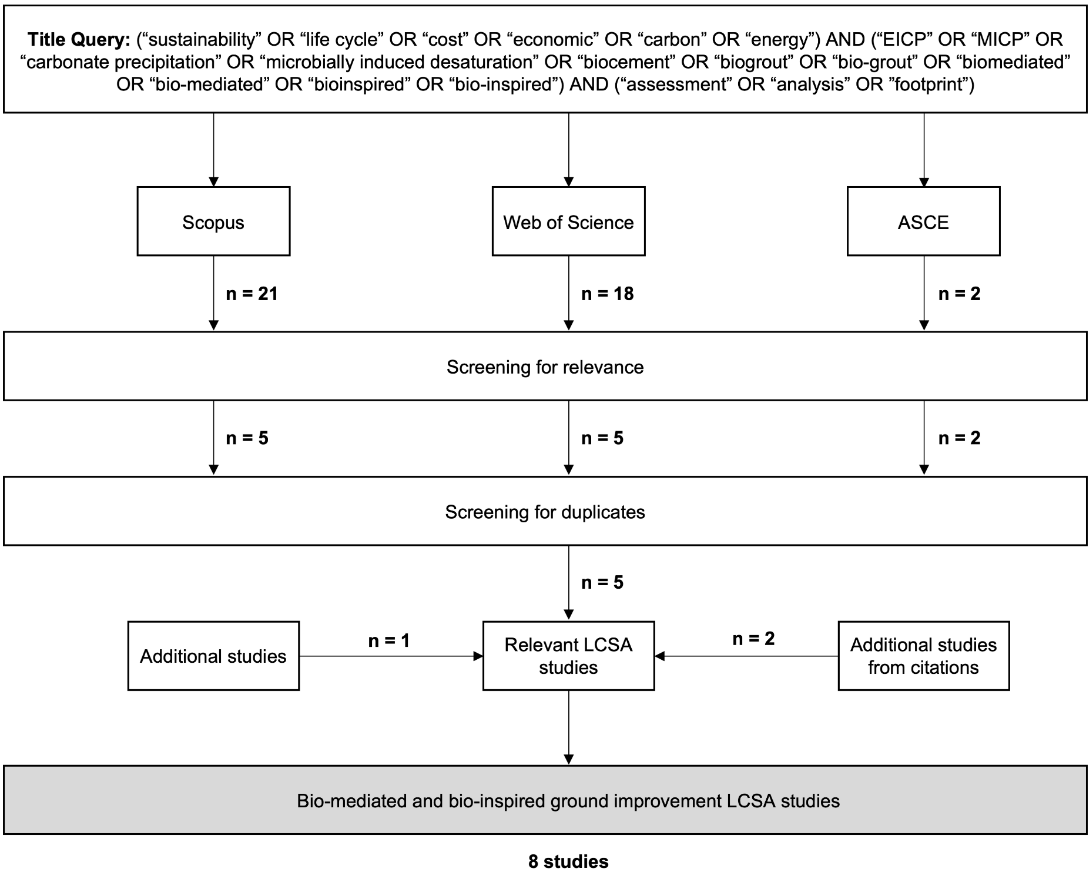

Figure 1. Flow diagram of the systematic literature search

2.5. Results

2.5.1. Articles Identified through Systematic Literature Review

Eight studies published between 2009 and 2023 were identified, three of which evaluate EICP, three evaluate MICP, one evaluates MID and MIDP, and one evaluates MID only. A summary of these studies is provided in Table 2. Six of these studies assess either one or multiple bio-mediated technologies or pathways and compare them to a traditional, cement-based ground improvement technique. Meanwhile, Martin et al. (2020) only provides a hotspot analysis of EICP in which they identify the key areas across the EICP life cycle where impacts are highest. Each study is a process-based LCA considering environmental impacts or cost. None of the identified studies includes a social life cycle assessment.

Table 2. Summary of identified sustainability assessment studies of bio-mediated and bio-inspired geologic hazard mitigation techniques

Primary Author (Publication Year)	**Publication Type**	**Location**	**Application**	**Sustainability Assessment**	**Functional Unit**	**Technologies**
Suer (2009)	Journal Article	Sweden	Roadway	LCA and LCCA	1 m^3 treated soil	MICP
Salemans (2010)	Industry Report	The Netherlands	Railway Track	LCA	The strengthening of 1000 m^3 sand layers beneath the railway track between Gouda and Goverwelle with a grain size of 0.2 mm to at least 1000 kPa.	MID, MIDP
Martin (2020)	Conference Paper	USA	Liquefaction Mitigation	LCA	Treatment of a 465 m^2 site in the United States (by creating biocemented	EICP

Primary Author (Publication Year)	**Publication Type**	**Location**	**Application**	**Sustainability Assessment**	**Functional Unit**	**Technologies**
					columns at 1.2 m center-to-center spacing that are 5 m in depth and 0.5 m in diameter. The target minimum unconfined compression strength of the treated soil is 250 kPa.	
Porter (2021)	Journal Article	Australia	N/A	LCA	1 kg of precipitated calcium carbonate	MICP, MIDP

Primary Author (Publication Year)	Publication Type	Location	Application	Sustainability Assessment	Functional Unit	Technologies
Deng (2021)	Journal Article	China	Foundation Reinforcement	LCA	1 tonne $CaCO_3$	MICP
Alotaibi (2022)	Journal Article	UAE	Roadway	LCA	A poorly graded native soil area of 10,000 m^2 (25 m by 400 m) to serve as an unpaved road for light vehicles	EICP
Hall (2022a)	Conference Paper	USA	Liquefaction Mitigation	LCCA	6.1 m (depth) x 24.4 m (width) x 12.2 m (length)	MID

Primary Author (Publication Year)	Publication Type	Location	Application	Sustainability Assessment	Functional Unit	Technologies
Raymond (2023)	Book Chapter	USA	Liquefaction Mitigation	LCA and LCCA	0.14 m^3 soil treated to a target shear wave velocity of 150 m/s	MICP

The life cycle studies considered ground improvement applications, including soil stabilization for roadways and railways, foundation reinforcement, and liquefaction mitigation. Porter et al. (2021) did not provide a specific application for MICP, instead focusing on the production of calcium carbonate only. Each EICP and MICP life cycle study considered a urea hydrolysis pathway. Porter et al. (2020) also evaluated another five pathways for MICP including denitrification (MIDP).

The frequency of LCSA applied to biogeotechnologies compared to conventional technologies has been uneven over time, but biogeotechnologies are over-represented in the literature relative to their frequency of application in real world projects. Figure 2 shows the results of literature reviews for both biogeotechnologies and conventional based on the number of studies published per year between 2009 (the first year an LCSA of a ground improvement technology was published) and 2023. What is evident, is that there has been uneven growth in LCSA-related studies since 2009, but that biogeotechnology LCSAs are growing in popularity alongside conventional ground improvement LCSAs.

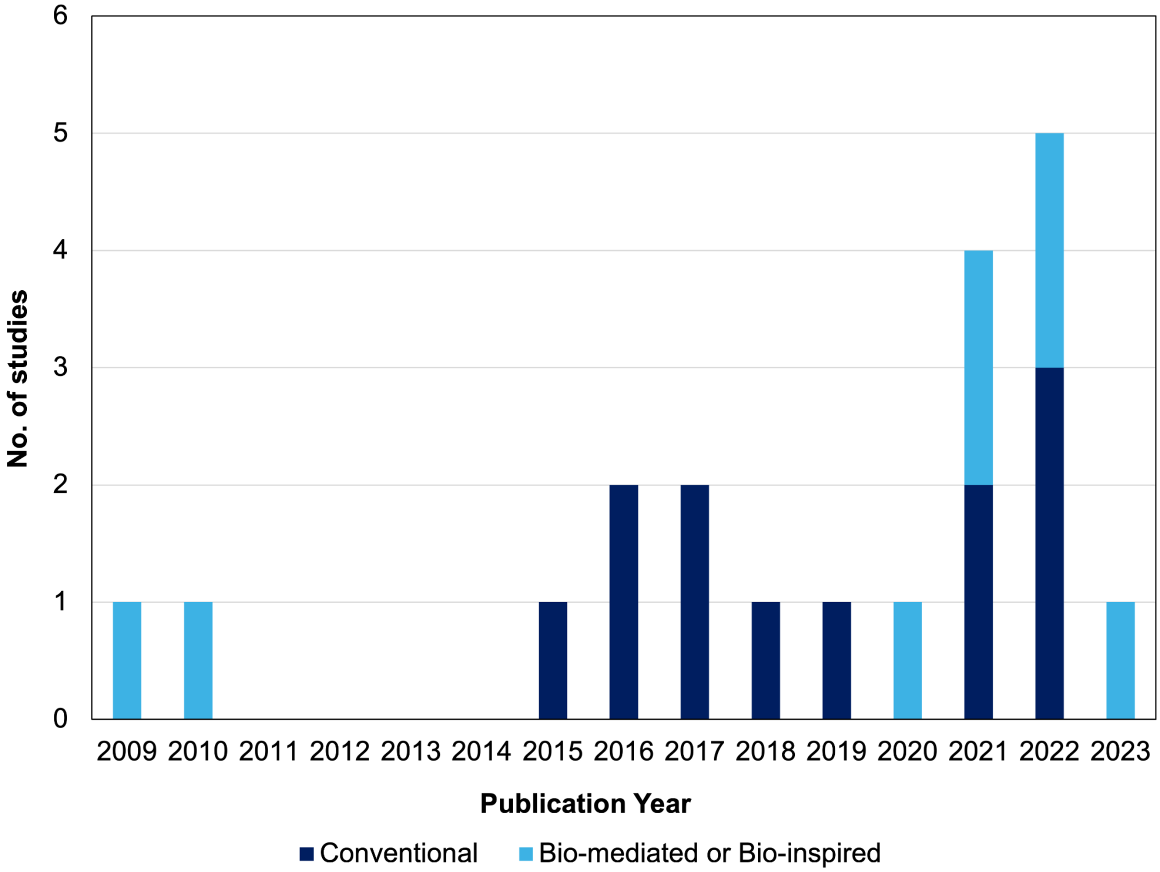

Figure 2. LCSA studies of conventional and bio-mediated or bio-inspired ground improvement technologies

2.5.2. Critical Review

Functional Unit

The functional unit of an LCSA serves as the basis for which technologies are evaluated over and compared (ISO, 2006a). The functional unit should specify the service provided by a ground improvement project and include relevant performance requirements such as the target strength of a soil structure (Kendall et al., 2018). Further, for bio-mediated technologies, because they often require multiple treatments over the service life of a project, the functional unit of a study should specify the duration of the project.

The functional unit of each reviewed study varies between those focused only on mass of carbonate produced or an area or volume of soil treated and those that also included performance requirements for the technologies considered (Table 2). Martin et al. (2020) and Salemans & Blauw (2010), use the most comprehensive functional units, specifying the volume of soil treated, target strength, and location of the study. Salemans and Blauw (2010) also specify soil grain size in their functional unit. No study considers service life in the functional unit. As such, no study evaluates impacts from potential re-applications of bio-treatment required over the service life of the projects.

Poorly defined functional units can result in an unfair comparison across technologies. For example, Porter et al. (2021), compare the production of 1 kg of precipitated calcium carbonate from various pathways; however, leaving performance requirements out of the functional unit omits potential differences in the service provided by each pathway. For example, MIDP produces calcium carbonate as well as nitrogen which provides mitigation against liquefaction through MID. For a fair comparison, each system must provide the same services.

System Boundary

Each reviewed study only considers the construction stage of the assessed ground improvement projects and within this stage, raw materials supply is the most assessed process (Table 3). Suer et al. (2009), provide the most comprehensive system boundary considering materials transportation, equipment mobilization, on-site equipment use, biogeochemical emissions, and construction waste transportation in addition to raw materials supply. The authors only, however, provide a qualitative assessment of biogeochemical emissions. No studies assess the impacts of quality assurance and quality control and Salemans and Blauw were the only authors to evaluate the impacts of biogeochemical emissions treatment, considering wastewater treatment to remove ammonium chloride from the system. Raymond et al. evaluate impacts of rinsing to remove ammonium, however, they do not include wastewater treatment in their analysis. All studies except Deng et al. (2021), Hall et al. (2022a), and Suer et al. (2009) include a quantitative assessment of the impact that bio-mediated process emissions have on the environment. Deng et al. (2021) and Salemans and Blauw (2010), are the only authors to evaluate the impacts of bacteria cultivation on total MICP impacts.

By omitting the use stage of ground improvement projects, the impact of treatment durability cannot be assessed and the total sustainability impacts may be underestimated if potential treatment re-applications are not evaluated. While the durability of treatment is currently unknown for EICP, MICP and MIDP, sensitivity analysis can be employed to assess the potential impact of treatment re-applications over the service life of the infrastructure.

Table 3. Life cycle processes for the construction stage considered in the system boundary of each reviewed study

	Technology			Assessment			System Boundary									
Primary Author (Publication Year)	**EICP**	**MICP**	**MIDP**	**LCA**	**LCCA**	**S-LCA**	**Raw Material Supply**	**Material Processing**	**On-site Fuel Supply**	**Bacteria Cultivation**	**Materials Transportation**	**Equipment Mobilization/Demobilization**	**Equipment Operation & Emissions**	**Process Emissions**	**QA/QC**	**Waste Management**
Suer (2009)		●		●	●		●	●	●		●	●	●	●		●
Salemans (2010)		●	●	●			●	●	●	●	●			●		●

	Technology			Assessment			System Boundary									
Primary Author **(Publication Year)**	**EICP**	**MICP**	**MIDP**	**LCA**	**LCCA**	**S-LCA**	**Raw Material Supply**	**Material Processing**	**On-site Fuel Supply**	**Bacteria Cultivation**	**Materials Transportation**	**Equipment Mobilization/Demobilization**	**Equipment Operation & Emissions**	**Process Emissions**	**QA/QC**	**Waste Management**
Martin (2020)	•			•			•							•		
Porter (2021)		•			•		•							•		

	Technology			Assessment			System Boundary									
Primary Author (Publication Year)	**EICP**	**MICP**	**MIDP**	**LCA**	**LCCA**	**S-LCA**	**Raw Material Supply**	**Material Processing**	**On-site Fuel Supply**	**Bacteria Cultivation**	**Materials Transportation**	**Equipment Mobilization/Demobilization**	**Equipment Operation & Emissions**	**Process Emissions**	**QA/QC**	**Waste Management**
Deng (2021)		•		•			•			•						
Hall (2022a)			•		•		•	•				•	•			

	Technology			Assessment			System Boundary									
Primary Author **(Publication Year)**	**EICP**	**MICP**	**MIDP**	**LCA**	**LCCA**	**S-LCA**	**Raw Material Supply**	**Material Processing**	**On-site Fuel Supply**	**Bacteria Cultivation**	**Materials Transportation**	**Equipment Mobilization/Demobilization**	**Equipment Operation & Emissions**	**Process Emissions**	**QA/QC**	**Waste Management**
Alotaibi (2022)	●			●			●	●			●		●	●		
Raymond (2023)		●		●	●		●							●		

Life Cycle Inventory

Transparency of methods used to develop a life cycle inventory (LCI) for each technology vary, with Suer et al. (2009) providing the most detailed information including primary data sources. Hall et al. (2022a) also use primary data from industry and provide transparent unit costs and calculations for their cost assessment. Due to lack of transparency regarding the models used by the other authors, reproducibility of these studies is low. The LCI databases utilized also vary and it should be noted that many studies utilize datasets from old databases which may not reflect current industry practices (Table 4). Further, life cycle inventory datasets are not currently available for key material inputs such as jack beans for EICP, with Martin et al. using a dataset on soybean production as a proxy for Jack Beans (Martin et al., 2020). None of the studies provide a complete life cycle inventory for the technologies assessed and this in addition to low reproducibility means that it is difficult to use this data in other sustainability assessments such as extensions of those published or applications to broader construction projects.

Table 4. Life cycle inventory and impact assessment methods

Study (Publication Year)	LCI Databases	Impact Assessment Model
Suer (2009)	Various literature sources and industry	N/A
Salemans & Blauw (2010)	ecoinvent (version unknown)	Eco-Indicator 99
Martin (2020)	ecoinvent 2.2	ReCiPe, TRACI
Porter (2021)	ecoinvent 2.2	AUSLCI, Cumulative Energy Demand 2.01
Deng (2021)	Not provided	Not provided
Alotaibi (2022)	ecoinvent 3.0	CML-IA
Hall (2022a)	Industry	N/A
Raymond (2023)	Not provided	Not provided

Biogeochemical Reactions

Consideration of the factors that influence the sustainability and technical feasibility of bio-mediated technologies, as outlined in Section 2, is limited for each study. All studies assume that reagent utilization is 100% efficient, omitting impacts from potentially unreacted material inputs, and only one study evaluates the impact of intermediary products on the environment. Salemans and Blauw (2010) assume that incomplete denitrification takes place for MID where 10% of the nitrogen input into the system for MID is converted to NOx and N2O. No study evaluates the reaction rate of the relevant biogeochemical processes, and none address durability of the treatment provided. As such, the studies potentially underestimated impacts as it is likely that treatment will need to be repeated over the service life of the infrastructure project. Further, the studies do not allow for a comparison of technical feasibility since the reaction rate and durability of each treatment is unknown.

Life Cycle Impact Assessment

Global warming potential and eutrophication potential are the most assessed impact categories in the identified studies with six studies quantifying each (Table 5). Four studies evaluate energy use and only two assess the cost of the evaluated technologies. No study assesses the social impacts of bio-mediated or bio-inspired ground improvement techniques. Salemans and Blauw (2010) assess the most comprehensive list of impact categories. However, the impacts are presented as a normalized Eco-Indicator 99 value making it difficult to discern the individual impacts and compare them with other technologies. Eco-Indicator 99 is a method used to weight various environmental impacts, producing a single impact score which can be used to compare different technologies (Goedkoop, 2007). While Suer et al. (2009) only quantify the energy use and cost of MICP, the authors do provide a qualitative assessment of the additional impact categories that each system input contributes to. The impact assessment models used vary across the studies making it difficult to complete direct comparisons of results (Table 4).

Table 5. Indicators assessed in each reviewed study

	Indicators														
Primary Author (Publication Year)	**Global Warming**	**Ozone Depletion**	**Acidification**	**Eutrophication**	**Human Health**	**Photochemical Ozone Formation**	**Ecotoxicity**	**Land Use**	**Smog Formation**	**Water Consumption**	**Particulate Matter**	**Energy**	**Cost**	**Social**	**Other**
Suer (2009)												●	●		
Salemans (2010)	●	●	●	●	●		●	●							●
Martin (2020)	●			●								●			

Primary Author (Publication Year)	Indicators														
	Global Warming	Ozone Depletion	Acidification	Eutrophication	Human Health	Photochemical Ozone Formation	Ecotoxicity	Land Use	Smog Formation	Water Consumption	Particulate Matter	Energy	Cost	Social	Other
Porter (2021)	●			●								●			
Deng (2021)	●		●	●		●					●	●			●
Hall (2022a)													●		
Alotaibi (2022)	●		●	●											●
Raymond (2023)	●			●								●			

Comparability of Assessments

A direct comparison of results cannot be achieved since the functional unit of each study varies and not enough information has been provided by the authors to normalize results to a consistent functional unit. For the studies that provide a hotspot analysis of bio-mediated or bio-inspired technologies, while they do not evaluate impacts relative to traditional technologies, the results can be used to determine the scale of possible impact reductions. For example, the impact of process emissions on the total global warming potential and eutrophication potential of each technology is reported to be significant compared to material production impacts which suggests that notable reductions could be achieved by capturing, avoiding, or treating these emissions. Additionally, data from these studies can be used to determine the potential impact reductions achieved by replacing commercial material inputs with alternative materials such as waste products from other industries. Further, some conclusions can be drawn regarding the ideal study scope for bio-mediated and bio-inspired studies as described below.

Project scale assessments are preferred over laboratory-scale studies because laboratory-scale assessments can distort performance and cost estimates. For example, LCCA calculations based on laboratory-scale data typically overestimate costs due to use of high-quality reagents that are not bought in bulk. Suer et al. (2009) report the cost of MICP at $2,554 per m3 of soil treated for a project-scale assessment and note that raw materials account for about 20% of the total cost. However, for treatment of a 0.14 m3 lab-scale soil column, Raymond et al. (2023) report a materials cost of $1,800. Scaling the Raymond et al. (2023) results lead to a cost of $12,857 per m3 suggesting that lab-scale cost data does not scale well to project applications.

Project-scale assessments are also more ideal because processes such as equipment rental and mobilization can only be modeled at this scale. While all other studies omit these processes, Suer et al. (2009), and Hall et al. (2022a) show the importance of including equipment rental, mobilization, and use emissions in LCSA. These can have high impacts on the energy use and cost of ground improvement techniques. Suer et al. (2009) find that these processes contribute to 61.4% of the energy use of jet grouting and 22% of the energy use of MICP. For cost, these contributions are 62.6% and 77.1% for jet grouting and MICP, respectively. Hall et al. (2022a) find that equipment and labor for installation and mobilization account for 57.8% of the total cost of MID and 44.5% of the total cost of permeation grouting.

For MICP, bacteria cultivation is another stage that should be evaluated since Deng et al. (2021) find that this accounts for 20% of materials production impacts. The system boundary for MICP must also include treatment of the effluent that remains after ammonium rinsing since this can present a high contribution to total results (Salemans and Blauw, 2010).

Uncertainty Assessment

Only two studies complete a sensitivity analysis of model input parameters and two studies performed scenario analyses. Alotaibi et al. investigate the impact of field emission assumptions and using waste non-fat milk as an input to the EICP process. By eliminating field emissions and using waste milk, the GWP of EICP can be reduced by 54% from a case where virgin milk powder is used and an upper bound of field emissions is considered. The eutrophication potential can be reduced by 92% for the same change in scenario. The authors do not, however, provide recommendations for how to eliminate EICP field emissions. The authors also provide a sensitivity analysis on the target unconfined compressive strength (UCS) of the soil demonstrating an exponential increase in environmental impacts as target UCS increases. The authors compare EICP to MICP using data from Deng et al. (2021) and show that at a target UCS of less than 1.5 MPa, EICP is favorable over MICP with regards to GWP. Deng et al. (2021), also demonstrate an exponential increase in GWP and energy demand as the target UCS of MICP-treated soil is increased. Deng et al. (2021) evaluate the relationship between MICP treatment, quantified as calcium carbonate content, and UCS based on a review of ten experimental MICP studies.

Raymond et al. (2023) provide the most comprehensive scenario analyses for the pathways of MICP assessing the impact of: reducing urea inputs, eliminating sodium acetate inputs, rate of ureolytic stimulation and augmentation, and ammonium rinsing. The authors demonstrate that a reduced urea input can reduce the GWP of MICP by roughly 20% and this in addition to removing sodium acetate as an input to the process can reduce the GWP by 29%. For this second scenario, the cost of MICP is reduced by 55%. Experimental work has shown that the urea reduction modeled by Raymond et al. (2023) can provide the same level of MICP treatment as provided by the baseline study (Gomez et al., 2018). The authors do not provide any potential differences in performance due to the removal of sodium acetate from the MICP inputs. Raymond et al. (2023) also report that a case with low ureolytic stimulation results in the lowest impacts while high ureolytic augmentation creates the highest impacts across GWP, eutrophication potential, and cost. While ammonium rinsing has a low impact on the GWP and cost of MICP, it provides significant reductions in eutrophication potential. For a case with low ureolytic stimulation, ammonium rinsing can reduce the eutrophication potential of MICP by 66%. Raymond et al. (2023), do not, however, discuss treatment solutions, or their environmental impacts, for the rinsed ammonium.

2.6. Recommendations for Sustainable Geologic Hazard Mitigation

To develop and implement sustainable geologic hazard mitigation techniques, critical issues highlighted above for bio-mediated and bio-inspired solutions must be resolved through alternative methods such as those presented in Table 6. This includes using substitutes for materials such as urea and urease enzymes and reducing transportation impacts to reach the full potential of environmental benefits of EICP, MICP, and MIDP.

Table 6. Alternative, sustainable design recommendations for bio-mediated and bio-inspired ground improvement technologies

Bio-mediated Technology	**Design Alternatives for Improved Sustainability**
EICP	• Replace commercial urease with alternative sources such as soybeans, jackbeans, and watermelon seeds (Javadi et al., 2018; Khodadadi et al., 2020; Lee and Kim, 2020). • Replace synthetic urea with recycled urine (Martin et al., 2020; Crane et al., 2022). • Replace non-fat milk powder with waste milk (Martin et al., 2020). • Collect and reuse unreacted urea and calcium chloride (Almajed et al., 2018).

MICP	• Replace synthetic urea with recycled urine (Chen et al., 2019). • Reduction of urea input (Raymond et al., 2023). • Collect and treat ammonium chloride such as through rinsing (Lee et al., 2019; San Pablo et al., 2020). • Reuse collected ammonium for fertilizer production (Yu et al., 2021). • Use food-grade yeast for bacteria cultivation instead of lab-grade media (Omoregie et al., 2019).
MIDP	• Seek out local substrate for calcium nitrate and calcium acetate to reduce shipping • Use site-specific water to mix added substrate (i.e., not introduce external water) (Hall et al., 2022b) • Target desaturation over precipitation when possible (Hall, 2021)

There are also barriers to implementation at the project scale. An example relates to the requirement of MICP bacteria cultivation on site which is yet to be demonstrated on a large-scale

(Terzis and Laloui, 2019). Another barrier is the disconnect between existing engineering design codes and the design methods that relate to bio-mediated and bio-inspired technologies. Related to this is the lack of formal education of engineers and scientists in biogeotechnics (DeJong et al., 2010). Further, for successful implementation of these solutions, a shift in how hazard mitigation projects are currently managed is needed since these projects require assessment from a biological perspective which is not current practice in geotechnical engineering. Finally, use of bio-mediated and bio-inspired geotechnical technologies requires interdisciplinary collaboration such as between geotechnical engineers and ecologists across each project stage of a biogeotechnical hazard mitigation project to ensure success (DeJong et al., 2015).

With regards to impact, each potential bio-mediated or bio-inspired alternative must be evaluated for its sustainability and technological performance to assess whether they reduce social, environmental, and economic impacts on a life cycle basis. Quantitative sustainability assessment, such as through LCSA, must be adopted to assess the technological and sustainability impacts of such technologies and drive their sustainable development. Clear LCSA guidelines are needed to facilitate the production of high-quality sustainability data on traditional, bio-mediated and bio-inspired technologies to allow for useful comparisons and to guide decision-making (Kendall et al., 2018; Song et al., 2020; Samuelsson et al., 2021). One issue regarding the adoption of LCA for ground improvement applications is the high cost of reference life cycle assessment data, which are often derived from commercial databases and are crucial for conducting an LCA (Cho et al., 2017). A standardized approach to geotechnical LCSA can assist in developing an open database of comparable and transparent life cycle data. Guidelines for standardizing geotechnical LCSA would also improve reproducibility of studies, would allow for comparison across studies, could facilitate integration into the geotechnical design process, and could lower the cost and barriers to conducting LCSA by supporting the development of open-source reference life cycle inventories for geotechnical processes and technologies.

Social assessment is important in holistically assessing the sustainability of a project and such guidelines must facilitate the assessment of the direct and indirect social impacts across ground improvement projects. While this is yet to be done for geotechnical projects, some construction-related studies have presented social impact assessments. For example, in one study comparing concrete and steel for use as building materials in Iran, the authors found that for impacts in many categories including health and safety and cultural heritage, steel resulted in more impacts, while concrete materials resulted in higher impacts for working conditions (Hosseinijou et al., 2014). Further, Dong and Ng (2015) present a social impact assessment methodology, the Social-Impact Model of Construction (SMoC), to evaluate construction projects based on expert surveys to determine the most important social impacts. The authors find that social impacts are higher during materials procurement than on-site construction processes.

For the successful project-scale and sustainable implementation of bio-mediated and bio-inspired geotechnical solutions, the barriers listed above must be addressed, including the lack of existing guidance regarding completion of LCSA. Adoption of LCSA across geologic hazard mitigation has the potential to reduce the social, environmental, and economic impacts that infrastructure and the built environment have on communities. Facilitating this adoption through a clear and comprehensive methodology for LCSA is crucial in realizing the influence that LCSA can have on sustainable development.

2.7. Conclusion

Emerging biogeotechnologies, including EICP, MICP and MIDP, are steadily gaining popularity as alternative ground improvement techniques for geologic hazard mitigation. While sustainability gains have been a key driving factor behind the development of these technologies, each technology still carries concerns regarding environmental impact, and the social impacts of these technologies are currently unknown. Further, current sustainability assessment methods do not allow for the production of high-quality and comparable data. For example, existing studies do not use comprehensive functional units which address the service provided by each technology. Existing studies also do not assess the whole life cycle of ground improvement projects from site investigation to construction, use, and end-of-life, though this is needed for a comprehensive assessment. These studies are largely not reproducible or transparent in their data collection methods and outdated datasets are commonly used which limits applicability of these studies to existing and future projects. A major drawback of the studies examined in this review is the lack of assessment of uncertainty across the project life cycles and potential by-products regarding the core biogeochemical processes that are induced by bio-mediated and bio-inspired technologies.

This review shows that quantitative sustainability assessment, such as LCSA, should be used to understand the impacts of bio-mediated technologies and identify areas where impact reductions can be made. Clear guidelines are needed to produce open, reproducible, and comparable LCSA for geotechnical applications such as ground improvement. These guidelines should provide clear advice about the selection of functional unit and system boundaries. Further, guidelines are needed to assist in the development of a life cycle inventory and completion of a life cycle impact assessment and uncertainty assessment. For emerging technologies, uncertainty assessment is particularly crucial since there is limited data available regarding the project-scale performance of such technologies as well as the industrial-scale production of bacterial and material inputs.

LCSA must include a social assessment and must be completed alongside a technological assessment. This must include an evaluation of impacts due to biogeochemical reactions as well as an assessment of performance such as through reagent utilization, degree of ground improvement provided for the given function, reaction rate, and durability. In tandem with these comprehensive biogeotechnical LCSAs, those of conventional ground improvement technologies must continue in development to provide baseline sustainability metrics against which emerging technologies can be compared.

3. FRAMEWORK FOR WHOLE LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ASSESSMENT OF GEOTECHNICAL EARTHQUAKE MITIGATION TECHNIQUES: A CASE STUDY ON PERMEATION GROUTING

3.1. Introduction

Life cycle assessment (LCA) has emerged as a key tool to evaluate and guide the sustainability of geotechnical engineering projects (Kendall et al., 2018; Song et al., 2020; Samuelsson et al., 2021). However, existing studies and frameworks do not capture the complete life cycle of such projects (Faruqi et al., 2023). Instead, they typically focus only on the construction stage of a project, omitting site investigation activities which are crucial in guiding geotechnical design (Littlejohn et al., 1994; Simons et al., 2002), as well as omitting the use and end-of-service-life stages. Further, while the use of LCA to evaluate geotechnical systems is growing, no guidance has been proposed for the completion or standardization of geotechnical LCA (Kendall et al., 2018; Samuelsson et al., 2021; Song et al., 2020). Also, existing studies have a limited scope regarding the project activities modeled and typically only assess a few impact categories (Kendall et al., 2018; Samuelsson et al., 2021; Song et al., 2020; de Melo et al., 2023) (Kendall et al., 2018b; Song et al., 2020; Samuelsson et al., 2021). Further problems have been identified with existing studies such as poor transparency regarding background processes including data sources and specific information on datasets used (Kendall et al., 2018). Additionally, while scenario analysis has been widely employed to assess the impact of uncertain choices or outcomes, quantitative uncertainty assessment is less common across geotechnical LCA (Song et al., 2020; Kendall et al., 2018).

Efforts have been made to standardize LCA within the construction sector but have typically focused on standardizing LCA at the material or product-level (e.g., Portland cement or steel beams) (Scalisi, 2022). For example, product category rules (PCRs) are developed to guide environmental product declarations (EPDs), and PCRs have been developed for many construction products (Ingwersen et al., 2013). These EPDs present the life cycle impacts of the manufacturing of construction products. No PCR or EPD has yet been published for geotechnical applications. Moreover, based on a review of available PCRs and EPDs, none have been generated for emerging technologies and materials used in geotechnical engineering projects. Yet policies, like the Inflation Reduction Act of 2022 in the United States, are coming into place that require EPD information to improve sustainable infrastructure design (Yarmuth, 2022). PCRs and EPDs at the material or product level are insufficient for characterizing the impacts of geotechnical technologies; clear guidelines on how to complete a geotechnical LCA are needed to facilitate development of PCRs and EPDs of geotechnical technologies.

Recently, the concept of whole building life cycle assessment (WBLCA) has become popular across the construction sector as a method of evaluating the environmental impacts of a building across each life cycle stage from raw material supply to end-of-service-life (Bruce-Hyrkäs et al., 2018). This definition of the scope of the LCA is key for buildings since the energy use across a buildings operation can account for more than 80% of the building's life cycle energy consumption (Sartori and Hestnes, 2007). This means that a LCA of only the construction stage of the project is not sufficient to capture the building's full impacts. The concept of whole life cycle assessment and life cycle cost assessment is yet to be explored in the context of geotechnical hazard mitigation projects. However, when evaluating these projects, it is important to assess the activities that occur across each life cycle stage of the project, particularly the use stage where potential damages and remediation activities related to hazards such as earthquakes may have high environmental impacts and costs associated with them.

Site investigation data, which can often be limited due to cost or practicality reasons, provides an understanding of subsurface conditions including geologic structures and soil parameters such as porosity and shear strength. Without a clear understanding of subsurface conditions, cost, time, and material overruns may occur during construction due to unanticipated conditions that require design changes (Clayton, 2001; Goldsworthy et al., 2004; Shrestha and Neupane, 2020). Not only does this impact the estimated sustainability of a project, but inadequate designs, those that do not respond to actual subsurface conditions, may lead to potential failure and safety issues. Subsequent remedial measures will invariably impact materials and energy consumption, and hence the sustainability, of a design (Basu et al., 2015). As such, subsurface uncertainties make it difficult to complete an accurate prospective LCA and LCCA of geotechnical projects before construction takes place. While increasing the scope of a site investigation program to reduce uncertainty in subsurface conditions incurs additional costs, studies have demonstrated that improved site investigation results in overall lower total project costs as it reduces the likelihood of under-designing or over-designing a project (Temple and Stukhart, 1987; Peacock et al., 1992; Jaksa et al., 2005). Developing a comprehensive model of the subsurface is key in evaluating the longevity, resilience, and sustainability of infrastructure (Basu and Lee, 2022; Phoon et al., 2022).

In this study, we present a framework and guidance for the whole life cycle assessment and life cycle cost assessment of geotechnical earthquake mitigation techniques. We provide an example implementation of this framework for a permeation grouting project for soil liquefaction mitigation. This framework aims to fill the existing gap of completing a comprehensive life cycle assessment and life cycle cost assessment in the geotechnical engineering sector.

3.2. Framework for Whole-Life LCA and LCCA

The framework herein lays out a clear structure for whole life cycle assessment and life cycle cost assessment of geotechnical earthquake mitigation projects. The framework aids the standardization of such LCAs and LCCAs. The core aim of the presented framework is to identify the need for evaluation of projects across their whole life cycle and to define the whole life cycle of a geotechnical earthquake mitigation project. The whole life cycle of these projects can be conceived of as two concurrent activity streams: the project stages and the life cycle phases across each of these stages. We define the key project stages as site investigation, construction, use, and end-of-service-life. The life cycle phases across each of these core project stages include raw material supply, materials transportation, materials processing, equipment operation, and waste management (Figure 3). We define each of these stages and phases below. We then provide guidance for completing a geotechnical LCA following the ISO 14040 and 14044 LCA standards.

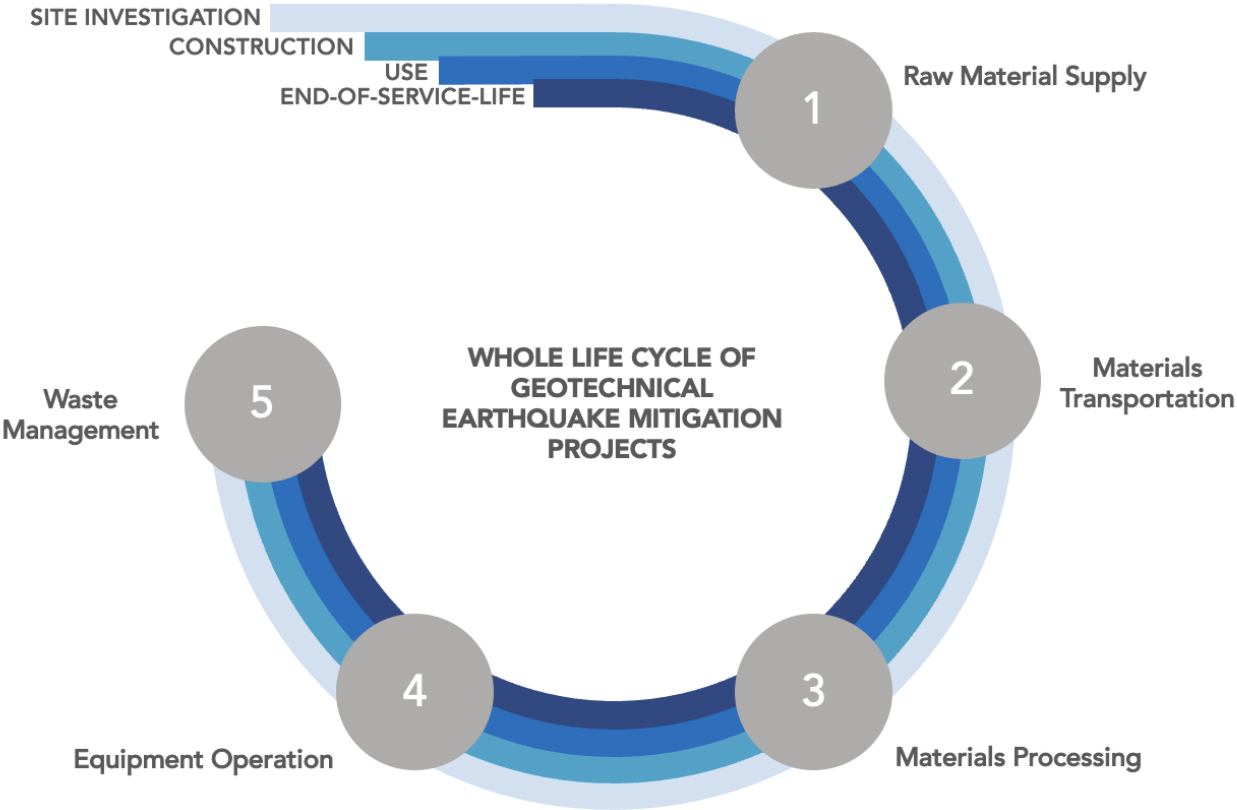

Figure 3. Framework for whole life cycle assessment of geotechnical earthquake mitigation projects

3.2.1. Whole Life Cycle Project Stages

Site Investigation

A site investigation program includes methods and tools that are used to characterize the subsurface, such as borings, cone penetration tests and standard penetration tests. Site investigation programs may be run across the life cycle of a project. For example, a site investigation program may be implemented before initial construction of a structure or ground improvement and then again during the service life of the structure prior to pre-emptive mitigation measures or prior to remedial measures. For each site investigation test, the following sub-activities should be evaluated: equipment mobilization, advancement of the testing equipment through the subsurface, sampling and testing, and grouting of the boreholes left after advancement (Purdy et al., 2022).

Construction

In this framework, we consider the construction stage of a geotechnical earthquake mitigation project as the first implementation of a mitigation measure, e.g. ground improvement. For mitigation below existing structures, this construction stage occurs during the use stage of the structure, after initial construction of the structure itself. For future structures, this construction stage occurs before the construction of the structure. Construction may include ground improvement measures such as deep soil mixing, permeation grouting and bio-inspired or bio-mediated solutions such as MID and EICP.

Use

We define the use stage of a geotechnical earthquake mitigation project as any activities that occur after initial construction of the primary mitigation measure, as described above. This may include the following activities:

- Re-application of treatment measures e.g., further injection of treatment chemicals to sustain gas desaturation provided by MID

- Remedial measures after an earthquake event in the case that mitigation measures do not sufficiently protect the structure. This involves demolition and reconstruction of the primary mitigation measure or an alternative mitigation measure. Reconstruction of the structure itself is left out of the scope of the whole life cycle of a geotechnical earthquake project.

End-of-Service-Life

The end of the project service life is considered in this framework as the end of structures lifetime once no further use stage activities occur. Since, for geotechnical projects, measures such as ground improvement remain in place after the end of the structures service life, this stage is likely to include minor activities only such as decommissioning of treatment wells.

3.2.2. Life Cycle Phases

Each of the project stages described above has its own life cycle from raw materials supply to end-of-life. For example, each activity across the site investigation and construction stages requires the production of raw materials, transportation of those materials to site, processing of those materials, and equipment mobilization and operation either for testing or implementation of an earthquake mitigation measure. The end-of-life of these stages may then include waste management, e.g., from spoils of boreholes, and/or grouting of wells used for grout pumping or testing equipment advancement. In

Table 7 we define each of the core life cycle phases shown in Figure 3 that occur across each stage of a geotechnical earthquake mitigation project.

Table 7. Description of life cycle phases across framework

Life Cycle Phase	**Description**
Raw Material Supply	This stage considers the upstream impacts of all raw materials which are considered as any finished product or material that is processed on-site or in transit to site such as for the case of equipment such as cement trucks. For example, the impacts of manufacturing cement, including the raw materials supply, transportation, and processing of cement production inputs, would be considered in this stage.
Materials Transportation	Materials transportation considers transportation of raw materials, as defined above, from the manufacturing plant to site. It is important that this transportation distance includes the distance between the manufacturing plant and the local supplier and not just the local supplier to site, a common omission that underestimates transportation impacts (Suer et al., 2009). Where possible, the source of materials should be obtained from industry sources to reflect the current marketplace and availability of such materials in the location of the study.

Materials Processing	Impacts from all on-site material processing such as material mixing should be assessed for this phase. This includes, for example, mixing of grout or treatment solutions on-site.
Equipment Operation	Equipment operation here refers to the core activities required either for testing or installation of a mitigation measure, other than materials processing. This phase should include equipment mobilization, demobilization, and any remobilizations over the course of construction e.g. if equipment cannot be left on-site and must be transported to a secure storage yard outside of construction hours. Where possible, equipment operation for quality control and quality assurance activities should also be included in this phase particularly if mobilization of any large equipment is required for these processes.
Waste Management	Waste management here may refer to management of any site investigation or construction spoils, excess materials that cannot be utilized for other projects e.g. if they are damaged. This should include transportation of waste as well as treatment or landfill processes. Additionally, this phase should include management of any groundwater, soil, or air emissions that may occur due to biogeochemical processes eg. flushing of ammonium chloride produced by EICP and MICP.

3.2.3. LCA and LCCA Methodology

To complete an LCA and LCCA that evaluates the whole life cycle of a geotechnical earthquake mitigation project as defined above, we provide guidance following the commonly cited ISO 14040 and 14044 standards (ISO, 2006a, 2006b). These standards present four stages of an LCA: goal and scope definition, life cycle inventory analysis, life cycle impacts assessment, and interpretation. Here, we present an additional stage, uncertainty assessment, as this is a crucial part of understanding and interpreting results (Figure 4). While ISO 14040 and 14044 are focused on LCA and environmental impacts, we recommend using the same structure to evaluate the life cycle costs of a project.

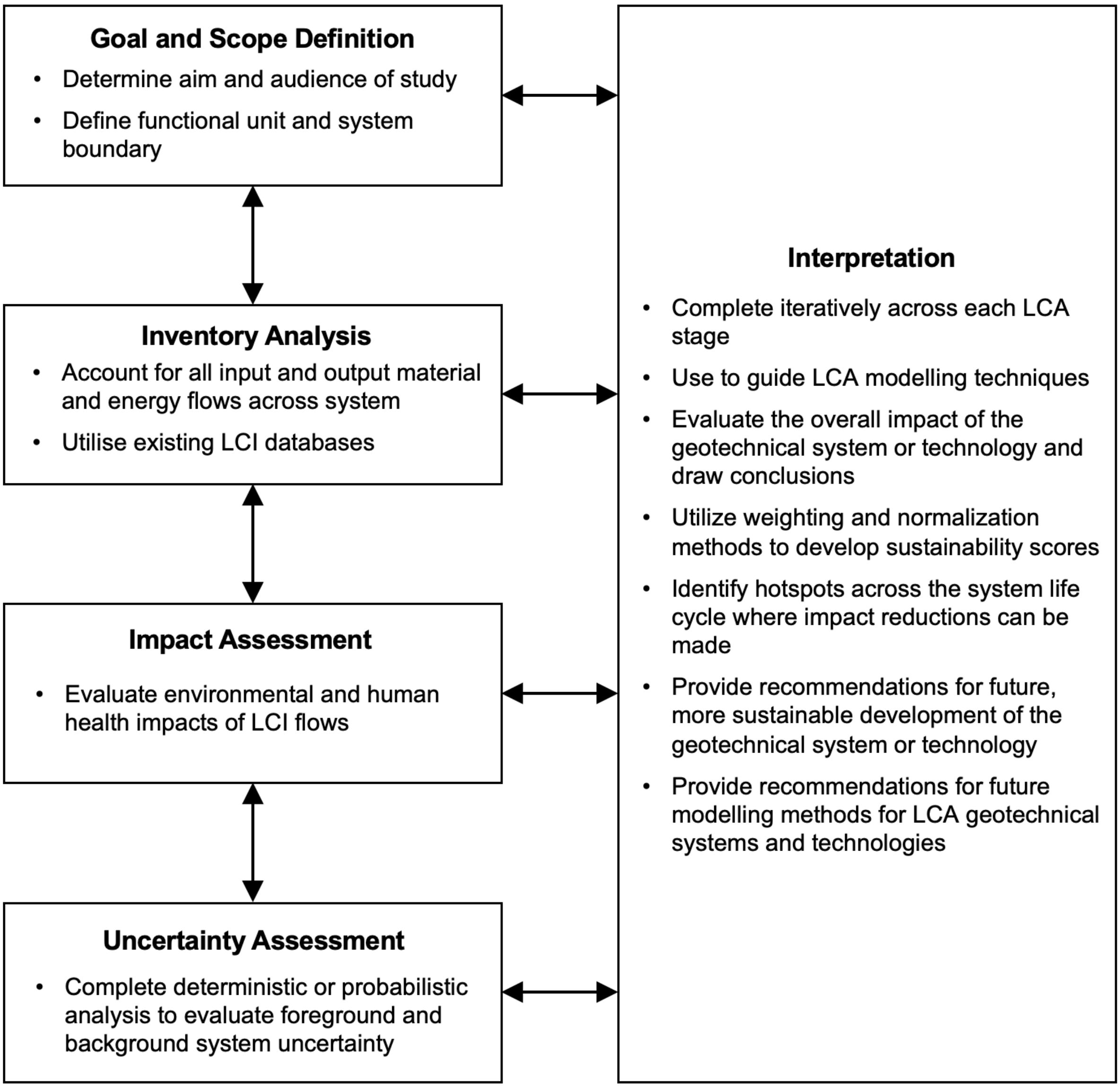

Figure 4. Stages of completing a geotechnical LCA (adapted and elaborated from ISO 14040)

Goal and Scope Definition

The goal and scope definition stage of an LCA involves determining the aim and audience of the assessment. The audience may include project engineers and designers, clients, policy advisors, the community in which a project is constructed, or other stakeholders. The scope of the LCA is then governed by the chosen goal. For example, for a comparative LCA, the scope is dependent on the service provided by each technology. When establishing the scope of the LCA, the functional unit and system boundary must be clearly defined.

Appropriate functional units for geotechnical systems vary across technology types and applications, and hence a standard functional unit cannot be provided. However, some general requirements include specificity in the functional unit with regards to:

- subsurface conditions
- depth and area of treatment
- service life (if the technology involves use phase and/or end-of-life activities)
- performance requirements such as strength and durability requirements

The system boundary and project stages considered in the LCA will be defined by the scope of the study, however, general guidance is provided here. The system modeled can be conceived of in two parts as the foreground system and the background system. The foreground system refers to the project parameters such as the design and construction of the system while the background system refers to the processes and activities that take place to develop each foreground system parameter. For example, the foreground system of a deep foundation installation project may include the consumption of cement and steel for pile construction and transportation of these materials to site. The background system represents the supply chain activities that occur to obtain those materials from their raw material state to their manufactured state on-site. For materials transportation, the foreground parameters would include the transportation distance and type of mode used for transportation while the background system considers, for example, the emissions that are released during production of the fuel required for transportation.

The impact categories assessed in the LCA must be considered when selecting a system boundary since the importance of including certain life cycle phases depends on each of the technologies considered and the dominant inputs and emissions of the phase. For example, bio-mediated process emissions from emerging ground improvement techniques have been shown to have high impacts on eutrophication, necessitating assessment of this impact (Raymond et al., 2021c; Alotaibi et al., 2022).

Life Cycle Inventory

A life cycle inventory, where all material and energy flows and emissions to air, water, and soil are tracked, must be developed based on the foreground system established in the goal and scope stage of the LCA. A project inventory of the foreground system must be completed in which the materials, processes, time, and labor requirements are estimated for each project stage. This stage typically requires input from design and construction engineers or contractors to obtain previous project data such as materials and equipment usage. Particularly with emerging technologies, this stage also requires collaboration with researchers and other stakeholders that can provide the field-scale or expected project-scale performance and implementation of these technologies compared to business-as-usual (BAU) technologies (Raymond et al., 2020). LCA practitioners should provide the underlying models for process- and activity-level data such as construction productivity rates, materials wastage rates, and raw material suppliers. Disaggregating activity-level data allows future practitioners to use relevant data for their projects without needing to source data from industry and/or researchers.

Life Cycle Impact Assessment

The impact assessment method employed shall reflect those that are commonly used in decision-making in the study location. For example, in the United States, the US EPA Tool for the Reduction and Assessment of Chemical (TRACI) should be employed (Bare, 2012). For global warming potential (GWP), the most recent Intergovernmental Panel on Climate Change (IPCC) recommended GWP values for each greenhouse gas shall be used. Compatibility between life cycle inventory datasets and life cycle impact assessments must be assessed to ensure that no impacts are occluded. For example, if the eutrophication-related flows of a technology are not reported in a reference LCI, this impact category should not be reported since impacts of the technology will be underestimated due to the scope of the reference LCA. However, as discussed in Chapter 2, impact categories such as eutrophication potential are crucial in understanding the impact of the built environment on ecosystems and, where possible, establishing models for quantification of these impacts across each life cycle stage should be completed.

Additional examples of environmental and ecological impacts relevant to geotechnical projects include those related to land-use and soil and subsurface modification, obstruction of surface or groundwater flow and provisions for wildlife crossings (Phillips et al., 2016; Raymond et al., 2020b). While these impacts are important to consider across geotechnical LCA, methods for their quantification are limited and require further development (Raymond et al., 2020). Future research in this field should address these missing impact indicators. This likely required collaboration with researchers from disciplinary fields such as soil science and ecology.

Interpretation

The interpretation stage of an LCA and LCCA is an iterative process which is completed across the whole assessment project. It can guide LCA and LCCA modeling techniques, be used to evaluate overall impacts and to draw conclusions. Weighting and normalization methods can assist in developing sustainability scores facilitating comparison of different geotechnical systems, aiding in decision-making. Hotspots can be identified enabling targeted impact reduction strategies. The interpretation stage in crucial for enhancing modeling, drawing conclusions, and offering recommendations for improving the sustainability of geotechnical earthquake mitigation techniques.

Uncertainty Assessment

Uncertainties arise across geotechnical LCA and LCCA through geotechnical design and subsurface uncertainties and through uncertainty in modeling the foreground and background system of an LCA or LCCA. A non-exhaustive list of these uncertainties is presented below in

Table 8. They can be modeled through quantitative assessment such as deterministic or probabilistic models and through sensitivity analysis such as one-at-a-time sensitivity analysis. This allows identification of the parameters which most greatly impact the overall uncertainty of LCIA results.

Table 8. Summary of uncertainties across geotechnical LCA and LCCA

Geotechnical uncertainties	• Subsurface uncertainties, e.g. soil properties and geologic structures • Design model uncertainties • Measurement uncertainties e.g. through cone penetration tests (CPTs) and standard penetration tests (SPTs) • Interpretation uncertainties e.g. translating CPT and SPT data to soil properties
LCA and LCCA uncertainties	• Transportation and mobilization distance uncertainties • Uncertainties across impact assessment models e.g. uncertainty in the global warming potentials of greenhouse gases • Materials production methods uncertainties • Unit cost uncertainties • Discount rate uncertainties\

3.3. Whole-Life LCA and LCCA of Permeation Grouting

Permeation grouting is one technology that can be used for earthquake-induced liquefaction mitigation. Through permeation grouting, the voids between cohesionless soil particles are filled by injecting a low viscosity microfine cement or chemical grout at low pressure into the soil structure (Welsh et al., 1998; Han, 2015). This improves the shear strength of the soil, reducing the likelihood of liquefaction occurring. One advantage of permeation grouting over other ground improvement methods such as deep soil mixing and vibro-compaction is that it can be implemented below existing buildings.

3.3.1. Methods

A LCA and LCCA are undertaken to evaluate the environmental and economic impacts of the whole life of a permeation grouting project. The LCA and LCCA are conducted considering an idealized site in Oakland, CA where liquefaction mitigation of a uniform, clean sand profile is required below a power station substation. A 24.4 x 24.4 m treatment area is established where grouting is implemented in a zone that begins 3 m below the surface, at the water table, and ends 15.2 m below the surface producing a treatment volume of 7,249 m^3 (Figure 5). Prior to grouting, a site investigation program consisting of CPTs and SPTs is conducted to determine subsurface conditions.

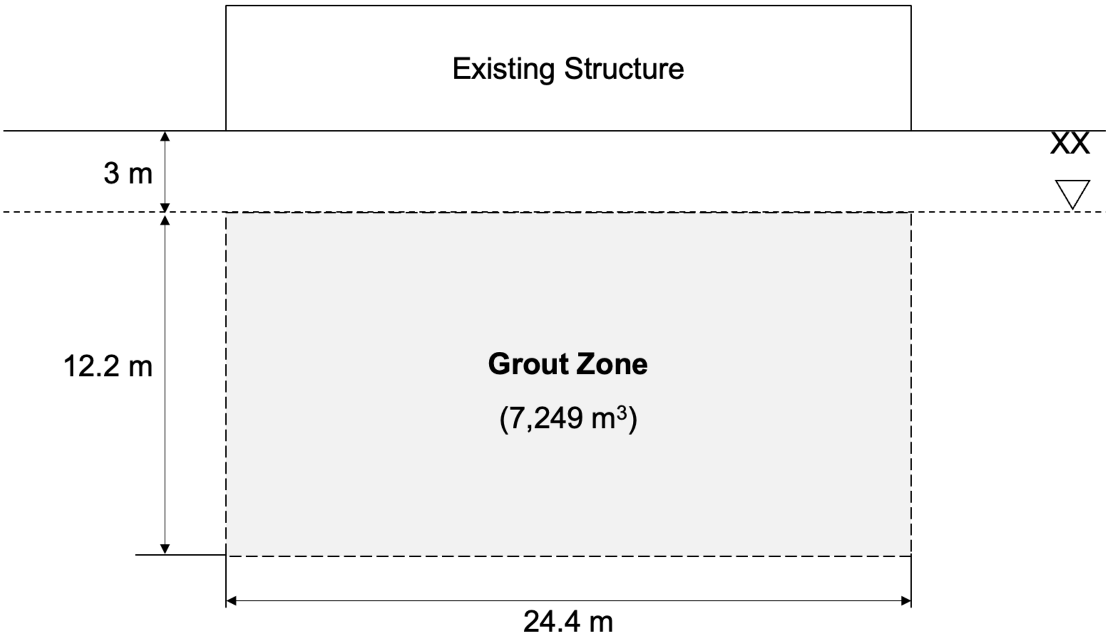

Figure 5. Grout zone established below existing structure

Goal and Scope Definition

The goal of the LCA and LCCA is to assess the grouting project described above through a hotspot analysis and to determine the influence of site investigation activities on the overall sustainability of a grouting project. The LCA and LCCA evaluate project stages from site investigation to the end of the project service life. The functional unit considered for this study is the treatment of 7,249 m3 of liquefiable sand with a porosity of 0.25 below a structure supported by a shallow concrete foundation. Treatment must prevent liquefaction of the soils from a Magnitude 9 earthquake for the duration of the structure's service life of 50 years. Across each project stage, raw material supply, materials transportation, equipment mobilization and demobilization as well as on-site equipment use are modelled. A system diagram of the project is presented in Figure 6.

This study excludes manufacturing of construction equipment since this has been shown to have a negligible impact on ground improvement project impacts (Shillaber, 2018). The use phase of the structure for which liquefaction mitigation is provided is not considered in this study since it is assumed that the service provided is sufficient to prevent damage from a seismic event. Hence, maintenance of the grouting is not required. Further, we assume that no damages occur should there be a seismic event over the project lifetime. This study excludes production of the PVC sleeveport pipes and waste management of grout since we assume these have a low impact on total results as compared to the impacts from the high volume of cement used.

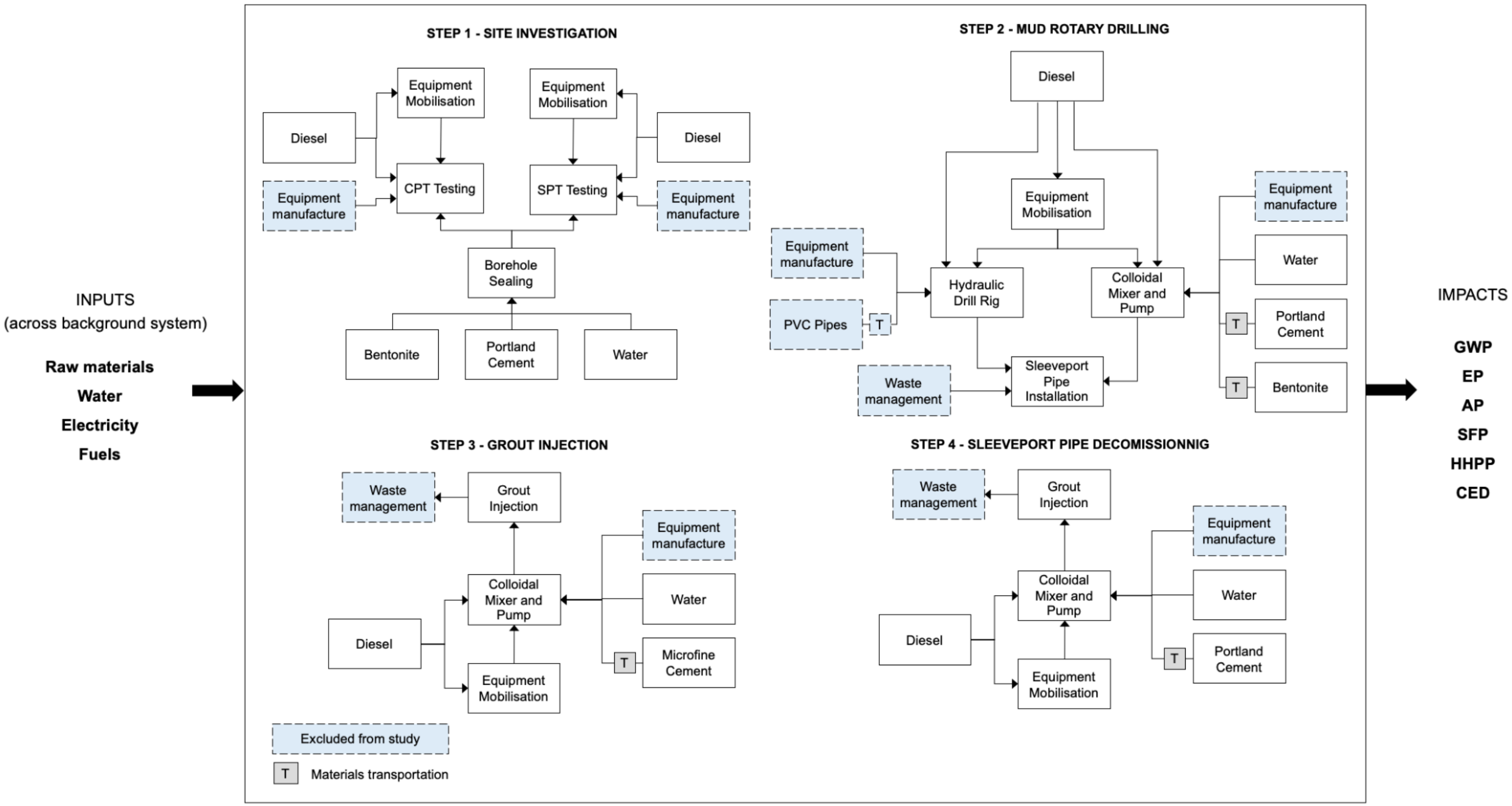

Figure 6. System diagram of permeation grouting project

Life Cycle Inventory

A life cycle inventory (LCI) of all input and output material and energy flows across the life cycle presented in Figure B is developed utilising reference LCI datasets to represent each material and process required. Reference LCI datasets are sourced from the ecoinvent and Sphera databases as shown in

Table 9 (Wernet et al., 2016; Sphera, 2022) A life cycle inventory dataset for microfine cement was developed by adding the electricity requirements for cement grinding to a finer particle size to a dataset for regular Portland cement production. We assume that 110 kWh electricity per tonne of Portland cement is required to grind Portland cement to microfine particle size (Sebaibi and Boutouil, 2020). Treated tap water for drinking is assumed to be used for the grout mix since potable water quality is preferred for cement grouts (Christodoulou et al., 2021). Emissions from equipment mobilization, use, and demobilizations, as well as diesel consumption are estimated using the California Air Resources Board Emission Factor model, EMFAC (California Air Resources Board, 2021). EMFAC estimates air emissions and fuel use for on-road vehicles. To estimate total impacts of mobilization the impacts of fuel production, all diesel, are added to the direct emissions from trucks. The methodologies used to estimate material and energy inputs over each project stage are described below.

Table 9. Reference LCI and LCIA datasets utilized

Item	Dataset	Region	Database (Year)
Water	Tap water from surface water	US	ecoinvent 3.8 (2021)
Bentonite	Market for bentonite	GLO	ecoinvent 3.8 (2021)
Portland Cement	Cement production, Portland	US	ecoinvent 3.8 (2021)
Electricity	Electricity grid mix - CAMX	CAMX	Sphera Extension XVII (2019)
Diesel	Diesel mix at filling station	US	Sphera Professional (2018)
Truck Transportation	Transport, freight, lorry 16-32 metric ton, EURO5	RER	ecoinvent 3.8 (2021)
Cone Penetration Test (CPT)	Cone penetration test	US	Purdy et al. (2022)
Standard Penetration Test (SPT)	Standard penetration test	US	Purdy et al. (2022)

During the site investigation program, five CPTs and one SPT are conducted to a depth of 16.8 m. As per Purdy et al. (2022), a roundtrip mobilization distance of 160 km is considered for CPT and

SPT equipment. No sampling time is considered for the CPTs since data is collected during the drilling phase. Samples are taken during SPT advancement every 1.5 meters and the sampling time is assumed to be 700 seconds per sample (Purdy et al., 2022). The CPT and SPT boreholes are sealed with a cement-bentonite mixture at the end of the site investigation program.

The raw material quantities required for sleeveport pipe installation through mud rotary drilling, and grout injection, including waste allowances, are provided in Table 10.

Table 10. Material quantities across permeation grouting construction stage

	Mud Rotary Drilling		**Grout Injection**	**Sleeveport Pipe Decommissioning**
Material	**Hydraulic Drill Rig**	**Colloidal Mixer and Pump**	**Colloidal Mixer and Pump**	**Colloidal Mixer and Pump**
Diesel (kg)	3.03×10^3	8.13×10^2	4.91×10^3	1.47×10^2
Water (L)	-	6.53×10^4	1.85×10^6	5.63×10^4
Portland Cement (kg)	-	2.19×10^4	-	5.63×10^4
Bentonite (kg)	-	4.65×10^3	-	-

Microfine Cement (kg)	-	-	4.36×10^5	-

Microfine cement from the US state of Idaho is used for this project and Wyoming bentonite is utilised. All materials are assumed to be transported to site via truck. Transportation distances and material origins are presented in Table 11.

Table 11. Materials transportation distances for permeation grouting project

Material	**Source**	**Truck Distance (km)**
Portland Cement	California	50
Bentonite	Wyoming	1766
Microfine Cement	Idaho	1198

Mobilization and demobilization of all grouting equipment is evaluated assuming a roundtrip distance of 160 km. The hydraulic drill rig is mobilized using a 5-axle semi-truck and the colloidal mixers pump, drill tooling and other miscellaneous items are mobilized using two 40-ft flatbed trucks. We assume that the site is secure, and equipment can be left overnight, requiring only one mobilization at the start of the project and one demobilization at the end of construction.

The sleeveport pipes are installed in an 'S' pattern with hole spacing at 1.5 m, requiring 256 grout holes with a diameter of 12.7 cm each. The sleeveport pipes are installed through mud rotary drilling and are backfilled with a cement-bentonite grout totaling 74.1 m3 including a 50% waste allowance based on industry standards. A 200 hp diesel-powered drill rig and 65 hp diesel-powered colloidal mixer with progressive cavity pump are used for the mud rotary drilling. The drilling rate is 183 linear meters per 8-hour rig-shift, requiring 22 days in total to drill the total drilling length of 3,901 linear meters.

To grout the treatment zone, a total of 1,812 m3 of microfine cement grout is required. The grout has a mass ratio of 4.25:1 water to microfine cement. A 10% waste allowance for the microfine cement grout is modelled.

The time required for injection is estimated as:

$$t_{inject} = \frac{7.48V_g}{Qn_{header}}$$

where t_{inject}= time to inject (minutes), n_{header} = number of headers, Q = injection rate. For this project, four headers are used, and the injection rate is 5.7 liters per minute resulting in a total injection time of 1064 hours over 133 days using a 65 hp colloidal mixer and pump.

The sleeveport pipes are decommissioned at the end of construction by pumping a 1:1 cement to water mixture into the pipes with a 65 hp colloidal mixer and pump.

Life Cycle Impact Assessment

The impact categories assessed in this study are governed by the indicators presented in the reference site investigation datasets utilised [Purdy et al., 2022]. These include global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), smog formation potential (SFP), human health particulate potential (HHPP) as well as cumulative energy demand (CED). Global warming potential is evaluated using the 100-year GWP values of greenhouse gases presented in the Fifth Assessment Report (AR5) of the IPCC (Myhre et al., 2013). While updated GWPs are available from the IPCC Sixth Assessment Report (AR6), AR5 values are used for harmonization with the site investigation reference dataset which uses AR5 GWPs. The remaining impact categories are evaluated through the US EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) v2.1 (Bare, 2012). Cumulative energy demand is assessed as the sum of all primary energy consumption and energy consumed during equipment use.

Life Cycle Cost Assessment

A LCCA is completed using data from a techno-economic analysis (TEA) of a similar case study on liquefaction mitigation based in Portland, OR (Hall et al., 2022). The volume of materials differs in this study due to differing site conditions, namely porosity, and this is updated in the model. Overhead and markup are estimated as 25% of the total construction costs and mobilization and demobilization costs are estimated as 10% of the project cost. Costs for site investigation are estimated from a dataset produced by Purdy et al. (2022).

Sensitivity Analysis

The impact of uncertainty in mobilization distance for site investigation and construction equipment on overall LCIA and LCCA results is assessed through a sensitivity analysis. A roundtrip mobilization distance of 120 km and 200 km is assessed in addition to the baseline assumption. Due to uncertain subsurface conditions, the grout volume required can vary by 30%

of the initial design, based on industry experience. As such, this uncertainty is also assessed through sensitivity analysis.

3.3.2. Results & Discussion

Life Cycle Impact Assessment

The LCIA results for the baseline permeation grouting study are presented in Figure 7 and

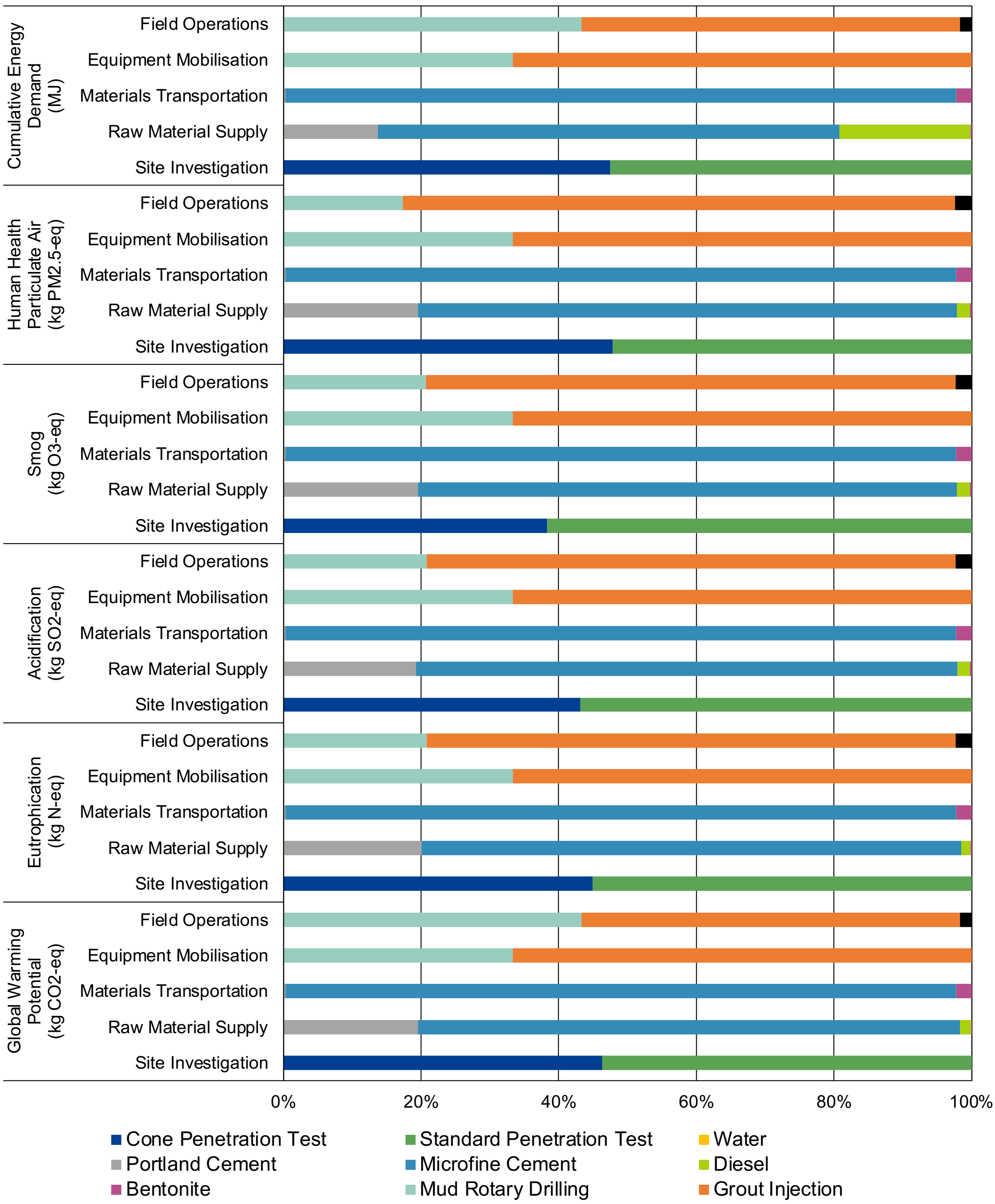

Figure 8. Contribution of materials and processes to permeation grouting LCIA results

Figure 8. Figure 7 presents the LCIA results for each life cycle stage and Figure 8

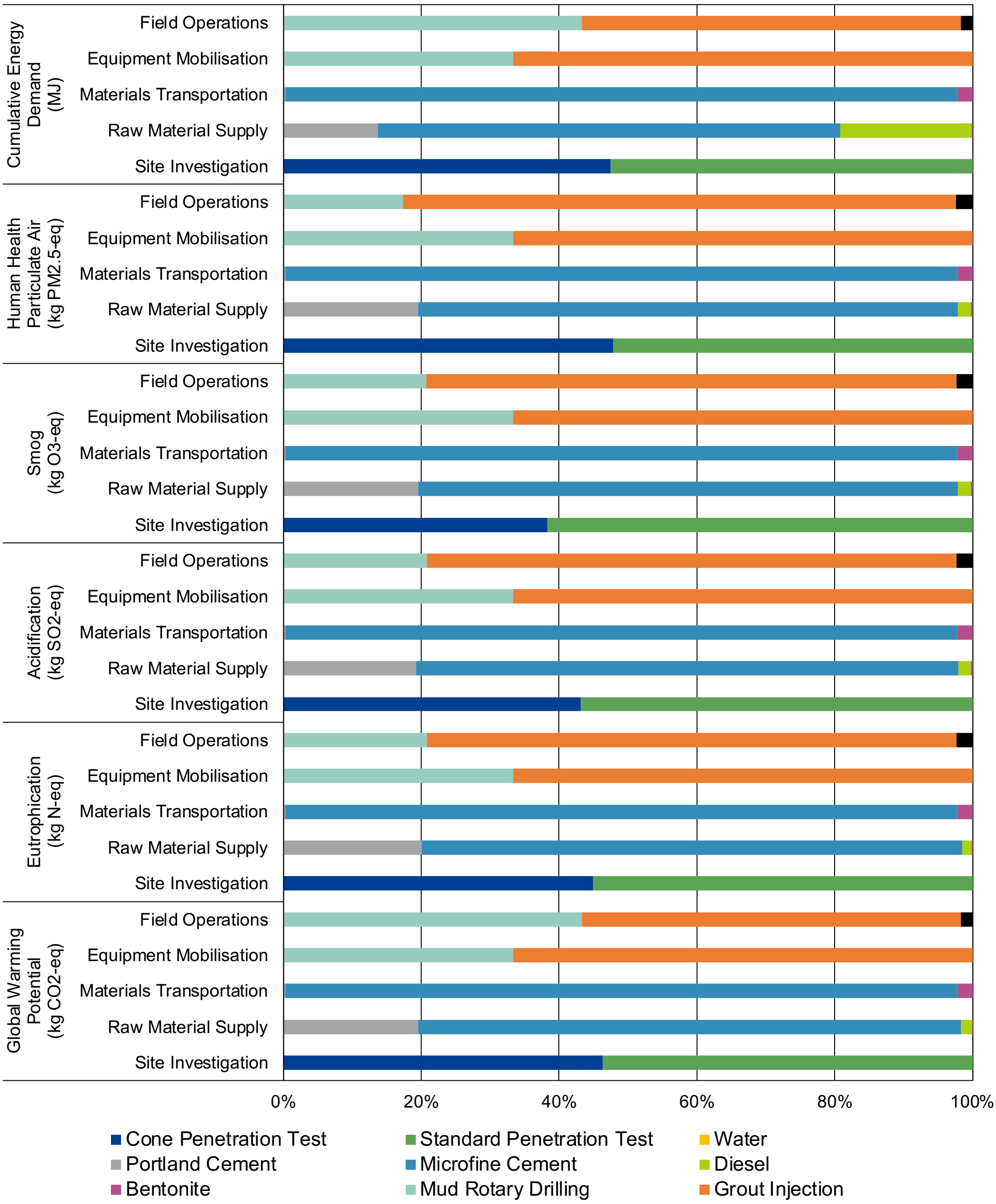

Figure 8. Contribution of materials and processes to permeation grouting LCIA results

presents the contribution of each material and process to each life cycle stage for all impact categories. Across each impact category, raw material supply, materials transportation and field operations contribute the greatest impacts and site investigation and equipment mobilization present minimal impacts. For each impact category, site investigation impacts are less than 0.5% of total impacts.

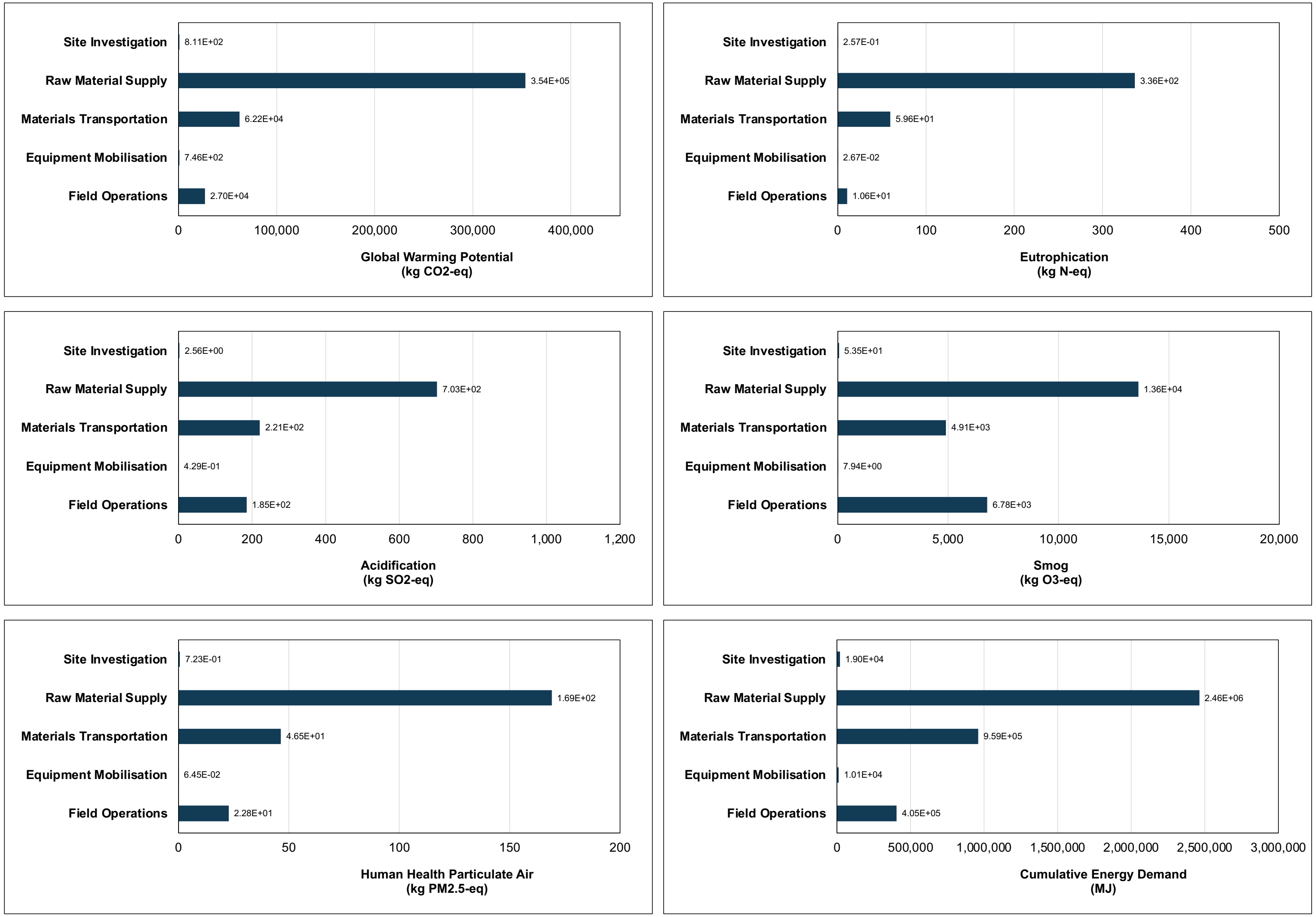

Figure 7. LCIA results for permeation grouting project

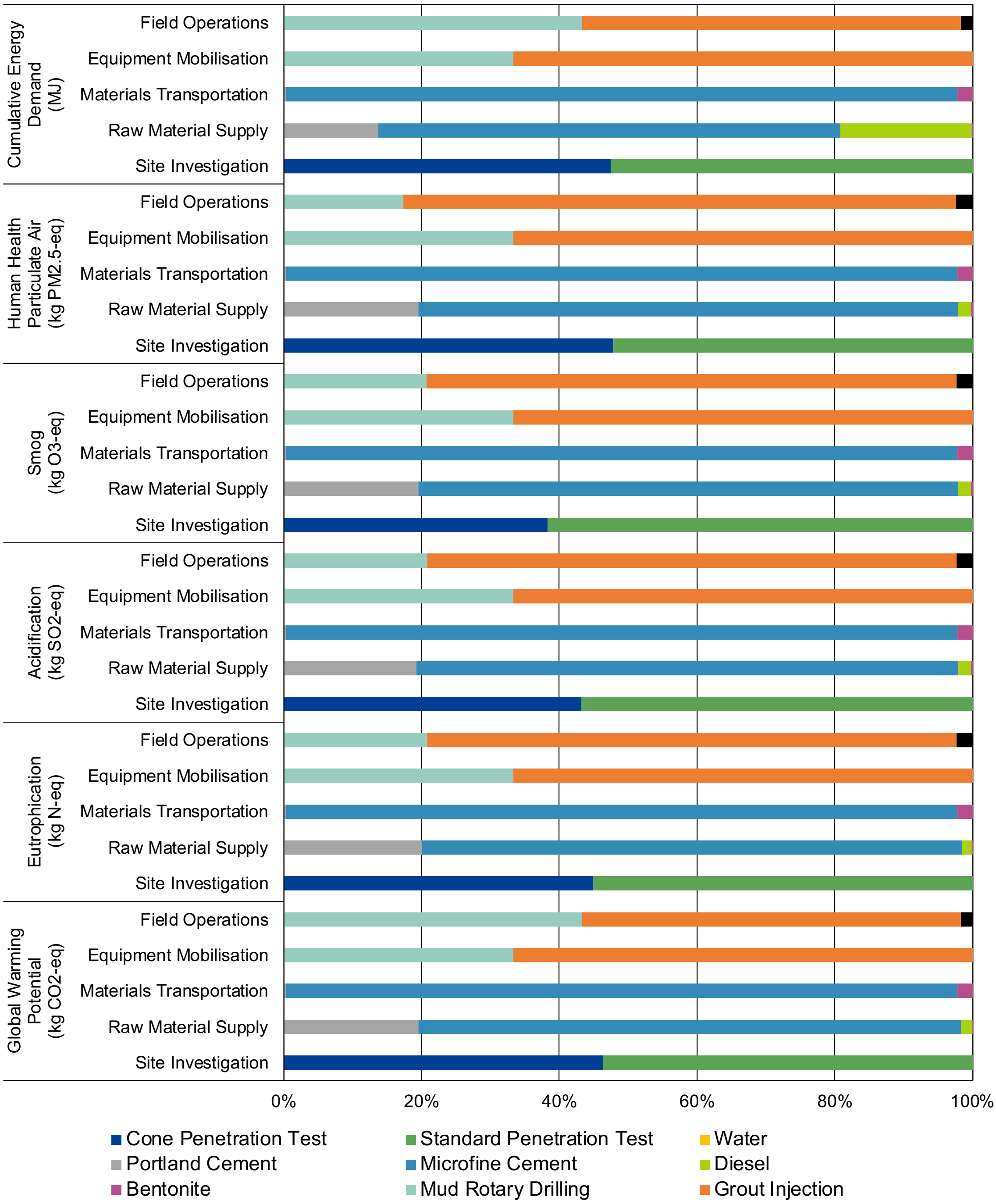

Figure 8. Contribution of materials and processes to permeation grouting LCIA results

The GWP of the grouting project is 444,584 kg CO_2-eq and 80% of this is due to raw material supply, most significantly by microfine cement production. Despite there being more CPTs performed compared to SPTs, 54% of the site investigation GWP is due to the single SPT performed. This is due to the sampling and borehole sealing required for the SPT that is not needed for the CPTs. The EP of the project is 407 kg N-eq and like the GWP, raw material supply contributes 83% of the EP, again mostly due to microfine cement consumption. Materials transportation contributes 14.6% of the project EP and GWP, largely due to microfine cement transportation from Idaho. Field operations account for 6% of the GWP and 3% of the EP of the project.

The AP and SFP of the permeation grouting project are 1,113 kg SO_2-eq and 25,369 kg O_3-eq, respectively. Compared to the GWP and EP, field operations contribute a greater amount to the AP and SFP of the project at 17% and 27%, respectively. The HHPP of the project is 239 kg PM2.5-eq and the CED is 3,855 GJ. Raw materials supply accounts for the majority of the HHPP and CED. Diesel production accounts for a higher amount of the raw material supply CED compared to other impact categories.

Life Cycle Cost Assessment

The total cost of the project is estimated at $1,893,178 and 61% of the costs is due to field operations including sleeveport pipe installation and grout injection (Figure 9). Similar to the LCIA results, site investigation has a very minimal impact on the cost, contributing only 0.32% to the total project cost. Raw material supply accounts for 29% of the project costs. The cost of the project, normalized by the volume of treated soil is $261/m3.

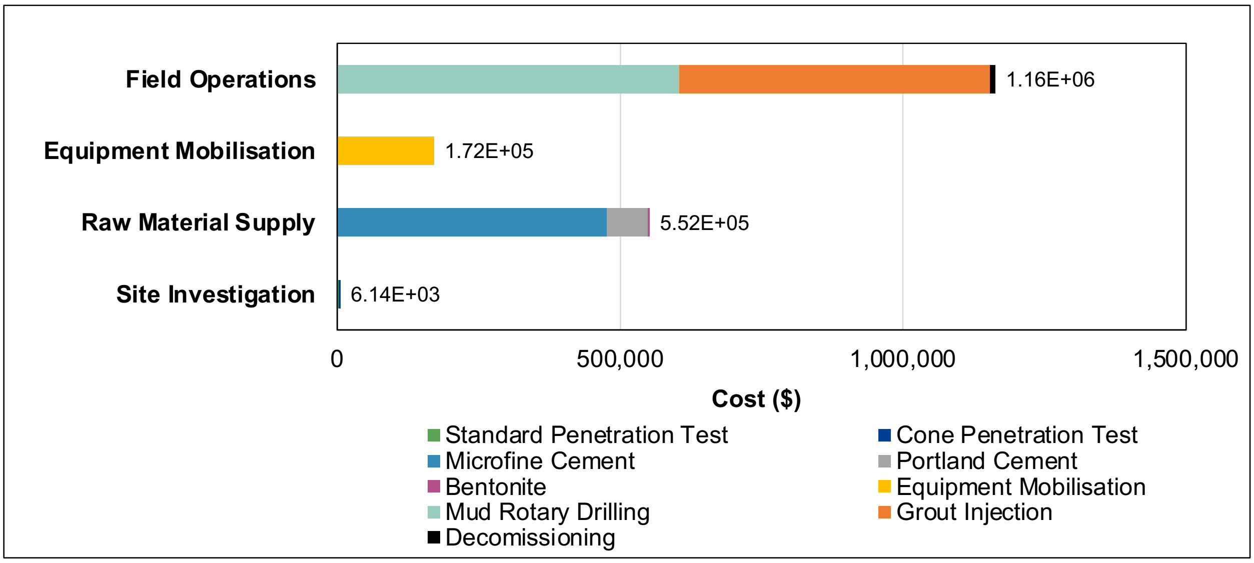

Figure 9. Life cycle cost assessment results for permeation grouting project

Sensitivity Analysis

The variability in mobilization and demobilization distance evaluated has a very minimal impact on LCA results. For example, increasing the mobilization distance to 200 km roundtrip results in a less than 0.04% increase in the project GWP. Since the cost of mobilization and demobilization for construction equipment is estimated from total construction costs and is not a function of mobilization distance, the impact of a change in mobilization distance on the cost of the project cannot be estimated. For site investigation activities, decreasing the roundtrip mobilization distance to 120 km results in a 0.8% decrease in cost and increasing the mobilization distance to 160 km results in a 0.8% increase in cost.

For each environmental impact category, a 30% decrease in grout volume from the baseline study results in a decrease between 17-21% in impacts (Figure 10). A 30% increase in grout volume results in an increase between 20-26% in environmental impacts. The project cost is most sensitive to uncertainty in grout volume. The uncertainty in grout volume results in a cost that is 10.6% the cost of the baseline study.

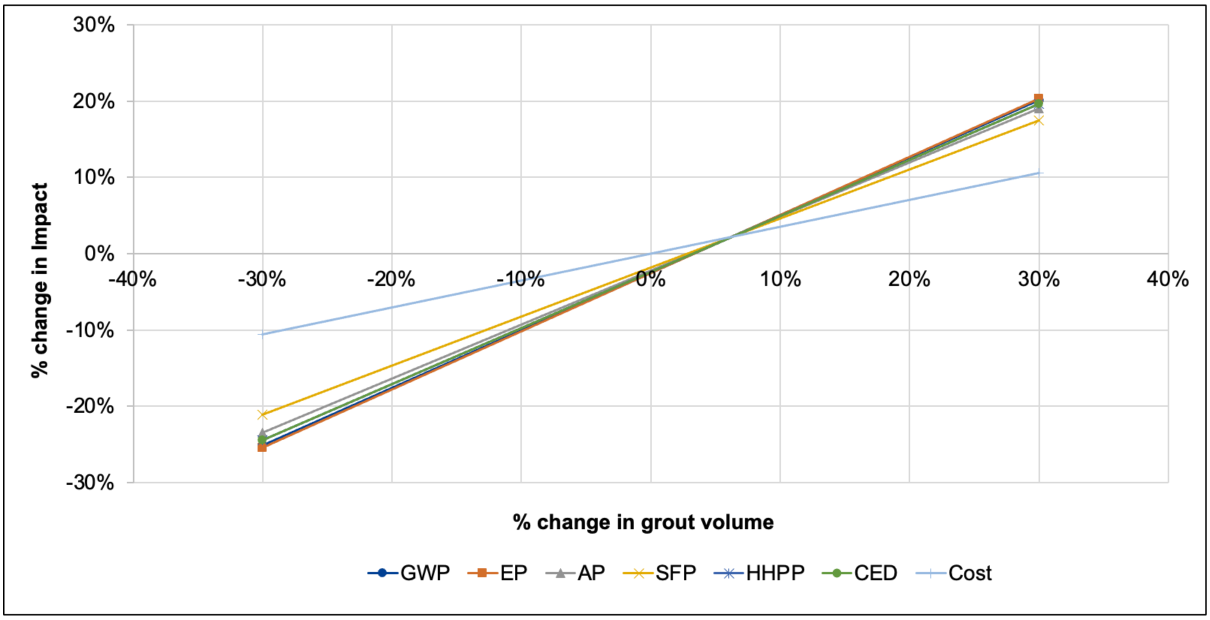

Figure 10. Sensitivity analysis results for grout volume uncertainty

Interpretation

The LCA and LCCA demonstrate that across the whole life cycle of a permeation grouting project, site investigation has a minimal impact on the total environmental impacts and cost compared to construction activities. However, the results also show that uncertainty in subsurface conditions, modeled through uncertainty in grout volume, can have a significant impact on the total environmental impacts and cost. This makes it hard to accurately complete prospective LCA during the design phase of a grouting project. As such, LCA and LCCA should always be performed both before and after the construction of a grouting project. By doing so and recording the as-built design, this more accurate data can be used to inform future project evaluations, particularly those at the same or a nearby sites, and potentially reduce cost, time, and materials overruns. Prior to construction, by increasing the scope of the site investigation program for the project, uncertainty in subsurface conditions could potentially be reduced. This would allow for an evaluation more reflective of the actual site conditions and may reduce overruns.

LCA of ground improvement projects often exclude the environmental impacts of equipment use during field operations, focusing only on raw material supply and occasionally materials transportation (Faruqi et al. 2023; Kendall et al. 2018). However, this study demonstrates that quantification of field operations impacts is necessary to provide a comprehensive image of project environmental impacts. This is particularly true for the AP and SFP of a grouting project.

Despite the low contribution of site investigation activities to both environmental impacts and cost, the distribution of impacts between other project stages differs between the environmental impacts and the cost of the project. For example, equipment mobilization and demobilization have a greater impact on cost than it does on environmental impacts. Also, the cost of field operations is greater than the cost of raw material supply while the environmental impact of field operations is much lower than those of raw material supply.

3.4. Conclusion

In this study we presented a framework for the standardized evaluation of the whole life cycle environmental impacts and costs of a geotechnical earthquake mitigation project. We define the whole life cycle of such projects as including the site investigation, construction, use, and end-of-service-life stages. Evaluating the impacts of each of these stages requires assessment across the life cycle activities of these stages including the following phases: raw material supply, materials transportation, materials processing, equipment operation, and waste management. We also presented guidance for the completion of LCA and LCCA following the ISO 14040 and 14044 standards, modified specifically for geotechnical projects and where we also include uncertainty assessment as a requirement.

We provided an example implementation of the proposed framework and guidance where we evaluated the life cycle impacts across the site investigation and construction stages of implementing permeation grouting for soil liquefaction mitigation. Previous LCAs have omitted site investigation from their scope, and this research contributes the first LCA to illustrate the relative impact of site investigation compared to other life cycle stages. This is key in understanding the impact that an increased site investigation program may have on overall project impacts and works towards understanding how geotechnical uncertainties can influence project sustainability.

The results of this study present a baseline evaluation of a permeation grouting project which can be used to model increases in project scope such as an increased-scope site investigation program. For the baseline study completed, raw material supply, materials transportation and field operations have the greatest impact on the environmental impacts of the project and raw material supply and field operations have the biggest impact on cost. Since subsurface uncertainty, modeled as uncertainty in raw materials consumption in this study, has a significant impact on results, reducing this uncertainty through more site investigation may greatly improve the design of a project. This study demonstrates the importance of completing a whole life cycle assessment of geotechnical projects to link uncertainty, design, and sustainability assessment for a holistic analysis of hazard mitigation projects.

4. LIFE CYCLE ASSESSMENT OF ENZYME INDUCED CARBONATE PRECIPITATION COLUMNS FOR GROUND IMPROVEMENT

4.1. Introduction

As mentioned in Chapter 2, enzyme induced carbonate precipitation (EICP) has been proposed as an alternative and possibly more sustainable biogeotechnology for applications such as fugitive dust control and ground improvement (Woolley et al., 2020b; Ahenkorah et al., 2021; Martin et al., 2021). EICP provides soil treatment through application of a solution typically containing a plant-derived urease enzyme, urea, calcium chloride, water, and nonfat milk powder to either the subsurface or surface of soil (Almajed et al., 2019; Martin et al., 2021). EICP induces urea hydrolysis, producing calcium carbonate and cementing soil particles together. Legumes from the Canavalia family, such as Jack beans and Sword beans, are most commonly used as a source of the urease enzyme in experimental work on EICP due to the high urease content of the enzyme (Khodadadi et al., 2017, 2020).

One application of EICP is the installation of columns below an existing or future building to improve the strength of the soil and provide foundational support for the structure (Kavazanjian et al., 2017). EICP columns are installed by injecting an EICP solution at multiple locations across a site producing cemented soil cylinders around the injection sites (Martin et al., 2020).

Life cycle assessment (LCA) has recently been applied to biogeotechnologies such as EICP to evaluate the relative environmental sustainability of these technologies compared to existing, business-as-usual geotechnical technologies (Faruqi et al., 2023). EICP has been evaluated through LCA for applications including fugitive dust control, road stabilization and foundational support (Alotaibi et al., 2022; Martin et al., 2020; Raymond et al., 2021). While Martin et al. (2020)

presented a hotspot LCA of EICP for foundational support, a comparison between EICP columns and existing technologies has not been completed. In this study, we build on Martin et al.'s work, completing a comparative LCA of EICP columns and permeation grouting, a cement-based incumbent technology used for ground improvement.

Through the EICP process, ammonium chloride is produced as a byproduct [Eqn (5)], and this has the potential to eutrophy and salinize water bodies. Eutrophication models are well established in LCA and are commonly used to evaluate the eutrophication potential of existing and emerging geotechnical technologies (Faruqi et al., 2023; Kendall et al., 2018). However, salinization models are scarce and salinity is not a commonly reported impact category in LCA. This is likely due in part to its omission from widely used life cycle impact assessment models such as the EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare, 2012) and commonly used life cycle inventory databases. Further, the complexity and variability of salinity composition and source may be a contributing factor to its exclusion. Since proxy measurements (i.e., electrical conductivity and total dissolved solids) are often used to measure and consider salinity rather than a more comprehensive analysis, this may introduce uncertainty in LCA models (Núñez and Finkbeiner, 2020). No existing LCA of EICP has assessed the impact of the chloride ions produced by the EICP process on salinity of groundwater.

Previous LCAs of EICP highlight the relatively high eutrophication potential of EICP compared to existing technologies due to the direct ammonium emissions from the EICP process itself (Alotaibi et al., 2022; Raymond et al., 2021). In these studies, EICP was applied to the surface of the soil and hence modeling for soil emissions due to the application of urea to the surface was included in the LCAs in addition to the ammonium emissions from the EICP process itself. Since, for EICP columns, the treatment is applied below the surface, it is unlikely that ammonia volatilization will occur from the application of urea to the soil (Rochette et al., 2013). Martin et al. (2020) found that ammonium emissions from the EICP process account for 97.5% of the total eutrophication potential of EICP columns.

To reduce the eutrophying impact of bio-mediated and bio-inspired technologies, researchers have recommended flushing the treatment area. For example, microbially induced carbonate precipitation (MICP), a bio-mediated ground improvement solution which also induces soil cementation, also produces ammonium chloride and flushing of this by-product has been proposed (Lee et al., 2019). With regards to the cost and performance of ammonium flushing, Raymond et al. (2023) report that flushing after MICP treatment can reduce the eutrophication potential of MICP by more than 50% without having any significant impact on project costs. Raymond et al.'s study was carried out for lab-scale MICP implementation, however, and hence their results may not reflect the cost of flushing a project-scale site, which could be high (Khodadadi et al., 2017). Raymond et al. (2023) also do not evaluate the impacts of treating the flushed wastewater, which Salemans and Blauw (2010) report to be high compared to other processes across the MICP life cycle. Almajed et al. (2018)found that flushing of EICP-treated soil samples with de-ionized water removes ammonium chloride from the samples. While by-product flushing may reduce the eutrophication and salinity impacts of EICP, this increases the water consumed across the EICP life cycle, another key consideration when evaluating sustainability.

In addition to the high eutrophication potential of EICP columns, Martin et al. (2020) also found that production of urea, the urease enzyme, and non-fat milk powder are significant contributors to the global warming potential and energy demand of EICP columns. Martin et al. omitted materials transportation and construction activities, which could make contribution analysis uncertain. A few other limitations include the use of older life cycle inventory datasets that may not reflect current industry practices, and the few impact categories that were assessed.

Herein, we aim to evaluate the environmental impacts of EICP columns relative to permeation grouting and identify the key contributors to EICP columns environmental impacts to guide impact reduction efforts. The LCA presented here expands on and updates Martin et al.'s 2020 study to present a LCA of EICP columns by:

- Adding an assessment of materials transportation, equipment mobilization and demobilization, and mixing and injection of the EICP treatment solution.
- Updating the reference life cycle inventory datasets utilized.
- Modeling additional environmental impact categories.
- Presenting a comparative assessment of EICP columns and permeation grouting with microfine cement.

4.2. Methods

4.2.1. Goal and Scope Definition

The goal of this LCA is to determine the environmental sustainability of EICP columns at their current stage of development and to guide future development of the technology towards improved sustainability. For both EICP columns and permeation grouting, we assess the following project stages: construction, use, end-of-service-life. Assessing the whole life of a ground improvement project, including site investigation activities, provides a clear picture of the overall sustainability of a project. However, in this assessment we omit site investigation activities since they contribute very little to overall ground improvement project impacts as discussed in Chapter 3. Site investigation activities contribute more to the cost of a project and in a life cycle cost assessment of EICP columns and permeation grouting they should be evaluated. The functional unit for this LCA is the treatment of a 465 m2 site in Tempe, Arizona to a target minimum unconfined compressive strength (UCS) of 500250 kPa.

To treat the soil outlined in the functional unit, 400 columns grouted with EICP are required, producing 393 m3 of grouted soil. The amount of treatment solution injected per volume of soil is 350 L/m3 and a total treatment solution volume of 137,445 L is required. The EICP treatment solution is mixed with an electric mixer, which has a power of 1.2 kW, for 2 minutes. The EICP treatment solution is injected through the tube-a-manchette pipes at a rate of 364 L/hr using peristaltic pumps with a power of 0.06 kW.

A system diagram of the EICP columns' cradle-to-grave LCA is presented in Figure 11. A permeation grouting LCA conducted by Faruqi et al (2023) is utilized in this study as the comparison system. The system diagram for permeation grouting can be found in Chapter 3. In both studies, equipment manufacturing is excluded, assuming this has negligible impacts in accordance with previous LCAs of geotechnical applications (Shillaber et al., 2016b).

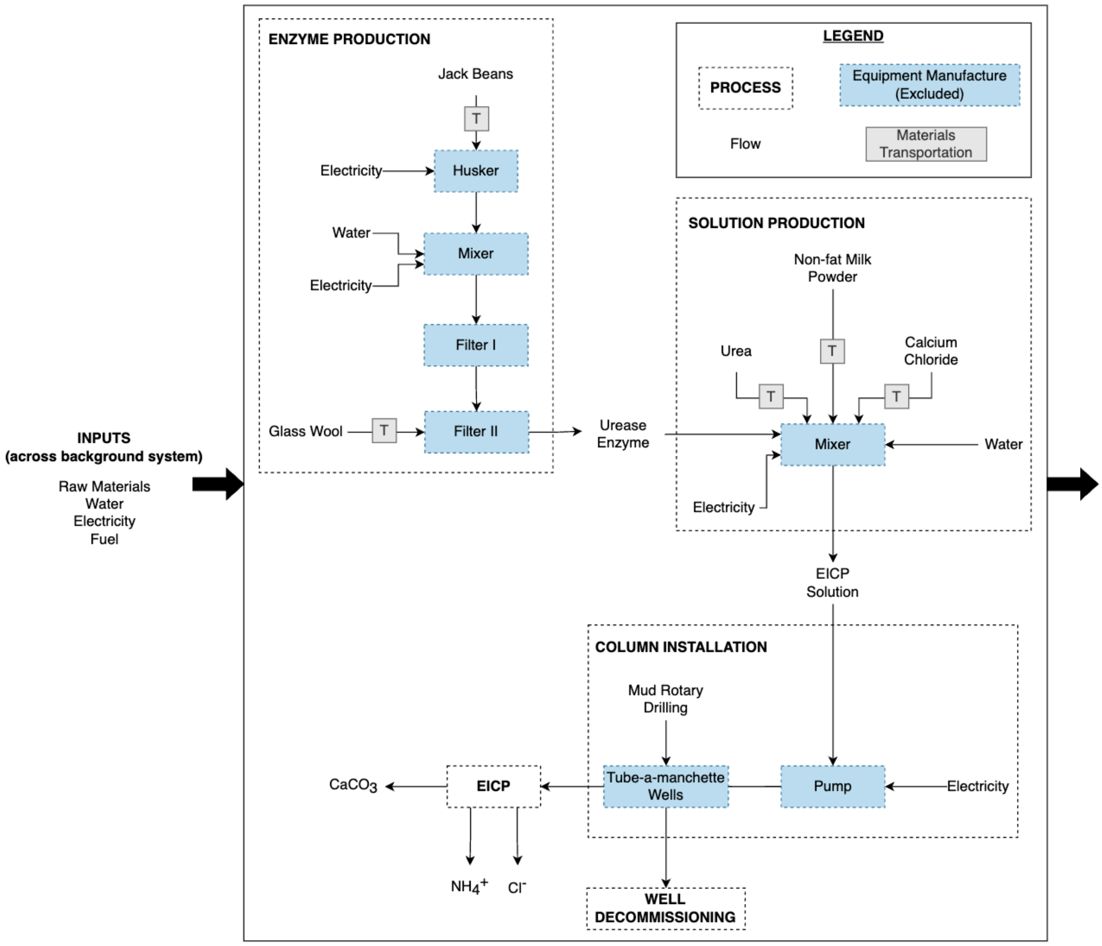

Figure 11. System diagram for EICP columns project

[GWP = global warming potential, CED = cumulative energy demand, AP = acidification potential, EP = eutrophication potential, HHPP = human health particulate potential, HTP = human toxicity potential (cancerous), SFP = smog formation potential]

The foreground system of EICP columns is modeled considering material and energy inputs and outputs for the urease enzyme production, EICP solution production, EICP column installation, EICP process, and well decommissioning. Across each process, materials transportation is included in the assessment. The life cycle inventory (LCI) data for mud rotary drilling for tube-a-manchette well installation, and for well decommissioning are taken from Faruqi et al. (2023). In these LCIs, equipment mobilization and operation are assessed in addition to materials and fuel consumption. In this model, we assume that the ammonium chloride byproduct of the EICP process is released into the groundwater and we do not assess treatment of this waste. While flushing has been proven to remove ammonium chloride from the system, the transport and fate of this compound after flushing is currently uncertain.

4.2.2. Life Cycle Inventory

The material and energy flows across the entire foreground system presented in Figure 11 are listed in Table 12 along with their corresponding reference LCI datasets. Where possible, LCI datasets produced for the US and Arizona were utilized. The LCI datasets are predominantly obtained from the Sphera and ecoinvent LCA databases (Wernet et al., 2016; Sphera, 2022)The emissions from equipment were evaluated for Tier IV equipment operated including the Salton Sea area, which has a similar climate to Arizona, using the California Air Resource Board's Emissions Factor model (EMFAC) (California Air Resources Board, 2021).

No LCI dataset was identified for urease enzyme production and thus required the development of a new reference LCI based on the expansion of some previous studies of urease enzyme production from Jack beans. We assume here that the processing of Jack beans and Sword beans from the Canavalia family are similar. Information on the crude extraction of the urease enzyme using Jack beans was taken from Javadi et al. (2021) and Martin et al. (2020). We assume batches of 5 L of urease enzyme are produced at a time. Each batch requires 3.88 kg of Canavalia beans and 13.3 L of water. The coffee bean husker used to dehusk the Canavalia beans has an average capacity of 350 kg/hr and a power of 2.2 kW. The de-husked Canavalia beans are then soaked in water and processed in a commercial-scale blender for 2 minutes. The blender has a capacity of 24 L and a power of 1.1 kW. This Canavalia bean mix is then filtered first through cheesecloth and then through glass wool. Martin et al. modeled this process using cheesecloth for filtration and found that the production of the cotton required for the cloth has surprisingly high impacts. This is because their model assumed that each batch of urease enzyme produced requires a new cheesecloth filter. In this study, we consider utilization of a reusable metal filter for the initial filtration process. We assume that each batch of urease enzyme produced requires a new mass of glass wool.

Table 12. Material and energy flows and reference datasets for EICP columns

Process	Flow	Amount	Reference database (Reference year)	LCI dataset (Region)
Enzyme Production	Jack beans (kg)	3.19×10^2	Sphera Extension XVII (2021)	Soybean, at farm (13% H_2O content) (US)
	Water (L)	1.10×10^3	Sphera Extension XVII (2021)	Tap water from surface water (US)
	Glass wool (kg)	1.37×10^1	Sphera Extension XIV (2021)	Glass wool (EU-28)

	Electricity (husker) (kWh)	2.01×10^0	Sphera Extension XVII (2019)	Electricity grid mix 1kV-60kV (AZNM)
	Electricity (blender) (kWh)	3.02×10^0	Sphera Extension XVII (2019)	Electricity grid mix 1kV-60kV (AZNM)
Solution Production	Urea (kg)	8.26×10^3	Sphera Extension XVII (2021)	Urea (stamicarbon process) (US)
	Calcium Chloride (kg)	1.35×10^4	ecoinvent 3.8 (2021)	Market for calcium chloride (RER)
	Nonfat Milk Powder (kg)	5.50×10^2	ecoinvent 3.8 (2021)	Milk spray-drying (RoW)

	Water (L)	1.37×10^5	Sphera Extension XVII (2021)	Tap water from surface water (US)
	Electricity (mixer) (kWh)	5.52×10^0	Sphera Extension XVII (2019)	Electricity grid mix 1kV-60kV (AZNM)
Column Installation	Mud rotary drilling (m)	2.00×10^3	See chapter 3	-
	Electricity (pump) (kWh)	2.27×10^1	Sphera Extension XVII (2019)	Electricity grid mix 1kV-60kV (AZNM)
Well Decommissioning	Well decommissioning (m)	2.00×10^3	See chapter 3	-

Aside from the Canavalia beans which are sourced from India, all materials are assumed to be sourced from within the US and either trucked to the construction site or transported by rail. For transportation distances greater than 600 miles, we assume that rail transportation occurs (Rodrigue, 2020). For these cases, a 50-mile truck transportation distance from the rail station to the construction site is considered. The transportation distances and material suppliers for each material are presented in

Table 13. Some assumptions are made for materials for which suppliers could not be found though are expected to be produced within Arizona. The reference LCI datasets used to model materials transportation are provided in

Table S- 1 in the Supplementary Information.

Table 13. Materials transportation distances for EICP columns by mode

Material	Source	Truck Distance (miles)	Rail Distance (miles)	Ship Distance (miles)
Urea (kg)	Donaldsonville, Louisiana	50	1450	-
Calcium chloride (kg)	Ludington, Michigan	50	1915	-
Nonfat Milk Powder (kg)	Tempe, Arizona	10	-	-
Jack beans (kg)	Guwahati, India	100	2029	16614
Glass wool (kg)	Maricopa County, Arizona	50	-	-

4.2.3. Life Cycle Impact Assessment

The global warming impacts of the technologies are modeled using the 100-year global warming potentials published in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel On Climate Change, 2023) The AP, EP, HHPP, HTP and SFP of EICP columns are modeled using version 2.1 of the TRACI. Blue water consumption and cumulative energy demand are also assessed. Blue water consumption here refers to freshwater consumption excluding rainwater. We present the LCIA results for urease enzyme production, a hotspot analysis of the EICP columns' life cycle, and a comparative analysis of EICP columns and permeation grouting.

4.3. Results & Discussion

4.3.1. Urease Enzyme Production

The results of the LCIA for urease enzyme production are presented in Figure 12 and Table 14.

Table 14. Results of impact assessment of 5L of urease enzyme production

Impact Category	**Value**
100-year GWP (kg CO2 eq.)	3.28E+00
Acidification Potential (kg SO2 eq.)	4.42E-02
Eutrophication Potential (kg N eq.)	6.14E-02

HH Particulate Air (kg PM2.5 eq.)	3.76E-03
Human Toxicity - Cancer (CTUh)	1.94E-07
Smog Formation (kg O3 eq.)	3.53E-07
Primary Energy (MJ)	8.70E-01
Blue Water Consumption (kg)	1.08E+02

Across each impact category, Canavalia bean production for which a proxy LCI dataset of soybean production was utilized, and transportation contributes highly to life cycle impacts. For smog formation potential, cancerous human toxicity, human health particulate matter, acidification, and global warming impacts, Canavalia bean transportation accounts for higher impacts than Canavalia bean production. While production of the urease enzyme requires on-site use of water for blending the Canavalia beans, this water consumption is minimal compared to the water that is used across the Canavalia bean farming process.

Glass wool production has notable impacts on the process since we assume that a new batch of wool is needed for each batch of urease enzyme produced due to residue clogging the wool filters. Impacts from electricity use required for dehusking the Canavalia beans and blending them are minimal for each impact category, contributing less than 2% to the GWP of the urease enzyme production process.

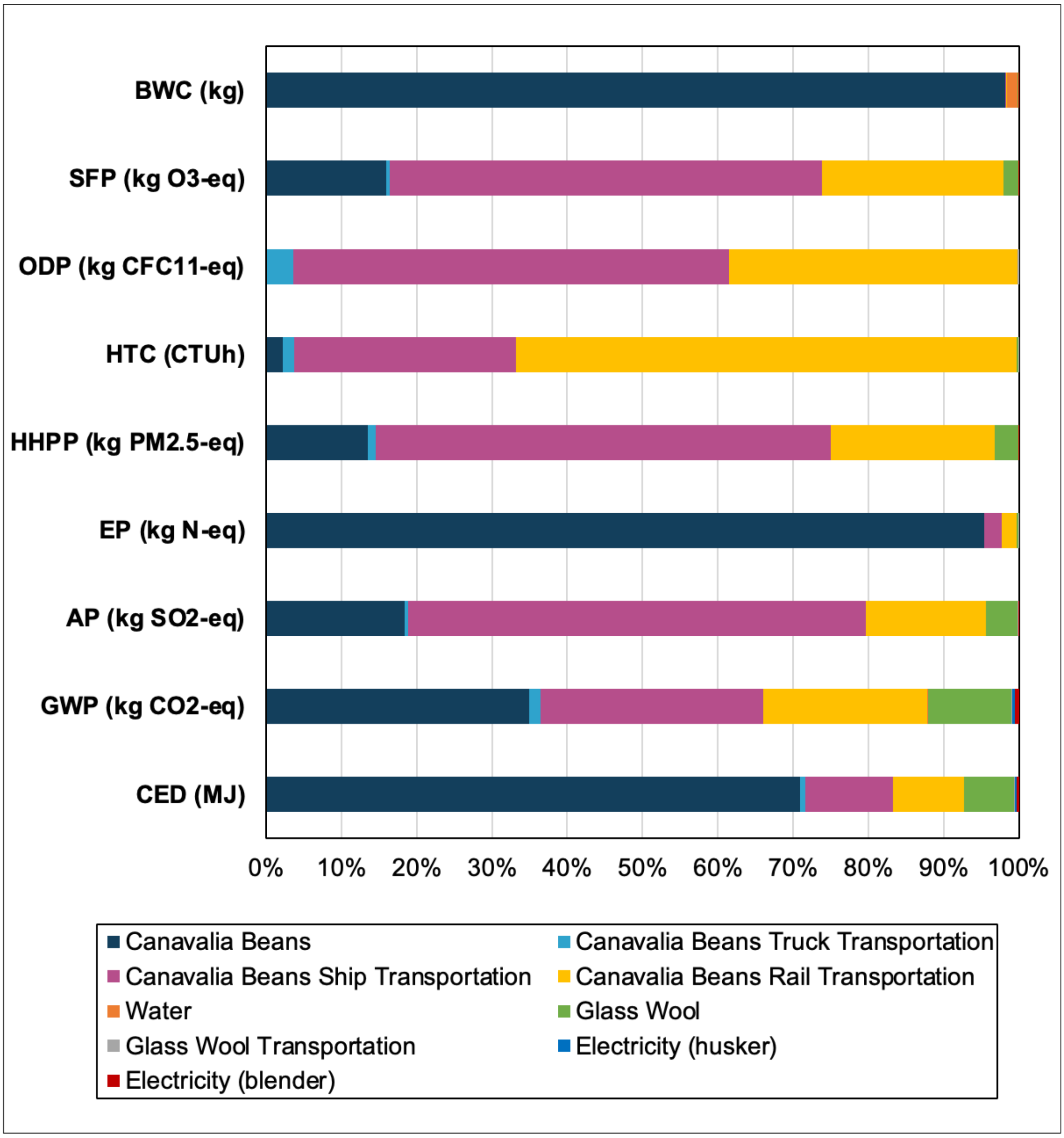

Figure 12. Contribution analysis for urease enzyme production

4.3.2. Hotspot Analysis of EICP Columns

A contribution of each process presented in Figure 13 to total EICP column impacts is shown in Figure z. Across all impact categories, the greatest contributors to impacts are calcium chloride production and transportation and urea production. Calcium chloride has the highest impact for all categories except primary energy, smog formation, and global warming potential.

For primary energy, the urea production process has higher impacts than calcium chloride production despite less urea being used in the EICP columns project, by mass. This suggests that the urea production process is energy-intensive. Regarding SFP, calcium chloride and urea transportation impacts are higher here compared to other impact categories since each material is transported from out-of-state. The GWP contributions of urea production and calcium chloride production are similar, again despite the greater portion of calcium chloride used for the EICP process.

Biogeochemical process emissions from the EICP process account for 98.5% of the eutrophication potential of the EICP columns project, suggesting that management of these emissions could significantly reduce the overall eutrophication impacts of the project. Urease enzyme extraction has minimal impacts on the EICP columns system though does contribute to 3% of the blue water consumption of the project. On-site water consumption accounts for 26% of the total blue water consumption across the project while the majority is due to water consumption across the calcium chloride production process.

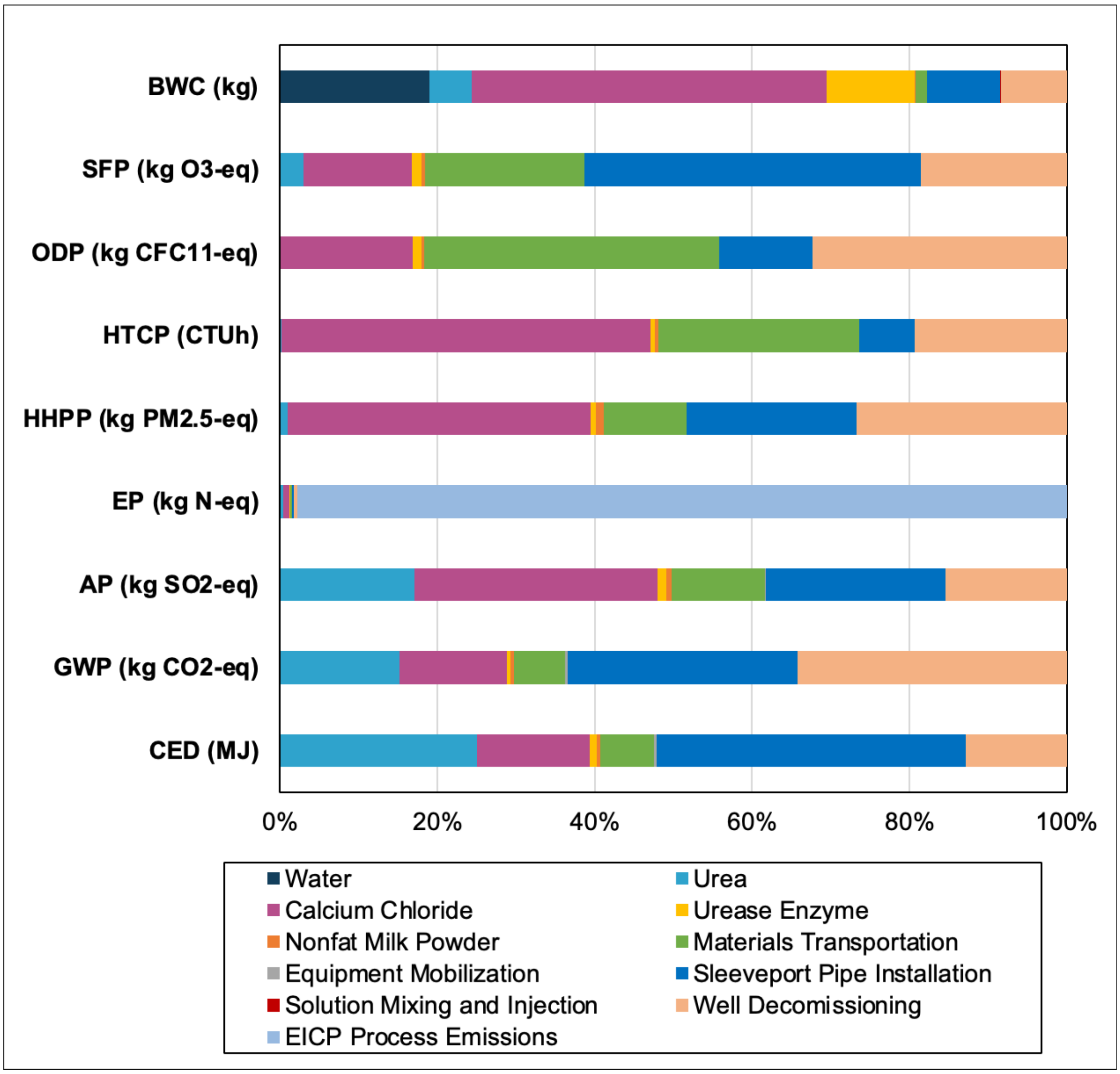

Figure 13. Contribution analysis for EICP columns

4.3.3. Comparative Analysis of EICP Columns and Permeation Grouting

Results from the comparative LCIA are presented in Figure 14. We find that permeation grouting has higher impacts than EICP columns in all impact categories except EP where the EP of EICP columns is roughly 41 times greater than that of permeation grouting largely due to the ammonium emissions from the EICP process. Excluding these process emissions from the analysis, the EP of each technology is similar with EICP columns having an EP of 111 kg

N-eq and permeation grouting having an EP of 123 kg N-eq. The small difference is mostly due to the greater materials transportation requirements for permeation grouting due to the large volume of microfine cement needed. These greater impacts due to materials transportation are reflected in each impact category assessed. Equipment mobilization impacts are insignificant for every impact category.

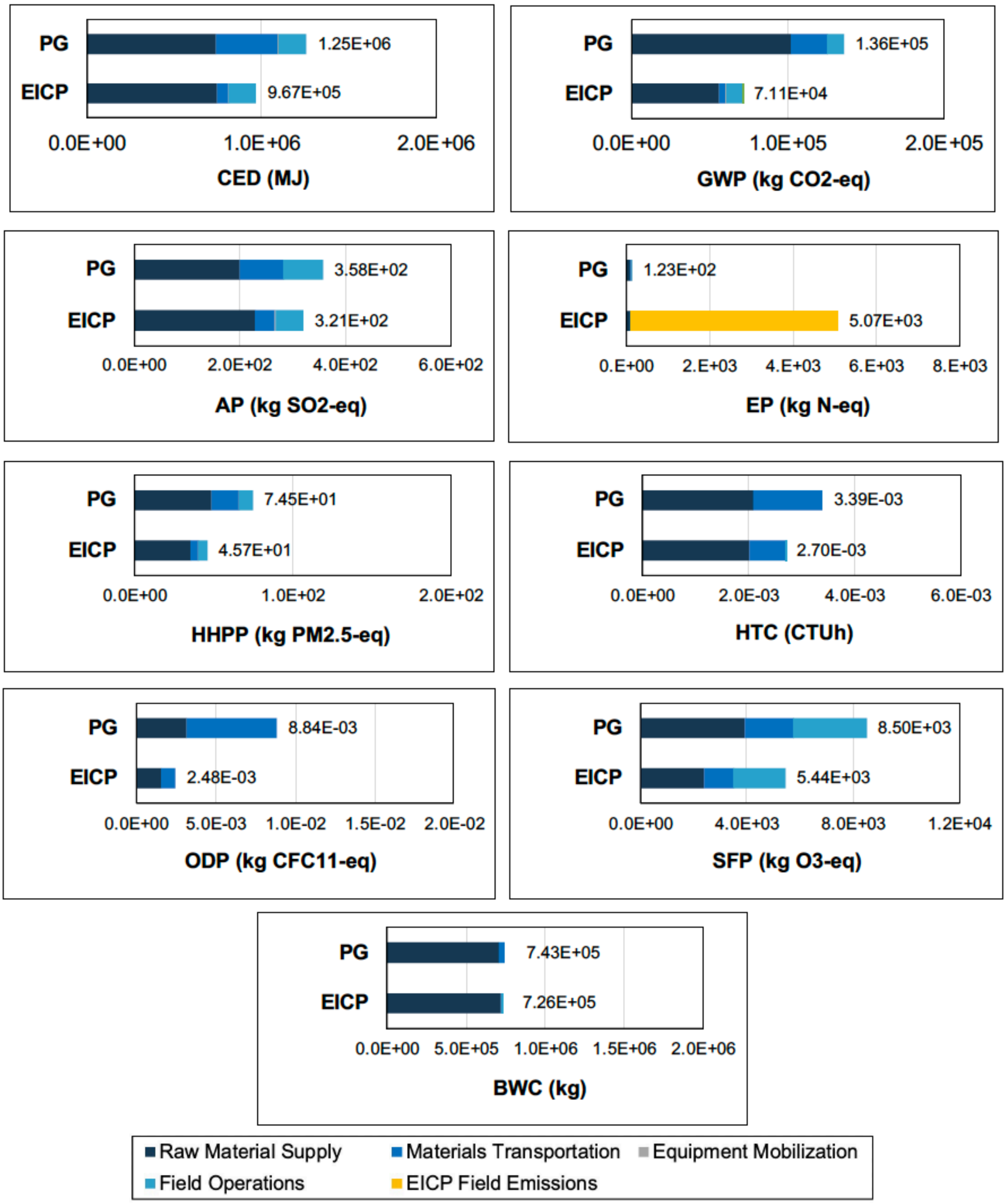

Figure 14. Comparative LCIA results for EICP columns and permeation grouting

The GWP of permeation grouting is nearly two times greater than that of EICP columns mostly due to the high GWP of microfine cement required for permeation grouting. Field operations impacts on GWP are similar for each technology. The higher raw material supply impacts for permeation grouting are reflected in all impact categories except AP and BWC. In the case of AP, impacts from raw material supply are higher for EICP columns since both urea and calcium chloride production have a higher AP than microfine cement production on a per kg basis. For BWC, while permeation grouting uses more water on-site, the BWC across calcium chloride production is nine times higher than that of microfine cement production on a per kg basis. This results in the BWC from raw material supply, and for each technology overall, being similar for both technologies.

Raw materials supply impacts from both technologies are also similar for HTCP, though the greater materials transportation impacts for permeation grouting result in the HTCP of permeation grouting being 1.3 times greater than that of EICP columns. The ODP of permeation grouting is larger than that of EICP columns mostly due to materials transportation. We would expect equipment mobilization impacts to be significant for the ODP of each technology, however, a drawback of using EMFAC for emissions modeling is that it does not report emissions relevant to ozone depletion.

The SFP of permeation grouting is 1.6 times greater than EICP columns due to greater raw material supply and materials transportation impacts. Across each category, impacts from field operations are similar for each technology.

4.4. Conclusion

In this study we evaluated the environmental impacts of EICP columns for foundation support and found that this emerging bio-inspired technology has lower impacts than permeation grouting with microfine cement, an existing technology used for foundation support, in all impact categories assessed except eutrophication potential. Findings from this LCA demonstrate that raw materials supply has the greatest impact on the life cycle environmental performance of EICP columns, except for the EP, followed by materials transportation. While GWP has historically been the most common environmental indicator assessed for geotechnical projects, this study along with existing literature on the environmental impacts of EICP for various applications highlights the importance of considering additional impact categories when comparing technologies. This is especially relevant for the eutrophication impacts of EICP as compared to existing technologies. As EICP develops for geotechnical applications, the high eutrophication impact of EICP must be addressed and mitigated where possible. While this assessment did not evaluate economic and social impacts, the results suggest that EICP can be used as an alternative to cement-based when environmental sustainability is a key performance indicator for geotechnical foundation projects.

5. OVERVIEW AND RECCOMENDATIONS FOR FUTURE WORK

5.1. Overview

The aims of this dissertation were to:

1. Complete a systematic literature review of LCSA studies of bio-mediated and bio-inspired geologic hazard mitigation projects.

2. Develop a framework to evaluate the environmental impacts and cost of the entire life cycle of a geotechnical earthquake mitigation project.

3. Implement the developed framework for two projects: a permeation grouting project and an EICP columns project.

In the systematic literature review conducted, eight relevant bio-mediated and bio-inspired LCSA studies were identified focusing on applications such as road stabilization and foundation reinforcement. The review highlighted deficiencies in the existing studies related to insufficient functional units, lack of assessment of biogeochemical reactions, and lack of transparency of LCI datasets used which is crucial for reproducibility. Existing studies also evaluated a limited scope of the project life cycle focusing only on the construction stage of a geologic hazard mitigation project. The studies demonstrated a promising potential for bio-mediated and bio-inspired geologic hazard mitigation techniques to reduce the environmental impacts and costs of mitigation projects.

The systematic literature review guided the development of a whole life cycle assessment and life cycle cost assessment framework for geotechnical earthquake mitigation projects. The framework defines four project stages (site investigation, construction, use, and end-of-service life) and five life cycle phases (raw material supply, materials transportation, materials processing, equipment operation, and waste management) that occur across each of these project stages. Adhering to and building on the ISO 14040 and 14044 standards, the framework provides guidance for completing geotechnical earthquake mitigation LCAs and LCCAs. It highlights the importance of standardizing such assessments.

The results of an application of the proposed framework on a permeation grouting project identified raw material supply, materials transportation, and field operations as major contributors to environmental impacts, while site investigation has minimal influence. The LCCA showed that field operations and raw material supply dominate project costs with site investigation again having minimal implications. Uncertainty in subsurface conditions, modeled through grout volume, significantly influences both environmental impacts and costs highlighting the importance of including this evaluation stage in an LCA and LCCA.

In another application of the proposed framework, we evaluated the environmental impacts of EICP columns as an alternative to permeation grouting. The results of this LCA show that biogeochemical process emissions from EICP columns significantly contribute to the eutrophication potential of EICP columns, suggesting potential benefits from managing these emissions. The results also highlight transportation as a significant contributor to environmental impacts across various impact categories. The LCA resulted in the production of a reference impact assessment for urease enzyme production from Canavalia beans which can be used in future LCAs of EICP-based projects.

5.2. Recommendations for Future Work

The work presented in this dissertation lays a foundation for future work relating to sustainability assessment of bio-inspired and bio-mediated geotechnics particularly work related to standardizing and guiding life cycle sustainability assessment of such technologies. The whole life cycle framework presented here can be improved and expanded upon by:

- Adding guidance for a life cycle social impact assessment, particularly to evaluate the direct social impacts of earthquakes and the social benefits of implementing mitigation techniques.

- Developing weighting and normalization techniques to determine overall sustainability scores for comparison across technologies. The methods should allow for customization of weighting and normalization values since the relative importance of environmental, economic, and social impacts may differ across projects. These techniques should facilitate input from various stakeholders including engineers, policy makers, and the affected community.

Related to the permeation grouting LCA and LCCA completed, future work could include:

- Performing sensitivity analysis on additional parameters such as variations in equipment types, grout formulations, and transportation distances to assess their impact on both environmental impacts and costs

- Evaluating the social impacts across the supply chain of project activities and materials

- Investigating the environmental and cost implications of managing waste materials generated through the grouting process and considering end-of-service-life options for grout affected soils.

With regards to the EICP LCA completed, future work could include:

- Expansion of the impact categories assessed to include those such as land-use change, soil erosion and acidification and salinity.

- Evaluating the cost and social impacts, such as labor conditions across the supply chain of each construction material and process, of EICP columns.

Further applications of the presented whole life cycle framework could include developing standardized guidelines such as product category rules to facilitate open reports such as environmental production declarations of geologic hazard mitigation techniques.

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SUPPLEMENTARY INFORMATION

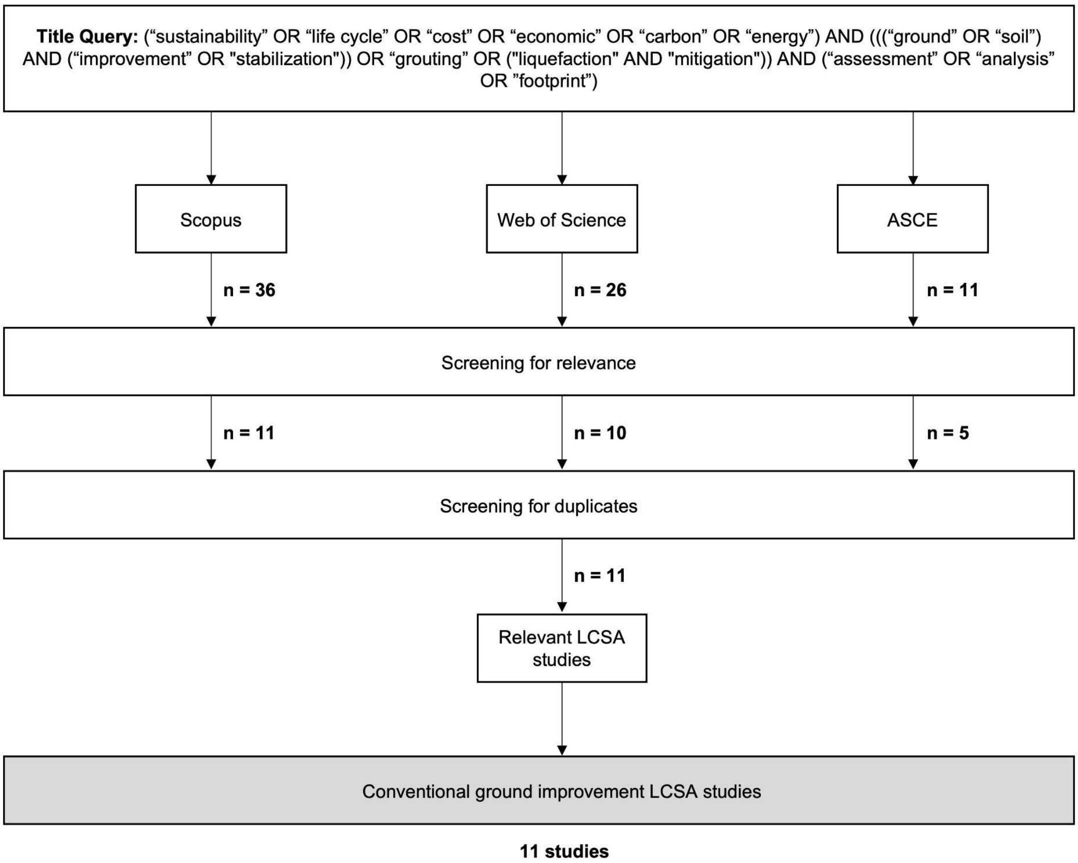

Figure S- 1. Flow diagram of the systematic literature search for conventional ground improvement technologies

Table S- 1. Reference LCI datasets for materials transportation

Process or flow	Reference database (Reference year)	LCI dataset (Region)
Truck transportation	ecoinvent 3.8 (2021)	Transport, freight, lorry 16-32 metric ton, EURO5 (RER)
Rail transportation	ecoinvent 3.8 (2021)	Transport, freight train, diesel (US)
Ship transportation	ecoinvent 3.8 (2021)	Transport, freight, sea, container ship (GLO)