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A review of life cycle greenhouse gas (GHG) emissions of commonly used *ex-situ* soil treatment technologies

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ABSTRACT

GHG emissions are important footprints because of increasing concern over climate change. Remediation methods produces GHGs in varying quantities based on which activities are involved through its entire life cycle and which contaminants are present, often because some contaminants are more difficult to remove from soil than others. Accounting for emissions from all phases of the project requires a life cycle assessment (LCA) approach. LCA can help in choosing the best available technology to reduce the environmental burden of the remediation technology or to improve the sustainability of the technology by implementing systematic approaches to ensure that future developments are optimized for environmental performance throughout the life cycle. The primary objective of this paper is to review existing LCA studies that report GHG emissions ($CO_{2\text{-eq}}$) or Global warming potential (GWP) from six ex-situ soil remediation technologies (ESRTs), including excavation and disposal, *ex-situ* thermal desorption, *ex-situ* soil vapor extraction, *ex-situ* bioremediation, excavation and incineration, and soil washing, and present the variability in GHG/GWP results and how this data can help in selecting an ex-situ soil remediation technology with a lower global warming potential. A second objective of this study is to compare the GWP levels of ex-situ remediation to the GWP levels of typical in situ remediation methods. Our results showed a large variation in GHG emissions of treated soil from six ESRTs varying from 3.1×10^{-7} t to 8.2 t CO_2-eq/m^3. Incineration had the highest mean GHG emissions (0.7 t CO_2-eq/m^3) and thermal desorption the lowest (0.07 t CO_2-eq/m^3). It was also found that there was a large variation range of GHG emissions from the ex-situ excavation and disposal method soil treatment technologies, varying from 3.1×10^{-7} t to 8.2 t CO_2-eq/m^3 of treated soil. This knowledge provides opportunities to increase sustainability of soil remediation throughout the investigation, design, construction, operation, and monitoring phases of site remediation regardless of the selected cleanup remedy. This shows data on LCA GHGs are useful to assess the impact of different scenarios and management practices on ESRTs.

Contents

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1. Introduction

Most systems and processes that require energy, emit greenhouse gases (GHG) and contribute to climate change (Raadal et al., 2011). Remediation activities often consume various chemicals, materials, and energy which are required for extraction, processing and transport of raw materials for use at remediation sites (Kim et al., 2013). Remediation techniques are often categorized as in-situ or ex-situ according to the removal or otherwise of the contaminated medium. In situ remediation does not require removal of contaminated soils and ground water. Therefore, this approach could be limited by its capacity to remove contaminated chemicals but may have lower costs of materials handling and environmental impacts (Lemming et al., 2010a). The ex situ remediation however involves excavation and extraction of soils and ground water for removal of contaminants. In some cases, the contaminated media may be moved to a treatment location (off-site treatment). This approach has advantages to select remediation techniques and therefore, is often effective in removing soil contaminants. However, the process uses extensive energy in excavation of contaminated soil for treatment either onsite, requiring less energy for transport or offsite, which most likely will require more energy for transportation of the contaminated soil to the treatment location. Amongst the different alternatives for site cleanup or remediation, the technology selected for the remediation amongst other factors may consider the kind of contaminants present at the site, the cleanup level, the time required for the remediation, economic resources, and the environmental impacts of the remediation process itself (Cappuyns, 2013a).

Any technique that remediates or manages the risk of contamination at a site has an environmental benefit as it eliminates or reduces exposure to contaminants. However, the remediation process or technique will introduce new environmental impacts due to the use of energy and materials, which cause emissions throughout their life cycle. These environmental impacts are often referred to as secondary impacts as opposed to the primary environmental impacts, which are related to the site, particularly the ex-situ remediation techniques (ESRTs) (Lemminget al, 2010a,b,c).

As Canada achieves its greenhouse gas emissions reduction target, activities carried out in each sector is important to contributing in achieving this goal. The waste management and remediation services in Canada contributed at least 3% of the total GHG emissions in 2015 (ECCC, 2017). GHG emissions are important footprints because of increasing concern over climate change (Kim et al., 2013). Generally, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) contribute to GHG emission, and carbon dioxide (CO_2) is the primary indicator of the greenhouse effect (Kim et al., 2014; Unfccc, 2011; IPCC, 2006). Various soil remediation activities result in GHG emissions, including operation of equipment and energy use; transportation of personnel, materials, and equipment; and the production of consumable materials. Ex-situ soil remediation will involve excavating large volumes of contaminated soil and transporting it to a proper treatment and/or disposal site whilst *in-situ* treatment involves the treatment of the contaminated soil medium in the site in which it was found (Lemming, 2018). In relation to GHG emissions, each remediation method can produce GHGs in varying quantities due to different activities involved through its entire life cycle to remove different types of contaminants. Because some contaminants are more difficult to remove from soil than others, they may require more equipment, chemicals, and consume more energy.

Accounting for emissions from all phases of the project requires a life cycle assessment (LCA) approach. Since the last decade, LCA has been gaining wider acceptance as a tool for the quantification of environmental impacts using global warming potential (GWP) which is a relative measure based on quantifying GHG emissions and evaluation of improvement options throughout the life cycle of a process, product or activity (Klöpffer and Grahl, 2014). In most industries such as waste management and remediation that use various technologies, LCA can help in choosing the best available technology to reduce the environmental burden of the remediation technology or to improve the sustainability of the technology by implementing systematic approaches to ensure that future developments are optimized for environmental performance throughout the life cycle (Morais and Delerue-Matos, 2010). Nunes et al. (2016) (Nunes et al., 2016) utilized LCA to compare treatment pathway alternatives applied to soil remediation with electrokinetic methods. Lemming et al. (2010a,b,c) evaluated environmental impacts of remediation of a chloroethene-contaminated site using LCA. However, to the best of our knowledge, no critical review using LCA has been performed to quantifying GHG emission and environmental impacts from *ex-situ* remediation techniques.

The primary objective of this paper is to review existing LCA studies that report GHG emissions from ex-situ soil treatment technologies. The secondary objective is to analyze the variability in GHG/GWP results and compare the GWP levels of ex-situ remediation to the GWP levels of typical in-situ remediation technologies (ISRTs). In addition, this study is to help good practice in selecting an ESRT with a lower GWP. This review is however, limited to the level of details that is provided on the models and data used in the LCA study. Furthermore, to provide a more comprehensive perspective of the environmental and total sustainability of ESRTs, other factors such as human health impacts, water consumption, jobs created, etc. have not been assessed.

2. Methodology

2.1. Search strategy and study evaluation

The methodology consisted of searching scientific databases for