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Optimization of field scale biopiles for bioremediation of petroleum hydrocarbon contaminated soil at low temperature conditions by response surface methodology (RSM)

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A B S T R A C T

Ex-Situ Bioremediation has been increasingly viewed as an appropriate remediation technology for hydrocarbon contaminated soils under cold climates conditions in countries like Canada. A response surface methodology (RSM) based on a factorial design was performed to investigate and optimize the effects of the microbial consortia application rate and amount of mature compost amendment on the TPH removal (964 μg g^{-1} initial concentration). 18 field-scale biopiles (16 m^3 each) were constructed, maintained and subjected to different microbial consortium and mature compost application rates under cold climate conditions over a period of 94 days. TPHs removal rates in the range of 74–82% was observed in the treatments setups where mature compost and microbial consortia were used simultaneously, compared to an average 48% of TPHs removal in control setup.

The interaction between these two factors were studied and modelled using a statistical regression model, which showed that the microbial consortia application rate, the mature compost amendment and their interactions had a significant effect on TPHs degradation with a coefficient of determination (R^2) of 0.88. Furthermore, using a numerical optimization approach, the optimum rates predicted via RSM were estimated at 4.1 ml m^{-3} and 7% for microbial consortia and compost application rates to obtain a maximum TPH removal of 90.7%.

1. Introduction

Contamination by industrial activities accounts for about 25% of the major Canadian urban landscape, with an estimate of 20–30 thousands brownfield sites across the country (De Sousa, 2006). Valuable real estate were often undervalued and underused in the past mainly due to considerable associated clean-up costs, representing a huge problem for the local economic development and potential reuse of the contaminated sites. However, recently there has been an increasing interest in redeveloping these sites as they are often located in the core sections of metropolitan areas and are prime candidates for urban development. Across the country, public and private sector are now using innovative policies and programs from local and provincial governments to overcome the value to remediate and redevelop contaminated sites; improving the local economy, the environment and the social benefits in a long term vision.

In Canada, approximately 60% of contaminated sites involve petroleum hydrocarbons (PHCs) contamination (Sanscartier et al., 2009). Current oil prices and growing demand have also resulted in high generation rates of oil, and subsequently an increase in oil spills around the world and in Canada. PHCs have been classified as priority environmental pollutants by the US environmental protection agency, due to their impact on human health and environment, representing a huge concern for the general public (ATSDR, 1999). As a result, government and private sectors are always in the search to develop new technologies and methods to minimize or mitigate the risks. Bioremediation is a cost-effective and environmental friendly remediation technologies that can be utilized for PHCs contaminated soils.

Bioremediation can be defined as an engineered process that uses biochemical mechanism in organisms to degrade environmental pollutants in soil, and transform them into less complex and harmless end products such as carbon dioxide and water (Coulon et al., 2010). Ex-situ bioremediation through biopiles have been considered as a feasible, cost effective and less destructive remediation technique for petroleum contaminated soils (Mohn and Stewart, 2000). Its use has been widespread over North America for the rehabilitation of different sites impacted by petroleum

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hydrocarbons. Biopiles can be defined as an above ground engineered system, heaping contaminated soils into piles and stimulating aerobic microbial activity by providing oxygen, nutrients and/or microbial consortia to degrade petroleum compounds adsorbed to the soil (Khan et al., 2004; Juwarkar et al., 2010; US EPA, 2012).

Although cold conditions delay bioremediation of oil hydrocarbons, bioremediation is increasingly viewed as an appropriate remediation technology for hydrocarbon contaminated soils in cold climates (Thomassin-Lacroix et al., 2002; Sanscartier et al., 2009). Margesin and Schinner (2001) denoted that even in cold regions such the Arctic and Antarctic regions, bioremediation has demonstrated to be a cost effective and non-disruptive method for contaminated soil with petroleum hydrocarbons.

Kauppi et al. (2011) investigated different strategies for the bioremediation of diesel oil contaminated soils under cold conditions including the addition of nutrients and bulking agents and aeration (biostimulation) and the use of microbial inocula (bioaugmentation). They concluded that in addition to delay due to cold conditions there were other bottlenecks affecting the outcome of bioremediation. The results showed that efficient oil degradation did not depend only upon the soil microbial community and bioaugmentation alone had no additional effect; but biostimulation via optimization of nitrogen and oxygen supply could significantly improve bioremediation of oil-contaminated soil by optimizing the conditions for the continuous growth of the consortium. They reported that diesel-fuel degradation was accelerated when both nutrients and wood chips were added into contaminated boreal soil but that neither one alone made a difference and the microbial growth increase was observed when the C:N relationship was optimized. Other studies have demonstrated that fuel degradation was enhanced if nutrients and proper oxygen conditions were available (Walworth et al., 2007; Chang et al., 2010). Beškoski et al. (2011) observed that bioaugmentation in combination with aeration and biostimulation enabled the successful remediation of contaminated soil by mazut (heavy residual fuel oil) at field scale. During the 5 months of treatment, the total petroleum hydrocarbon (TPH) content of the contaminated soil was reduced by 94%, from 5.2 to 0.3 g kg^{-1} dry matter, while for the untreated control pile the TPH was reduced only by 10%. Similarly, Thomassin-Lacroix et al. (2002) demonstrated a successful bioremediation of diesel-fuel in Artic contaminated soil by removing 83% of TPH over a period of 65 days in small-scale biopiles at low temperatures, using bioaugmentation, with an enrichment culture from the same site, and biostimulation by fertilization with phosphorous and nitrogen.

Some research studies have reported the use of compost as a source for providing nutrients to support and enhance bioremediation of organic wastes. Megharaj et al. (2011) suggested that the addition of compost stimulated the microbial growth by supplementing nutrients and carbon source, and thus enhanced the rate of organic pollutants degradation. Namkoong et al. (2002) added sewage sludge or compost as an amendment to the contaminated soil in different ratios, obtaining the best result at a mix compost ratio of 1:0.5, with 98.5% of TPH degradation and a kinetic value of 0.113 day^{-1} for diesel oil, which was spiked at 10,000 mg kg^{-1} sample on a dry weight basis in a lab scale reactor.

Factorial experimental design and response surface methodology (RSM), as a statistical analysis approach, is an efficient and widely used methodology to analyze, compare and optimize the simultaneous application of different factors or treatment technologies in bioremediation process (Sharma et al., 2009). Zahed et al. (2010) optimized nitrogen and phosphorous concentration via RSM for removal of n-alkanes from crude oil contaminated seawater samples in batch reactors. Numerical optimization predicted 98% removal over a 20 day period in lab conditions, using nitrogen and phosphorous concentrations of 13.62 and 1.39 mg L^{-1}, respectively. Mohajeri et al. (2010) employed RSM to optimize oil concentration biomass, nitrogen and phosphorous concentrations in bioremediation of weathered crude oil sediment samples during 60 days trial, obtaining 83% removal under the optimum conditions.

There is limited existing information on the performance of biopile bioremediation of petroleum hydrocarbons and its optimization especially at field scale and under cold climate conditions. Therefore, the present study aims to evaluate the effect of different operational factors (microbial consortia application rate and mature compost amendment) on the bioremediation of petroleum contaminated soils and to optimize the process under cold conditions and at field scale using a factorial design and RSM. By determining the best possible set of parameters or factors it would be possible to achieve a higher biodegradation rate using the minimum rates of application of microbes and compost. For this purpose, field-scale biopiles were constructed and subjected to different treatments based on an experimental design to study the effect of different microbial application rate and mature compost amendment in a soil treatment facility at Moose Creek, Ontario, Canada from November 2012 to February 2013.

2. Materials and methods

2.1. Materials

Excavated soil from a contaminated site, in Val-des-Bois, in the Outaouais region of Quebec, Canada, containing petroleum hydrocarbons were hauled and transported to a treatment facility in Moose Creek, Ontario, Canada during October 2012. The details of the site have been described elsewhere (Gomez and Sartaj, 2013). The contaminated soil was segregated, screened and stockpiled on a paved area for further analysis and treatment.

The soil was characterized and classified as sand (81.3%), based on 5 random composite samples and according to the USCS classification system (Table 1). Petroleum hydrocarbon analyses were conducted in accordance to accredited lab standard procedures, following Canada-Wide Standard for Petroleum Hydrocarbons in soil (CCME, 2001). The TPH analysis indicated that F2 (>C10–C16) and F3 (>C16–C34) fractions accounted for almost all (96%) of extractable TPH compounds in the contaminated soil.

Mature compost used in this study was obtained from a local composting facility processing municipal solid waste. The compost characteristics are presented in Table 2.

The microbial consortium used for the experiment was a commercial liquid product that contained a concentrated blend of bacteria strains native to Canada, non-pathogenic, and strains are

Table 1
Physical-Chemical characteristics of petroleum contaminated soil.

Parameter	Value
pH @ 25 °C	7.79 ± 0.02
Grain size sieve analysis[a]	
Gravel (>2.00 mm) (%)	10.3
Sand (0.075–<4.75 mm) (%)	86.4
Silt and clay (<0.075 mm) (%)	3.3
Total Petroleum Hydrocarbons (μg g^{-1} dw)[b]	924 ± 127
F1 – Volatile Fractions (μg g^{-1} dw)	27 ± 4
F2 – Semi-Volatile Fractions (μg g^{-1} dw)	455 ± 67
F3 – Non-Volatile Fractions (μg g^{-1} dw)	442 ± 62

Uncertainties are one standard deviation from the mean ($n = 5$).
[a] Soil classified as sand, according to the USCS classification system.
[b] Based on Canadian Wide Standards Tier 1 Method. TPHs are the sum of all the fractions.