

# On the Use, and Reuse, of Polymers for the Treatment of Hydrocarbon Contaminated Water Via a Solid–liquid Partitioning Bioreactor

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*Aqueous environments contaminated with diesel components pose a threat to the native biota due to the intrinsically toxic nature of the many hydrocarbon compounds present. In the event of diesel being released into an aqueous environment it is imperative that the contaminant is recovered in a rapid manner to ensure the safety of aquatic organisms as well as to maintain desired water quality. The research presented in this study investigates the potential of polymeric sorbents to recover diesel from a contaminated aqueous source. Thermoplastic materials, such as styrene butadiene derived polymers, were shown to substantially reduce diesel levels in excess of 98% with 90% of this recoverable fraction being removed in less than 30 min. Recyclable materials, such as used automobile tires, were shown to obtain similar results with added potential benefit including lower cost and reuse of a waste material. The polymeric sorbents were also biologically regenerated and this was accomplished in a solid–liquid two-phase partitioning bioreactor, in which 65% of the initial diesel contamination was degraded within a 9 day period. The result of this work was the demonstration of a low cost, reusable remediation technology for the recovery, and destruction of diesel from aqueous environments.*

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## Introduction

Diesel fuel represents a significant environmental contaminant originating from such sources as leaking underground storage tanks and transfer pipes as well as accidents at filling stations or during transportation. Diesel released into the environment is susceptible to migration, often resulting in the contamination of underground aquifers and receiving waters, such as lakes and rivers.<sup>1</sup> The presence of diesel in these aquatic environments has been shown to be detrimental to the natural biota<sup>2–4</sup> and therefore rapid recovery of diesel contaminant is imperative to ensure safety and survival of aquatic life.

The application of sorbent materials represents a popular method for recovery of diesel from water. A general overview by Adebajo et al.<sup>5</sup> outlined three main classes of sorbents that included inorganic materials,<sup>6,7</sup> natural organic materials,<sup>8,9</sup> and synthetic organic materials.<sup>10</sup> Desirable performance characteristics of these materials include high sorptive capacity, high rate of uptake, oil recovery from sorbent, and reusability of sorbent<sup>5</sup> however, in many instances these materials are limited in their ability to be regenerated. On the other hand, engineered thermoplastics represent a class of materials that satisfy the above criteria and may be routinely and successfully regenerated via biological means.<sup>9</sup>

Compared with traditional sorbent materials, engineered thermoplastics are beneficial as they are capable of releasing sorbed contaminants under ambient conditions, are reusable and are non-biodegradable.

Bioremediation offers a low cost, environmentally benign solution for treatment of diesel contaminated water. The literature contains numerous reports describing the capacity of microbes to degrade hydrocarbons.<sup>11–14</sup> Although bioremediation may occur naturally in the environment, if feasible, accelerated biodegradation may occur in a bioreactor where growth conditions such as temperature, pH, and nutrient levels may be conveniently controlled. Studies have shown that under controlled conditions, mixed microbial populations are capable of degrading dilute concentration of diesels by up to 90%.<sup>14,15</sup>

The motivation of this study was to demonstrate a low cost, reusable, remediation strategy for the treatment of diesel contaminated water by combining the advantages of thermoplastic sorbent materials, and accelerated bioremediation. Thermoplastic polymers were investigated as potential sorbents as these materials have been shown to effectively absorb organic molecules from water and soil.<sup>16,17</sup> The use of recyclable thermoplastics, in particular used automobile tires, was studied to demonstrate the potential of a waste material to remediate a waste contaminant. Regeneration of the sorbent material occurred in a solid–liquid two phase partitioning bioreactor (TPPB) that contained a mixed microbial population of diesel degrading bacteria. The release of diesel from the sorbent material followed by its subsequent

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biological destruction remediated the sorbent material thus enabling the potential for its reuse.

## Materials and Methods

### Chemicals and polymers

All chemicals were purchased from Fisher Scientific (Nepean, Canada) and were of scientific grade. Diesel fuel was purchased from Esso (Kingston, Canada) and was a commercial grade. Table 1 gives a list of the polymers used in the study as well as their suppliers and molecular structure.

### Analytcs

Model hydrocarbons, cyclooctane (CO), 2,2,4,4,6,8,8 heptamethylnonane (HMN), and 1-octadecene (OCT) were analyzed using a Perkin Elmer gas chromatograph (GC) with flame ionization detector (FID). The column used was a J&W Scientific DB-5 chromatographic column 30 m in length and 0.53 mm inner diameter (Agilent, USA). Samples were diluted in methanol prior to injection.

Aqueous systems were assayed for dissolved and free diesel using a modified analytical procedure taken from Murray and Lockhart.<sup>18</sup> Sample preparation involved removal of all polymeric materials followed by contacting aqueous samples with 20% v/v of hexane. Samples were vigorously agitated for 3 min followed by 2 min of centrifugation to ensure separation and recovery of the solvent extract. Hexane extract was then injected into an HP 5890 GC equipped with a split/splitless injector, SPB-1 fused silica capillary 30 m and a 0.25 mm inner diameter (Agilent, USA) and FID detection. The injector temperature was 225°C and the detector temperature was 300°C. Oven temperature was programmed to ramp up from 40 to 150°C at a rate of 10°C/min followed a 12°C/min increase in temperature until the oven reached 280°C, at which time temperature was held for 15 min. The total run time was 42.83 min. External diesel standards were used to quantify the concentration of diesel present in aqueous samples. Negative controls were performed to confirm the use of contaminant (diesel) free water and solvent, and positive controls were used to assess the extraction efficiency and reproducibility of the process.

Biomass concentrations were determined as optical density using a Biochrom Ultraspec 3000 UV/Vis spectrophotometer at a wavelength of 650 nm.

### Sorption of diesel from water using polymeric materials

Preliminary polymer selection utilized three model contaminant hydrocarbons (CO, HMN, and OCT) to assess the affinity for diesel among a wide range of candidate polymers. Select polymers were screened for their ability to remove the three model hydrocarbons from methanol. Methanol was used as it enabled greater loading of the model compounds, compared to water, and simplified analytics thus permitting investigation of a greater number of potential adsorbents.

Experiments were carried out in 20-mL glass vials to which 5 mL of methanol, 0.5 g of candidate polymer, and equal parts of the three model contaminants were added. The concentration of the model contaminants ranged between 50

**Table 1. List of Polymeric Materials Use in the Study their Suppliers, and Their Structure**

| Polymer         | Supplier                    | Molecular Structure                 |
|-----------------|-----------------------------|-------------------------------------|
| SBS             | Kraton (USA)                | Styrene-butadiene-styrene copolymer |
| RRT             | Recovery Technologies (CAN) | Recycled rubber tire (automobile)   |
| PEL             | Sigma Aldrich (USA)         | Low density polyethylene            |
| PET             | Recycled water bottle       | Polyethylene terphthalate           |
| Desmopan (PU)   | Bayer (GER)                 | polyurethane                        |
| EVA 40W         | Dupont (CAN)                | Ethylene vinyl acetate              |
| Silicone rubber | Mastercraft (CAN)           | polydimethylsiloxane                |

and 2,000 mg/L in order to provide a partition relationship between methanol and polymer which would then be used for performance comparison. The vials were sealed and agitated at 200 rpm and 20°C for a 48-h period after which the methanol was analyzed via GC. The mass of hydrocarbons sorbed by the polymer was determined by subtracting the mass of hydrocarbons in the water from the mass of hydrocarbons within polymer free control vials.

Preliminary polymer selection resulted in the selection of two candidate polymers for further study involving the recovery of diesel from water. Experiments were carried out in 20-mL glass vials containing 10 mL of water and 0.5 g of polymer. The concentration of diesel within the vials was varied from 500 to 10,000 mg/L and therefore included both dissolved as well as free diesel fractions. The vials were sealed and then agitated at 200 rpm and 20°C for 7 days, after which time the water was assayed for the presence of diesel as described above.

The effect of varying the mass fraction of sorbent to water was investigated. Experiments were performed in an identical manner as the sorption tests described previously. Glass vials contained an initial diesel concentration of 5,000 mg/L to which varying mass fractions of sorbent were added ranging between 1 and 20%. The vials were sealed and agitated for 24 h after which time the water was assayed for diesel.

The rate at which diesel was absorbed from water by the polymers was also studied. Experiments were carried out in a similar manner as described above however, this experiment used ten 20-mL glass vials containing an initial diesel concentration of 5,000 mg/L. The vials were sealed and agitated as described above and were periodically sacrificed (starting at  $t = 5$  min) and analyzed to determine the concentration of diesel remaining in the water.

The rate of diesel release from diesel loaded polymers into aqueous medium was qualitatively assessed. Loading of the polymer beads with diesel occurred in a 1,000-mL shake flask. Polymers (100 g) were contacted with 50 mL of diesel in a 300 mL of distilled water. The water was present to facilitate mixing and assist in the even distribution of both polymer and diesel. The shake flask was agitated at 180 rpm and 20°C for 24 h after which the polymers were removed from the shake flask, lightly dried with a paper towel to remove excess water and then placed within a Bioflo III bioreactor (New Brunswick Scientific, USA) containing 2 L of minimal salts medium.<sup>19</sup> The system was agitated at 175 rpm and maintained at 30°C and a pH of 6.7 with an aeration rate of 1 L/min. Water samples were periodically taken and analyzed for the presence of diesel.

Methanol was chosen as an extractant for the desorption of diesel from the polymers as it was shown to have no effect on the physical structure of the polymers. Desorption experiments occurred in 20-mL glass vials in which a small mass of polymer (0.1–0.5 g) was contacted with 5 mL of methanol. The vials were sealed and agitated at 200 rpm and 20°C for 24 h. A partition coefficient for diesel between methanol and polymer was determined and based on the concentration of diesel within the methanol extract, the mass of diesel remaining in the polymer was calculated. Desorption tests were carried out to determine the biodegradative loss of diesel during polymer regeneration experiments.

### ***Selective enrichment of a diesel degrading microbial consortium***

A microbial consortium capable of degrading diesel as the sole source of carbon was enriched from a sample of diesel contaminated soil. Selective enrichment was carried out in a 125-mL shake flask containing 0.5 g of soil, 50 mL of tryptic soy broth medium (TSB) and 500 mg/L of diesel provided selection pressure. The flask was incubated for 48 h at 180 rpm and 30°C after which time the content of the flask were centrifuged at 3,500 rpm for 15 min. The supernatant was decanted and the cell pellet was washed in fresh mineral salts medium.<sup>19</sup> The cells were centrifuged and supernatant decanted for a second time after which the cell pellet was resuspended in minimal salts medium and used to inoculate a seed reactor (Bioflo I bioreactor, New Brunswick Scientific) containing 1 L of minimal salts medium and diesel (1,000 mg/L) serving as the sole source of carbon. The reactor was maintained at 30°C, agitated at 200 rpm and aerated at 100 mL/min. The system was fed 1,000 mg/L of diesel every other day to ensure adequate growth and medium losses were replaced with fresh mineral salts medium as required. The seed bioreactor was operated for a period of 3 weeks.

### ***Biological regeneration of polymeric sorbent***

Polymeric sorbent loaded with diesel was regenerated via microbial degradation representing a strategy for treatment of the polymer beads. One hundred grams of polymers were initially loaded with ~300 g diesel / kg polymer. The polymers were placed in a Bioflo III (New Brunswick Scientific, USA) bioreactor containing 2 L of aqueous medium<sup>19</sup> and the system was maintained at a pH of 6.7, an aeration rate of 1 L/min, a temperature of 30°C and agitated at 175 rpm. The system was inoculated with a microbial consortium taken from the seed reactor. Biomass concentrations were monitored as described previously and the disappearance of diesel was determined through desorption of polymer beads in methanol. A sterile control reactor, void of biomass, was operated under identical conditions to monitor the abiotic fate of diesel within the system.

## **Results and Discussion**

### ***Sorption of diesel from water using polymeric materials***

The absorption and release of small organic molecules into polymeric materials has been shown to be analogous to that of solvent extraction.<sup>20</sup> Much work has been done in the

area of solvent selection, as applied to its use within TPPBs<sup>21</sup> and this research has served as the basis for work pertaining to the identification of polymeric materials possessing affinity for target contaminants.<sup>19</sup> To further assist the selection process a guideline was developed to direct polymer selection and of the list of criteria compiled, cost and polymeric structure (as it relates to polarity) were the most notable.<sup>22</sup> These criteria formed the basis of the systematic screening process used to identify candidate sorptive materials for recovery of diesel from water.

Because of the highly non-polar nature of diesel,<sup>23</sup> it was anticipated that polymers composed of non-polar structures would possess superior absorptive affinity. Polymers such as styrene butadiene styrene copolymer (SBS), recycled rubber tire (RRT), and low-density polyethylene (PEL) were chosen for this reason while polymers containing polar structures, such as ethylene-co-vinyl acetate (EVA) and polyurethane (PU) were chosen, essentially as negative controls, to demonstrate the inability of these polymers to sorb hydrocarbons. Recyclable materials, such as RRT, PEL, and polyethylene terephthalate (PET), were investigated for use within this study as they satisfied the criteria of low cost. Utilization of recyclable materials is also advantageous as it represents an additional application for waste materials once their initial service is complete and use of recyclables avoids generation of new sorptive materials.

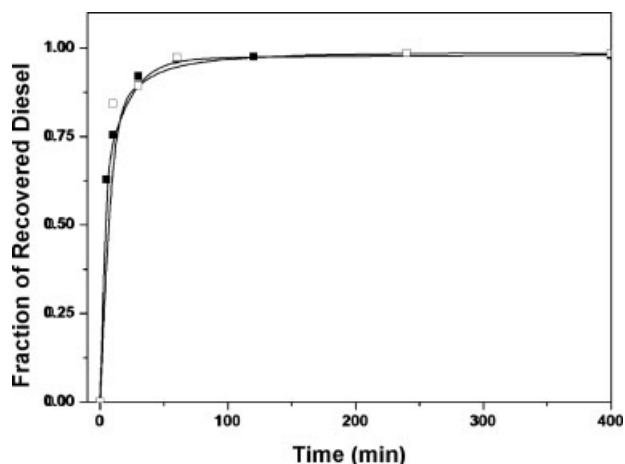
Preliminary polymer screening was used to quickly identify suitable polymers capable of sorbing hydrocarbon contaminants. To expedite the selection process, three model hydrocarbons were contacted with the sorptive materials. The three model hydrocarbons cyclooctanol (CO), 2,2,4,4,6,8,8-heptamethylnonane (HMN), and 1-octadecene (OCT) representing cyclic, branched, and long chain hydrocarbons, respectively, were selected to embody the key components of a diesel mixture and to simplify analytics. On the basis of the results SBS, RRT, and silicone demonstrated superior sorptive affinity (data not shown). Two common recyclable materials, PET and PEL, did not remove an appreciable mass of hydrocarbons and this may be attributed to their highly crystalline nature which hinders absorption of hydrocarbons within their polymer structure.<sup>9</sup> As predicted, EVA and PU were unable to absorb any of the model hydrocarbons, possibly due to the polar segments contained within their structure. As a result of this study, SBS and RRT were chosen for further study. In addition to their superior sorptive capacity, use of SBS and RRT benefit from low cost (US\$3.30 and US\$0.55 per kg), commercial availability and in the case of RRT represents waste reuse.

SBS and RRT were used to investigate the potential of sorptive materials to remove diesel from water. The extremely low-water solubility of diesel, as a whole, makes it difficult to quantify a traditional partition coefficient for diesel between water and a polymer, therefore, the efficacy for which a polymer removes diesel (both in solution and as free fractions) from the aqueous system was used to describe performance.

Table 2 provides the results of diesel removal from water using SBS and RRT. On the basis of these results, SBS was able to remove in excess of 98% of initial diesel levels while RRT removed 99%. This affinity for diesel was expected as in the literature styrene butadiene derived polymers have been reported to absorb 40–75 times their mass in oil.<sup>24</sup> This report supports the selection of SBS and RRT for the recovery of diesel however, as the aim of the current study was to

**Table 2. Recovery of Diesel from Water Using SBS and RRT**

| Polymeric material | Initial aqueous concentration (mg/L) | Final aqueous concentration (mg/L) |
|--------------------|--------------------------------------|------------------------------------|
| SBS                | 860                                  | 9.5                                |
|                    | 1770                                 | 4.5                                |
|                    | 6470                                 | 74                                 |
|                    | 8340                                 | 27                                 |
| RRT                | 10960                                | 121                                |
|                    | 500                                  | 7.2                                |
|                    | 1260                                 | 5.5                                |
|                    | 5040                                 | 10.9                               |
|                    | 7300                                 | 12.5                               |
|                    | 11980                                | 22.6                               |

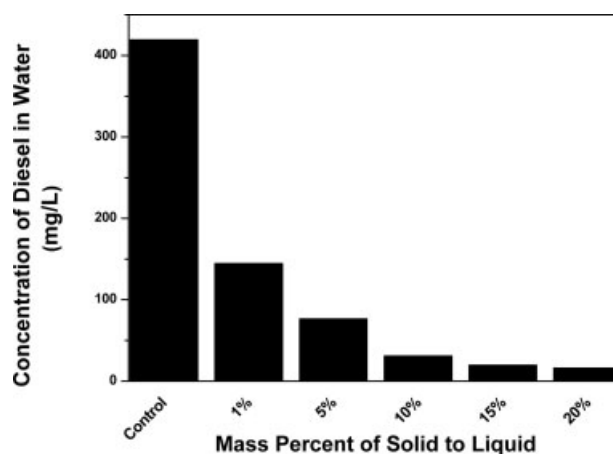
**Figure 1. Rate of diesel recovery from water.**

Solid squares represent recovery with RRT and hollow squares represent recovery with SBS. Solid lines represent sorption trends.

recover relatively dilute levels of diesel from water it may be unreasonable to expect such high loadings.

Given the efficacy of SBS and RRT to remove diesel from water over a selected range of initial concentrations, performance of the sorptive materials, in particular rate of removal and most effective solid to liquid ratio, were investigated. In the event that diesel is released into an aqueous environment it is imperative that the contaminant be recovered in a rapid manner to minimize migration and mitigate toxic effects imparted upon the natural biota. As result, the rate at which SBS and RRT would recover diesel from water was assessed (Figure 1). Uptake of diesel was rapid for both polymeric systems with 90% of total absorbed diesel fraction taken up in 20 min.

From a practical consideration, understanding the most advantageous solid to liquid mass ratio at which to operate would minimize material requirement and limit cost. The dominant mechanism of diesel recovery by SBS and RRT is absorption and this differs from a surface adsorption phenomenon which is responsible for diesel removal in organoclay, granular activated carbon (GAC), and polymeric/natural fibre mats.<sup>6</sup> Although both phenomena require contact between diesel and the sorptive material to facilitate recovery, the capacity of absorptive systems is not affected by reduced surface to volume ratios. As result, a favorable solid to liquid ratio should exist and based on the results (Figure 2) it appears that, for the given 24 h experiment an effective solid to liquid ratio was between 5 and 10% (Figure 2), with “diminishing returns” being observed at higher ratios. The

**Figure 2. Effect of the solid to liquid mass ratio of polymer on diesel recovery from water.**

The control value represents the starting concentration of diesel in all the experimental systems.

data presented in Figure 2 also confirm that the underlying mechanism is absorption rather than surface adsorption. If the system operated purely on surface sorption the capacity for diesel or any other target compound would increase linearly with the available surface area. The observed diminishing returns (Figure 2) are typical for equilibrium partitioning as seen is solvent extractions, an absorption phenomenon, where sequential extraction steps would yield higher extraction efficiencies. Although surface adsorption may play a role in the removal of diesel from water using SBS and RRT, absorption is the predominant mechanism.

The rapid sorption of diesel suggests the potential use of SBS and RRT as sorbents in the continuous treatment of contaminated water. Given the relative abundance of RRT, in addition to its inexpensive nature, it may be ideally suited as a preliminary filtration medium to reduce the impact of heavily polluted waters on granular activated carbon (GAC) polishing units. A similar example application has been previously described by Alther<sup>7</sup> who used an organoclay filter to reduce contaminant loading entering a GAC filter thus enhancing operational times and reducing replacement costs of GAC. Unlike organoclay, RRT is less difficult to handle and possesses the capacity to be regenerated, thus permitting reuse.

### **Biological regeneration of polymeric sorbent**

The aim of this aspect of the study was to demonstrate the regeneration of the polymer sorbent in an environmentally benign manner to allow for future polymer reuse, and to provide a means for the ultimate destruction of the contaminants. This concept of polymer regeneration and contaminant destruction was carried out in a two-phase partitioning bioreactor (TPPB) in which the polymer sorbent served as a reservoir and delivery agent of diesel to an awaiting mixed microbial population. The capacity of microbes to metabolize hydrocarbons has been widely reported<sup>11</sup> and for this study a microbial consortium was selectively enriched from a sample of hydrocarbon contaminated soil. Growth of the microbial consortium in the seed reactor occurred solely on diesel and over a period of 3 weeks cell concentration was observed to steadily increase (data not shown) thus indicating growth and viability.



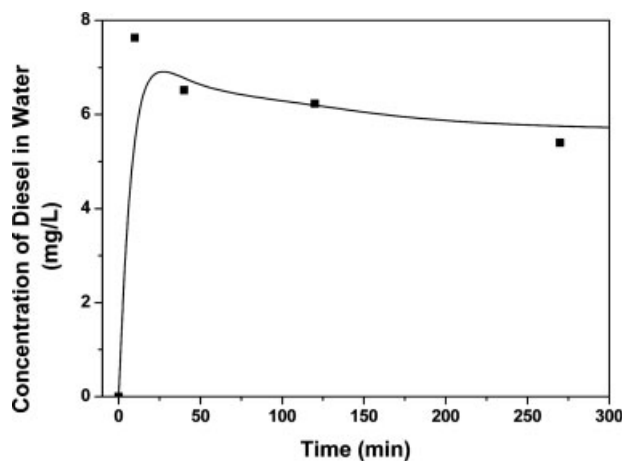


Figure 3. Rate of diesel transport from diesel loaded SBS into water.

Solid line illustrates the trend of diesel release into the water.

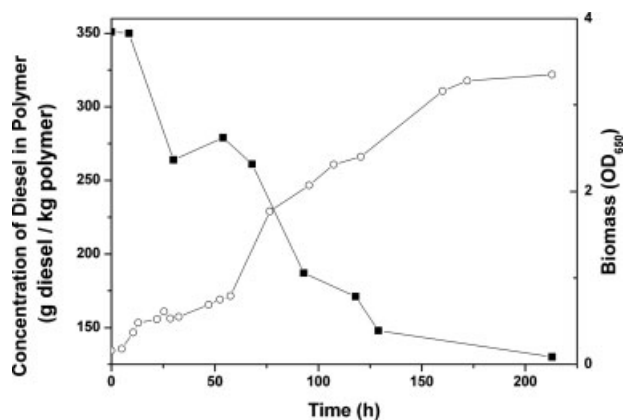


Figure 4. Regeneration of diesel loaded SBS. Circles represent the accumulation of biomass.

Squares represent diesel concentration in SBS. Diesel concentration in SBS was determined via desorption of a small mass of SBS polymer.

Timely delivery of substrate in a TPPB is imperative and an experiment was performed to assess the capacity of SBS to release diesel into the aqueous medium. On the basis of the results (Figure 3), diesel is rapidly released from the polymer with a diesel level of 8 mg/L achieved within 5 min. The system maintained this concentration of diesel after a 7 day period thus confirming that the system was in equilibrium. The rapid release of diesel from the polymer ensures that the microbes will be supplied with a continual source of substrate.

Regeneration of polymeric materials in TPPBs has been shown previously to be an effective means of contaminant destruction<sup>19,25</sup> and has been shown to enhance biodegradative capacity.<sup>15</sup> In this study, SBS polymers were regenerated in a TPPB over a 9 day period. During this period, diesel levels within the polymer were reduced by ~65% (Figure 4). Loss of diesel was attributed to biodegradation as shown by the increase in biomass during this period, in addition to operation of a parallel sterile control which showed only a 10% loss in diesel.

Similar extents of diesel biodegradation have been reported in the literature, for example, Vieira, et al.<sup>14</sup> observed a biodegradative removal efficiency of ~60%. The inability of the microbes to fully metabolize the entire mass

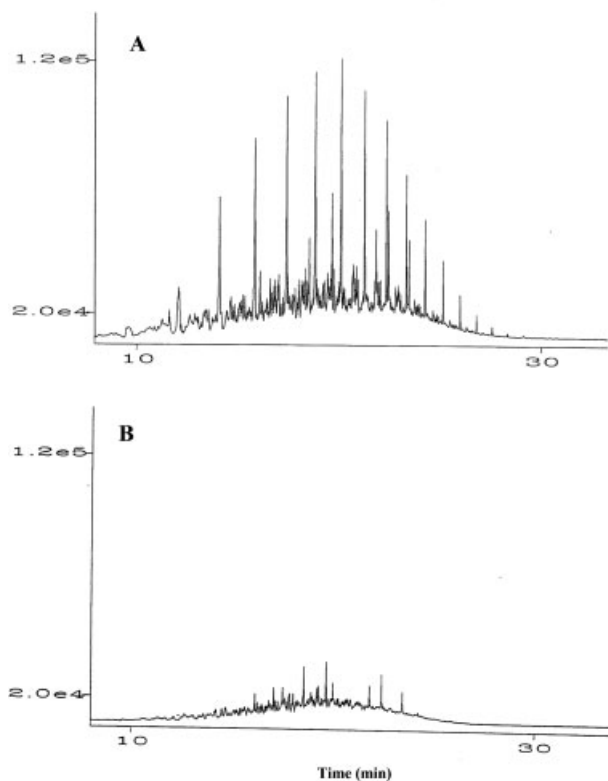


Figure 5. GC chromatograph illustrating the presence of diesel within SBS at the start of the remediation process (A) and at the conclusion,  $t = 9$  days (B).

The sharp peaks in A represent linear hydrocarbons while the chromatographic hump represents the unresolved complex mixture (A and B). The  $x$ -axis represents time and the  $y$ -axis represents the signal output.

of diesel may be due to its complex nature as it consists of a mixture of linear hydrocarbons and more heavily substituted aromatic compounds.<sup>23</sup> Inspection of chromatographs taken at the onset of the experiment and after 9 days (Figure 5), reveal that most of the linear hydrocarbons (large chromatographic peaks) were rapidly degraded, while the less degradable unresolved complex mixture (chromatographic hump) remained. It is possible that the microbial population used in this study metabolized the more easily degradable linear hydrocarbon compounds and were unable to attack the more recalcitrant diesel fractions contained within the unresolved complex mixture. A study by Penet et al.<sup>26</sup> has shown similar biodegradative behavior as observed in this study. Penet was able to show that although microbes from uncontaminated soils may degrade diesel, far superior biodegradation removal efficiencies may be achieved using microbes from contaminated soils. It is not unreasonable to assume that the microbes enriched for in this study were not well adapted to metabolizing the full range of diesel compounds and to address this issue, future work may involve selective enrichment of more heavily contaminated soil.

In addition, due to the more hydrophobic nature of many of the remaining recalcitrant compounds, particularly those contained within the unresolved complex mixture, it is reasonable that release of these contaminants from the polymer was inhibited. Studies have shown that release of hydrophobic compounds, such as polychlorinated biphenyls, from polymeric materials is limited and their slow release may negatively affect microbial activity.<sup>25</sup> With many of the

linear hydrocarbons degraded and delivery of the recalcitrant compounds impeded, the microbial consortium may not have been supplied with sufficient substrate to ensure survival. Work is currently being performed to develop a means of enhancing the desorption and delivery of toxic substrates from polymers into aqueous solution.

The method developed in this study described a technique for the rapid recovery of diesel from water coupled with the degradative capacity of microbes to remediate the diesel laden sorbent thus enabling its reuse. SBS and RRT demonstrated excellent percent recovery of diesel from water (in excess of 98%). As well, the rate of recovery was rapid with both systems achieving 90% removal within less than 30 min. Using a two-phase partitioning bioreactor, the polymeric material was regenerated thus enabling its reuse. The proposed system is beneficial as it is operated under ambient conditions, makes use of a waste material otherwise destined for a landfill and permits regeneration of sorbent material in an environmentally benign manner.

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### Literature Cited

- Li J, McAteer P. Urban oil spills as a non-point pollution source in the golden horseshoe of southern Ontario. *Water Qual Res J Can.* 2000;35:331–340.
- Bhattacharyya S, Klerks PL, Nyman JA. Toxicity of freshwater organisms from oils and oil spill chemical treatments in laboratory microcosms. *Environ Pollut.* 2003;122:205–215.
- Lytle DA, Peckarsky BL. Spatial and temporal impacts of a diesel fuel spill on stream invertebrates. *Freshwater Biol.* 2001;44:693–704.
- Khan N, Warith MA, Luk GA. Comparison of acute toxicity of biodiesel, biodiesel blends, and diesel on aquatic organisms. *Air Waste.* 2007;75:286–296.
- Adebajo MO, Frost RL, Klopogge JT, Carmody O, Kokot S. Porous materials for oil spill cleanup: a review of synthesis and absorbing properties. *J Porous Mater.* 2003;10:159–170.
- Carmody O, Frost R, XI Y, Kokot S. Adsorption of hydrocarbons on organo-clays-implications for oil spill remediation. *J Colloid Interface Sci.* 2007;305:17–24.
- Alther G. Using organoclays to enhance carbon filtration. *Waste Manag.* 2002;22:507–513.
- Lim TT, Huang X. In situ oil/water using hydrophobic-oleophilic fibrous wall: a lab-scale feasibility study for groundwater cleanup. *J Hazard Mater.* 2006;B137:820–826.
- Choi HM, Cloud RM. Natural sorbents in oil spill cleanup. *Environ Sci Technol.* 1992;26:772–776.
- Tungittiplakorn W, Lion LW, Cohen C, Kim JY. Engineered polymeric nanoparticles for soil remediation. *Environ Sci Technol.* 2004;38:1605–1610.
- Atlas RM. Microbial degradation of petroleum hydrocarbons: an environmental perspective. *FEMS Microbiol Rev.* 1981;45:180–209.
- Hess A, Hohener P, Hunkler D, Zeyer J. Bioremediation of a diesel fuel contaminated aquifer: simulation studies in laboratory aquifer columns. *J Contam Hydrol.* 1996;23:329–345.
- Olson JJ, Mills GL, Herbert BE, Morris PJ. Biodegradation rates of separated diesel components. *Environ Toxicol Chem.* 1999;18:2448–2453.
- Vieira PA, Vieira RB, Franca FP, Cardoso VL. Biodegradation of effluent contaminated with diesel fuel and gasoline. *J Hazard Mater.* 2007;140:52–59.
- Ward O, Singh A, Van Hamme J. Accelerate biodegradation of petroleum hydrocarbon waste. *J Ind Microbiol Biotechnol.* 2003;30:260–270.
- Prpich GP, Adams RL, Daugulis AJ. Ex situ bioremediation of phenol contaminated soil using polymer beads. *Biotechnol Lett.* 2006;28:2027–2031.
- Amsden BG, Bochanusz J, Daugulis AJ. Degradation of xenobiotics in a partitioning bioreactor in which the partitioning phase is a polymer. *Biotechnol Bioeng.* 2003;84:399–405.
- Murray DAJ, Lockhart WL. Microextraction and gas chromatographic analysis of selected petroleum hydrocarbons in water and fish tissue. *J Chromatogr.* 1981;212:305–311.
- Prpich GP, Daugulis AJ. Biodegradation of a phenolic mixture in a solid-liquid two phase partitioning bioreactor. *Appl Microbiol Biotechnol.* 2006;72:607–615.
- Schumack L, Chow A. Extraction of aromatic organic compounds by polyurethane foam. *Talanta.* 1987;34:957–962.
- Bruce LJ, Daugulis AJ. Solvent selection strategies for extractive biocatalysis. *Biotechnol Prog.* 1991;7:116–124.
- Rehmann L, Daugulis AJ. Polymer selection for biphenyl degradation in a solid-liquid two phase partitioning bioreactor. *Biotechnol Prog.* 2007;23:814–819.
- Marchal R, Penet S, Solano-Serena F, Vandecasteele. Gasoline and diesel oil biodegradation. *Oil Gas Sci Technol.* 2003;58:441–448.
- Zhou MH, Cho WJ. Oil absorbents based on styrene-butadiene rubber. *J Appl Polym Sci.* 2003;89:1818–1824.
- Rehmann L, Daugulis AJ. Biodegradation of PCBs in two-phase partitioning bioreactors following solid extraction from soil. *Biotechnol Bioeng.* 2008;99:1273–1280.
- Penet S, Vendevre C, Bertoncini F, Marchal R, Monot F. Characterisation of biodegradation capacities of environmental microflora for diesel oil by comprehensive two-dimensional gas chromatography. *Biodegradation.* 2006;17:577–585.

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