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Microbial uptake of diesel oil sorbed on soil and oil spill clean-up sorbents

Subhasis Biswas, Sanjeev K Chaudhari and Suparna Mukherji*
Centre for Environmental Science and Engineering (CESE), Indian Institute of Technology Bombay, Powai, Mumbai-400076, India

Abstract: Sorbent effects in the microbial uptake of diesel oil were determined for black cotton soil (BCS) and two oil spill clean-up sorbents, ie peat sorb and spill sorb. Biodegradation studies were conducted in mass transfer limited batch slurry microcosms using microorganisms capable of direct interfacial uptake of diesel oil. Under identical loading conditions, the amounts of diesel oil initially loaded on the various sorbents were 178, 288 and 649 mg g^{-1} for BCS, spill sorb and peat sorb, respectively. Total biodegradation of sorbed diesel was comparable for all the sorbents (45–52 mg), however, the biodegradation rates were significantly different. Peat sorb demonstrated a distinct initial lag phase, the biodegradation rate in spill sorb was initially slower, whereas biodegradation at a high rate commenced immediately for BCS. The maximum biodegradation rates observed for BCS, spill sorb and peat sorb microcosms were 7.9, 5, and 2.9 mg day^{-1}, respectively. Thus, the maximum biodegradation rate increased as the diesel oil loading decreased. Our results indicate that spill clean-up sorbents have greater bioavailability limitations compared with soils and this is linked with their significantly higher loading capacity and internal porosity.

Keywords: diesel oil; clean-up; microbial degradation; biodegradation; bioavailability; sorption; NAPL

INTRODUCTION

Million of tons of oil are spilled each year, accidentally and deliberately, into the environment during transport, storage and processing of the oil. For example, the *Exxon Valdez* incident in 1989 released 11.2 million gallons of crude oil into the Alaskan region. These spills have major adverse effects on the adjacent ecosystem and also pose detrimental social and economic consequences.[1–3]

Oil spill clean-up sorbents have been historically used to contain oil spilled in the sea. These sorbents can be classified into three groups, namely inorganic mineral products, organic synthetic products and organic vegetable products. The inorganic mineral products include perlite, vermiculites, sorbent clay, dolomite, graphite, etc. These materials do not show adequate buoyancy and their oil sorption capacity is generally low. The organic vegetable products are generally natural fibres, such as kenaf, cotton, and milkweed floss. These sorbents are preferred as they are mostly biodegradable and safe for disposal. Some synthetic products, eg polypropylene, polyurethane foam, polyethylene terephthalate (PET) and teflon, are also widely used in oil spill clean-up due to their low cost and availability. The oil sorption capacities of these sorbents are generally high and vary depending upon the type of sorbent over a range of 0.26–86 g of oil per unit mass (g) of sorbent. Although a significant portion of oil can be recovered from some sorbents, such as fir fibres and exfoliated graphite, such that they can be reused for a few cycles, the eventual disposal of these sorbents with sorbed residual oil remains an important issue. Incineration or landfilling of sorbents is not desirable due to the adverse environmental effects often associated with these techniques, ie toxic air emissions and subsurface soil and groundwater contamination by oil components.[4–9] For used oil spill clean-up sorbents and contaminated soil, bioremediation may be an effective remediation technique. Extensive studies have been carried out for determining the bioremediation potential of terrestrial soil contaminated with oil.[10–18] However, no significant research, except by Setti *et al*,[6] has been reported for biodegradation of oil sorbed on spill clean-up sorbents.

Bioavailability plays an important role in biodegradation of oil. In two-phase systems (water–oil), several studies have indicated that the rate of dissolution from a NAPL (non-aqueous phase liquid) determines the rate of microbial uptake and dissolution is facilitated by microorganisms producing external biosurfactants and bioemulsifiers.[19–21] Yet other studies have reported direct uptake of oil from the oil–water interface by microorganisms that attach to

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* Correspondence to: Suparna Mukherji, Centre for Environmental Science and Engineering (CESE), Indian Institute of Technology Bombay, Powai, Mumbai-400076, India
E-mail: mitras@iitb.ac.in

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the interface.[22,23] Increased cell-surface hydrophobicity induced in response to growth on a NAPL has been implicated in facilitating uptake. However, in three-phase systems when oil is sorbed on a sorbent, its accessibility to microorganisms may decrease further. Several researchers have demonstrated that sorbed compounds initially remain loosely bound on to the soil surfaces or remain in the soil macropores from where desorption is rapid, thus leading to high initial uptake. However, with time the compounds penetrate further and enter into the micropores, and become highly desorption-resistant.[24–27] A few studies suggest that sorbed compounds are directly available to microorganisms without prior desorption.[28–30] This has been attributed to the capability of certain microorganisms to attach to interfaces of sorbed/separate phase substrate using surface structures such as fimbriae and capsules. Setti *et al*[6] have reported enhanced bioavailability of oil sorbed on oil spill clean-up sorbents such that overall biodegradation was higher in systems with sorbents in comparison to systems without sorbent. This was attributed to improved interaction between the oil and the microorganisms derived from the formation of water–cell–sorbent interfaces.

The present study was designed around three sorbents, a soil and two oil spill clean-up sorbents. The biodegradability of diesel oil sorbed on these sorbents was studied using a culture, designated as ES1, with demonstrated capability of direct interfacial uptake in a two-phase oil–water system. The main objective of this study was to determine and compare the impact of sorption phenomenon on bioavailability of diesel oil for a soil as well as for two oil spill clean-up sorbents so as to understand the mechanistic difference. Bioavailability limitations for spill clean-up sorbents have not been previously reported in the literature. Such a study would also indicate the risk involved in disposing of spent oil spill clean-up sorbents in the environment and the feasibility of using biodegradation as a tool for removing oil from the sorbents so as to facilitate sorbent reuse. If the oil is sequestered within the sorbent such that microbial uptake occurs at a very slow rate even under favourable conditions, reuse of sorbents is not practically feasible. The sorbents used included peat sorb and spill sorb.

MATERIALS AND METHODS

Microbial culture

The microorganisms used in this study were enriched from deep sea sediments procured from the Enron oil field in Bombay High (Mumbai, India). Mukherji *et al*[31] have demonstrated that this bacterial culture (ES1) is capable of utilizing diesel as the sole source of carbon and energy. Although uniform colony types are observed on plates, ongoing studies on TEM imaging (Transmission Electron Microscope, FEI TECNAI G2 12, Eindhoven, Netherlands) reveal two distinctly different types of rod-shaped cell morphologies, short thicker rods and elongated rods, 1.2 and 1.7 µm in length, respectively (unpublished results). Biochemical tests indicate they belong to the genus *Pseudomonas*. Growth characteristics of the ES1 culture on diesel oil (500 cm^3 flask containing 100 cm^3 media and 1 cm^3 diesel oil) and the rate and extent of diesel oil degradation by the ES1 cultures has been reported by Mukherji *et al.*[31] The lag period was found to be 3–4 days or less, depending on the initial concentration of microorganisms spiked, media conditions and age of the inoculating culture. The stationary phase commenced at about 4 days beyond the lag phase, ie typically at beyond 7–8 days. The concentration of diesel-degrading microorganisms at the end of log growth phase was about 2×10^8 [most probable number (MPN) cm^{-3}]. No evidence of diauxic growth was observed in spite of the complex composition of the substrate, diesel oil. In these sorbent-free batch cultures with 1 cm^3 diesel, actively growing ES1 cultures could degrade 39% of diesel oil in 8 days where abiotic losses could account for only 10%; 80% of the degradation was of aliphatics. Column chromatography indicated 73% of the diesel used is comprised of aliphatics whereas 18% is aromatic. In two-phase systems the maximum diesel degradation rate observed was 87 mg day^{-1} for an initial oil loading of 820 mg. The cultures did not demonstrate toxicity to oil components, moreover, cultures acclimatized to diesel oil over a period of time showed poor growth characteristics on dextrose. Ongoing studies reveal that this culture utilizes diesel oil by direct interfacial uptake as indicated by high cell surface hydrophobicity and negligible release of extracellular biosurfactants and bioemulsifiers (unpublished results).

Sorbents

Black cotton soil (BCS) was obtained from Sahapur, Maharashtra, India, while peat sorb and spill sorb were procured from Ladji Polycrafts (P) Ltd and Jayant Bros & Co (P) Ltd (Mumbai, India) respectively. Soil samples were dried, ground and sieved through 0.7 mm mesh. Spill sorb and peat sorb were used as received. The organic matter content of these sorbents was determined by loss on ignition method by putting the pre-weighed samples in a muffle furnace at 600 °C for 15 min. The moisture content was measured by oven drying. Particle density and bulk density, of these sorbents were also determined using methods outlined in Ref 32. The sorbents characteristics are listed in Table 1.

The maximum diesel oil loading capacities for black cotton soil, spill sorb and peat sorb were 0.21 g g^{-1}, 1.18 g g^{-1} and 4.35 g g^{-1}, respectively, measured in the presence of the bulk water phase. When measured in the dry state the capacities were about 1.6 times higher.

Slurry microcosms for diesel biodegradation

Each microcosm was a batch slurry system comprising sorbent and aqueous phase at a fixed ratio of

Table 1. Characterization of sorbents

Sorbent	Form and size	Moisture (% wt)	Organic matter content (% wt)	Particle density (g cm^{-3})	Bulk density (g cm^{-3})
BCS	Sieved through 0.7 mm mesh	7.45 ± 0.88	8.31 ± 0.06	2.48	1.24
Spill sorb	Granular, passed through 2.8 mm mesh	3.22 ± 1.22	53.86 ± 0.85	1.04	0.34
Peat sorb	Loosely packed, powder form, passed through 1.7 mm mesh	13.47 ± 0.45	89.98 ± 0.53	1.60	0.16

1:10 (w/w) contained in a 120 cm^3 crimp-sealed serum bottle. The sorbent comprised 4 g of soil or 1 g of an oil spill clean-up sorbent. Use of a larger mass of soil compared with spill clean-up sorbents was necessitated by the significantly lower diesel oil loading capacity of the soil and due to its larger bulk density compared with that of the spill clean-up sorbents. The sorbents were autoclaved five times at 120 °C at 15 psi to kill the indigenous heterotrophic microorganisms. The sorbents were first equilibrated for 2 days with 1 cm^3 of filter-sterilized diesel. Sorption was facilitated by tumbling the crimp-sealed serum bottles end to end at 6 rpm in a tumbler (Trishul, Mumbai, India) in the dark for 2 days. Subsequently, the supernatant was removed by centrifuging at 2000 rpm for 10 min and replaced by an equivalent volume of sterile mineral media. The nutrient media composition was as specified in earlier studies (media 2).[31] The liquid medium was inoculated with 0.5 cm^3 of ES1 culture in the late log growth phase to ensure a high initial concentration of cells in the microcosms. The serum bottles were tumbled end to end at 6 rpm in the dark. At each predetermined time interval, a set of bottles was taken out, including controls without microorganisms. The two experimental vials were analysed for diesel oil content in the supernatant as well as in the sorbed phase. The supernatant diesel oil content was determined by liquid–liquid extraction and corrected with the predetermined extraction efficiency. The residual diesel oil associated with the sorbent was determined by Soxhlet extraction with dichloromethane as per Ref 11. The values were corrected for artifacts caused by extraction of waxes and appropriate predetermined extraction efficiencies, as depicted in Table 2, were applied. The amount of diesel oil degraded was determined by comparing with the controls. Only one set of controls was available. Statistical analysis was performed by propagation of error assuming the same average percent error in controls as for the experimental microcosms. Quantification of hydrocarbon-degrading microorganisms at any time was performed by sacrificing a pair of experimental vials. Mineral medium was added to the vials which were subsequently vortex-mixed for 5 min to resuspend microorganisms into the aqueous phase. The aqueous phase was sampled, appropriately diluted and the number of hydrocarbon degraders determined by the most probable number (MPN) method adopted and modified from Song and Bartha.[10] A set of five tubes was used for each dilution. Each tube contained 5 cm^3 mineral medium, 1 mg dm^{-3} resazurin and 50 mm^3 sterile diesel. Colour change due to reduction of resazurin by microbial oxygen consumption was observed after 7 days of incubation at 30 °C, and the MPN values were obtained from the MPN index for five tubes.

Table 2. Soxhlet extraction of sorbents

Sorbent	Extraction efficiency of diesel oil (%)	Solvent extractables in sorbent without oil (%)
BCS	97.17 ± 0.28	–
Peat sorb	92.12 ± 0.52	4.73 ± 0.58
Spill sorb	87.57 ± 0.42	5.76 ± 0.33

RESULTS AND DISCUSSION

Diesel biodegradation on the three sorbents, normalized to initial diesel loading, is reported in Fig 1. The initial mass of diesel oil in the BCS, spill sorb and peat sorb microcosms was determined as 178 ± 3 mg, 288 ± 7 mg and 649 ± 11 mg, respectively, based on the zero-day controls. This represents loading at 21%, 24% and 15% of the maximum loading capacity, respectively. The residual mass of diesel oil in the aqueous supernatant was found to be negligible and close to the detection limit in all the microcosms (less than 6 mg over the entire period) and some random variations were observed.

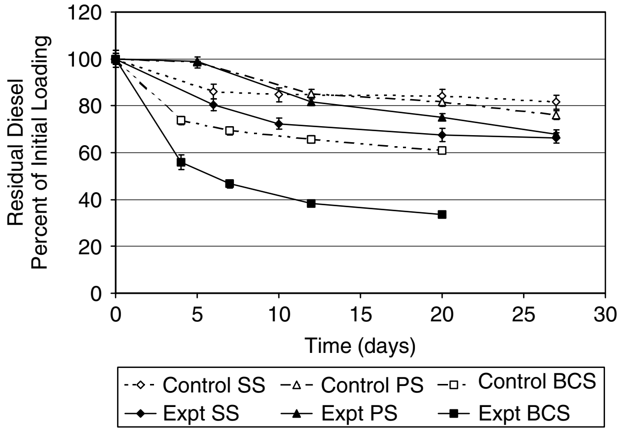

Figure 1. Percent residual diesel in various sorbent microcosms normalized to initial diesel loading (error bars represent standard deviation about the mean value).

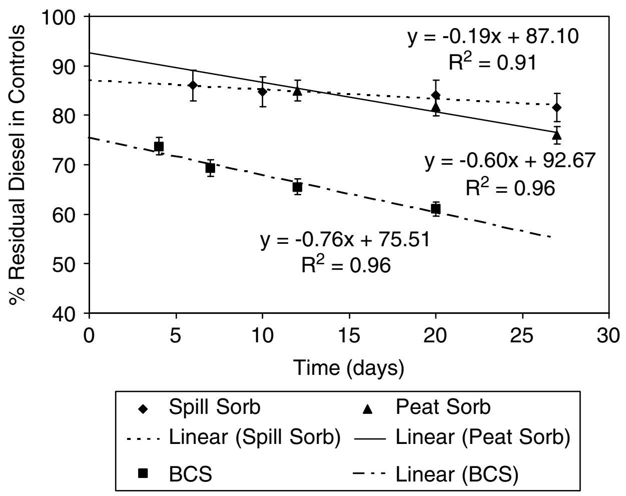

Figure 2. Linear trend in abiotic loss for various sorbent microcosms (error bars represent standard deviation about the mean value).

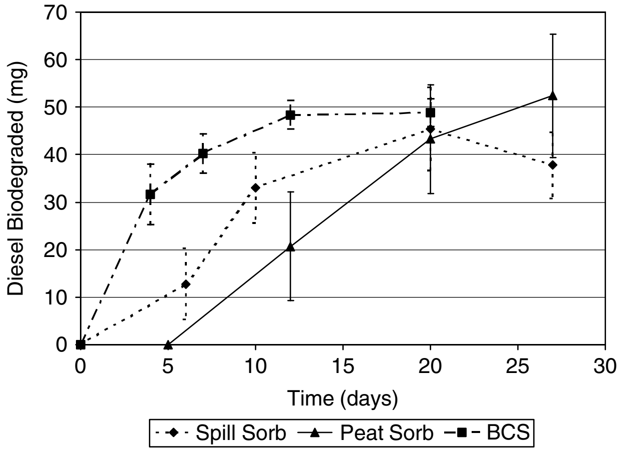

Figure 3. Diesel biodegradation in various sorbent microcosms (error bars represent standard deviation about the mean value).

The maximum abiotic losses observed in the various microcosms were 69 ± 4 mg, ie 39% of loading at 20 days for BCS; 53 ± 9 mg, ie 18.5% of loading at 27 days for spill sorb; and 156 ± 14 mg, ie 24% of loading at 27 days for peat sorb. Peat sorb with the highest diesel oil loading gave the highest abiotic loss. The overall residual diesel oil in the control microcosms decreased almost linearly with time, indicating a linear trend in the abiotic loss due to processes such as volatilization (Fig 2). Similar linear trends in abiotic loss have also been reported by Margesin and Schinner[33] and Chaineau *et al*[34] in oil-contaminated soil/sediment microcosms. However, for peat sorb there was negligible loss over the first 5 days. The trend in loss is depicted by the linear fits to residual diesel (normalized to initial loading) versus time, for data points from which measurable loss is recorded in the controls (beyond time zero for BCS and spill sorb and beyond 5 days for peat sorb). The loss rate normalized to initial loading is highest for BCS, intermediate for peat sorb and least for spill sorb, as indicated by the slope of the linear fits in Fig 2. It is likely that in addition to the initial loading the loss rate is also dependent on the external surface area. Assuming spherical particles, the specific external surface area ($a_{ex}{}^{o}$) (L^2/M) is inversely related to the product of particle radius (r_p) and particle density (ρ_s). Based on particle size and specific gravity information provided in Table 1, and the fact that 4 g of BCS was used compared with 1 g of the spill clean-up sorbents, it appears external surface area was largest in the BCS microcosm, intermediate in the peat sorb microcosms and least in the spill sorb microcosms. Thus, abiotic loss in the microcosms is dependent both on the initial diesel oil loading and on the exposed surface area of the sorbents.

Figure 1 indicates that in all the microcosms with microorganisms, diesel oil removal was higher than in the microorganism-free systems. The rate and extent of biodegradation is better illustrated through Fig 3 which depicts the mass of diesel biodegraded (loss in systems with microorganisms relative to controls) over time in the sorbent microcosms. The extent of biodegradation is very similar in microcosms with all the three sorbents, ie 49 ± 3 mg in the BCS microcosm, 45 ± 9 mg in the spill sorb microcosm and 52 ± 13 mg in the peat sorb microcosm. The rate of biodegradation is strongly dependent on the type of sorbent. The maximum diesel degradation rate observed is 7.9 mg day^{-1} (0–4 days) for BCS; 5 mg day^{-1} for spill sorb (6–10 days) and 2.9 mg day^{-1} for peat sorb (5–20 days). The degradation of diesel in the BCS microcosm occurred without any discernable lag phase and the maximum rate was observed over the first four days. Within 12 days biodegradation was essentially complete, 27% of the diesel oil initially loaded was biodegraded and no further biodegradation occurred although abiotic losses continued to occur. At 12 days the abiotic loss was 34.5% and the overall loss of diesel was 61.5% of the initial loading. Rapid biodegradation trends for diesel sorbed on soil have also been reported in the literature. For example, Harrison *et al*[13] demonstrated 40–50% loss of diesel within 7 days for sandy grey soils. Margesin and Schinner[33] showed 43–55% diesel degradation for a diesel-contaminated soil after 30 days of incubation.

In the spill sorb microcosm, the biodegradation rate is initially slower, and the maximum rate is achieved between 6 and 10 days. The biodegradation rate falls significantly by the 10th day and there is no further biodegradation beyond the 20th day. On the 20th day, loss due to biodegradation is 16%, abiotic loss is 16% and the overall loss is 32% of the initial loading. A lag phase of about 5 days is observed in the peat sorb microcosm beyond which biodegradation at a constant rate (this is also the maximum observed degradation rate) proceeds up to the 20th day and the rate declines subsequently. On the 27th day, loss due to biodegradation is 8%, abiotic loss is 24%, and the overall loss is 32% of the initial loading. Normalized to initial loading, the overall loss in peat sorb and spill sorb microcosms is comparable. However, in peat sorb the abiotic loss is higher compared with biodegradation loss, whereas in spill sorb the abiotic loss and biodegradation losses are comparable.

The biodegradation behaviour in these microcosms may potentially be affected by factors such as recalcitrance of diesel oil components, limitations of oxygen and nutrients, and availability of substrate. In all the microcosms with sorbents the maximum mass of diesel biodegraded (relative to control) was found to be in the range of 45–52 mg (Fig 3), over the period of the study. However, the degradation profile in the three microcosms was very different. In the BCS microcosm more nutrients were available compared with the spill clean-up sorbent microcosms and the diesel oil loading was least. It demonstrated the shortest lag phase and the highest degradation rate. This may be due to the high external surface area available in the BCS microcosm. Moreover, due to the low diesel oil loading most of the oil was probably associated with the external surface. In the spill sorb and peat sorb microcosms less nutrients were available compared with the BCS microcosms and the loading was almost 1.6 and 3.6 times that in BCS, thus, some nutrient limitations may have existed. However, a similar extent of degradation was observed in all the microcosms. This is indicative of oxygen limitations. Since peat sorb and spill sorb were loaded with more diesel oil than BCS, recalcitrance of diesel oil components does not seem to explain the slow biodegradation of diesel oil in peat sorb and spill sorb microcosms.

In a two-phase oil–water system, typically higher initial oil content has been correlated with a higher biodegradation rate,[35] however, a reverse trend is observed in this study. This decrease in maximum biodegradation rate with increase in loading is also opposite to the trend observed for abiotic loss. The results may be related to the distribution of oil on the external surface and within the pore structure of the sorbent matrix. The high loading capacity of spill clean-up sorbents may be correlated with their greater organic matter content and greater internal porosity. The sorbent porosity values determined based on particle density and bulk density were 0.5, 0.67 and 0.9, for BCS, spill sorb and peat sorb, respectively. Thus, diffusion of oil from the internal pores to the exterior surface may have increased the lag time and decreased the maximum degradation rate for the spill clean-up sorbents. Desorption and microbial uptake is known to be faster from the external surface of particles and macropores.[25–27] Nocentini *et al*[16] had reported that biodegradation of oil sorbed on soil levels off after an initial rapid phase due to slow desorption from micropores. Peat sorb, which demonstrates the highest diesel oil loading capacity and higher abiotic loss rate normalized to loading, demonstrated the lowest degradation rate. Spill sorb with intermediate diesel oil loading capacity demonstrated the slowest abiotic loss rate normalized to loading, but demonstrated a higher maximum biodegradation rate compared with peat sorb. The low degradation rate in peat sorb compared with spill sorb may be partly due to the lower number of hydrocarbon-degrading microorganisms in the peat sorb microcosm, as demonstrated in Fig 4. The biodegradation results for spill clean-up sorbents are indicative of greater bioavailability limitations compared with soils. Their high loading capacity is hypothetically dependent on greater internal porosity such that the ratio of internal to external surface area is large, as indicated by their larger particle size and significantly lower low bulk density values. Further studies on pore size distribution within spill clean-up sorbents need to be carried out to better understand these bioavailability limitations. The values for BET (Brunauer Emmett Teller) surface area for nitrogen sorption have often been used as an indicator of the degree of microporosity within sorbents. However, when the spill clean-up sorbents were ground with a mortar and pestle (to an average size of 0.3 mm and 0.2 mm for spill sorb and peat sorb, respectively, since BET surface area for large size particles cannot be determined directly) the BET surface area was determined as 2.5 and 2.1 $m^2\,g^{-1}$ for spill sorb and peat sorb, respectively, whereas BCS depicted a comparatively higher BET surface area of 33 $m^2\,g^{-1}$ (SMARTSORB, SMART Instruments, Mumbai, India). This indicates that the internal pore structure in spill clean-up sorbents is destroyed by grinding, thus, fine micropores as present in sorbents such as activated carbon are not primarily responsible for oil sorption in these spill clean-up sorbents.

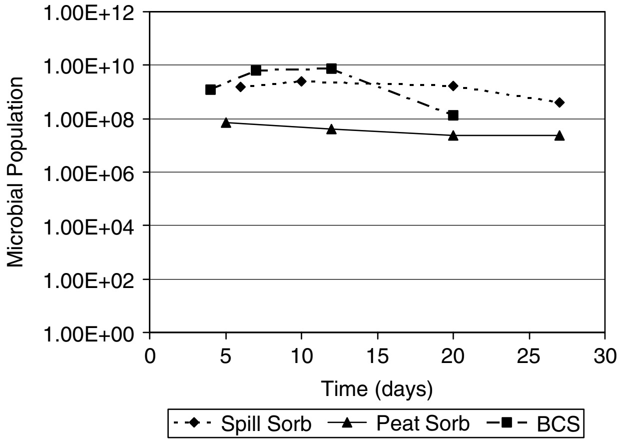

Figure 4. Most probable number (MPN) of diesel-degrading microorganisms in various sorbent microcosms.

In order to elucidate bioavailability issues, our studies were designed as mass transfer-limited systems. This was ensured using a high initial concentration of microorganisms. The concentration of microorganisms inoculated in the various microcosms was close to the carrying capacity of these systems such that the microbial concentration in the microcosms showed no significant growth, as depicted in Fig 4. The average number of diesel-degrading microorganisms in the BCS, spill sorb and peat sorb microcosms were $3.8 \pm 3.7 \times 10^9$, $1.5 \pm 0.8 \times 10^9$, $3.9 \pm 2.2 \times 10^7$, respectively, the trends being consistent with the maximum diesel degradation rate observed in the various microcosms. The microbial population in the BCS microcosm initially increased and subsequently decreased as no significant biodegradation occurred after the 12th day. For spill sorb microcosms, the microbial population showed a marked decrease beyond the 20th day when biodegradation levelled off. The peat sorb microcosms demonstrated a declining trend in microbial population over time and the number of microorganisms was significantly lower than in the other two microcosms. It is possible that the method used for measuring the hydrocarbon degraders in the microcosm was inadequate in desorbing all the microorganisms associated with the sorbent. This is quite likely for peat sorb due to its high porosity and this factor may explain the declining trend observed.

Ongoing studies in our laboratory with the ES1 cultures indicate that these cultures do not produce external biosurfactants since the aqueous phase surface tension is not lowered significantly, rather the diesel oil uptake capacity of the ES1 culture is linked with hydrophobic cell surfaces induced in response to growth on diesel oil. Cell surface hydrophobicity facilitates uptake of diesel oil from the oil–water interface such that mass transfer into the aqueous phase (dissolution) is not a prerequisite for uptake. Since the mass of diesel oil released into the aqueous phase was found to be negligible, throughout, it is possible that these cultures directly degraded diesel oil sorbed on the external surface of the sorbent and prior desorption was not a prerequisite for biodegradation. Greater internal porosity of oil spill clean-up sorbents may have impeded uptake due to the inaccessibility of microorganisms to diesel oil sequestered within the pores. A similar mechanism was proposed by Bosma *et al*[25] for biodegradation of α-hexachlorocyclohexane (α-HCH) in soil slurry systems.

In our studies, a lag phase was observed before biodegradation commenced in the peat sorb microcosms, the biodegradation rate was initially slower in the spill sorb microcosms while biodegradation commenced at the maximum rate in the soil microcosms. The lag observed in the peat sorb microcosms was unexpected due to the high initial concentration of cells spiked into the microcosms. Our biodegradation study results for diesel sorbed on peat sorb is in contrast to those reported by Setti *et al*.[6] They reported enhanced and very high biodegradation of heavy oil in the presence of natural sorbents such as keratin, chitin and chitosan where the presence of sorbents reduced the lag phase. However, in their systems the amount of oil applied was much higher than the sorption capacity of the sorbents and excess free phase oil was present during the biodegradation studies. Association of free phase oil with the external surface of the sorbent may have provided greater interfacial area, thus facilitating microbial uptake. Bioavailability limitations due to sorbed oil are not depicted in their systems. In contrast, in all our studies excess free phase oil was removed after the initial equilibrium period such that only sorbed oil was present.

Thus, biodegradation of sorbed oil on spill clean-up sorbents and regeneration of sorbents for reuse through biological treatment is possible. However, the time required for regeneration may be higher compared with those indicated based on studies with soil due to bioavailability limitations posed by the inherent nature of these sorbents.

CONCLUSION

In this study the feasibility of bioremediation of spill clean-up sorbents was experimentally evaluated in mass transfer-limited systems, spiked with high initial microbial concentration. The bacterial culture used was capable of direct interfacial uptake of diesel oil in a two-phase oil–water system. Although the extent of biodegradation in the various microcosms was comparable, the maximum degradation rate was highest for BCS, biodegradation at the maximum rate commenced immediately and it also demonstrated the highest abiotic loss rate normalized to initial oil content. In the spill clean-up sorbents, biodegradation at the maximum rate did not commence immediately upon start-up. Peat sorb demonstrated a distinct lag period with negligible biodegradation, and its maximum degradation rate was lower compared with spill sorb. Spill sorb demonstrated the slowest abiotic loss rate. Greater association of oil with the external surface of the sorbent compared with oil within internal pores may have caused lower bioavailability limitations in the BCS microcosms. Our study shows that the biodegradation of diesel oil sorbed on spill clean-up sorbents is possible but the degradation rate is slower than for soil due to enhanced bioavailability limitations.

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