

Report for 2002MD4B: Sustainable Oil and Grease Removal from Stormwater Runoff Hotspots using Bioretention

- Dissertations:
 - Hong, Eunyoung, 2002, Sustainable Oil and Grease Removal from Stormwater Runoff Hotspots using Bioretention, "MS Dissertation, Department of Civil and Environmental Engineering, A.J. Clark School of Engineering, University of Maryland, College Park, Maryland, 167 pages.
- Other Publications:
 - Hong, Eunyoung, Eric A. Seagren, and Allen P. Davis, 2002, Sustainable oil and grease removal from stormwater runoff hotspots using bioretention, "presented at" PennTec 2002, the 74th Annual Conference and Exhibition of the Pennsylvania Water Environment Association, State College, Pennsylvania, June 23-26, 2002.

Report Follows:

Problem and Research Objectives

Urban stormwater runoff affects the quality of receiving water bodies by carrying a significant load of contaminants that have accumulated on urban surfaces (Vogt, 1995; Line et al., 1996; Wu et al., 1998). One of the important components of this contaminant load is oil and grease (O&G) pollution, which represents a significant source of hydrocarbons to the environment (Stenstrom et al., 1984). The hydrocarbons from urban runoff may later be found in aquatic sediments (Wakeham, 1977) and open water, and ultimately may accumulate in the tissues of aquatic life. Thus, these hydrocarbons may result in a variety of negative environmental effects.

A major input of this O&G is from vehicle emissions, mostly from crankcase oils (Stenstrom et al., 1984). Thus, controlling O&G discharges from impervious areas in automotive-intensive “hotspots”, such as roadways, parking areas and commercial properties, can reduce the amount of O&G transported in urban stormwater runoff to receiving water bodies. In this research, it was hypothesized that the removal of O&G from urban runoff could be accomplished via sorption, filtration and subsequent biodegradation in the stormwater best management practice of bioretention, by using a thin surface mulch layer as a contaminant trap.

The objectives of this research were to: (1) evaluate the capacity of the mulch layer to capture dissolved and particulate-associated O&G contaminants via physical and chemical mechanisms during a simulated storm event, and (2) evaluate the rate and extent of O&G biodegradation in the mulch layer in between storm events. A mass balance approach was employed to evaluate the fate of hydrocarbon contaminants during the simulated storm events and to quantify the amount of contaminant biodegraded after the storm events.

Methodology

Stormwater runoff simulation experiments were performed using a bench-scale bioretention reactor (Figure 1), made using a porcelain Büchner funnel (253-mm I.D., 110-mm bowl depth), and containing a 3-cm thick layer of leaf mulch (mulch source: Department of Public Works, College Park, MD). The only microorganisms supplied to the system were the native microbes present in the mulch. The contaminants selected for the bench-scale stormwater runoff simulation experiments included naphthalene, toluene, and commercial automobile motor oil (Shell, SAE Grade 10W-40), which were added to simulated runoff (Davis et al., 2001). The naphthalene, toluene, and motor oil were added in dissolved (all three) or particulate-associated (naphthalene only) form to the simulated runoff with influent concentrations of ~1.6, 2.7, and 30.8 mg/L,

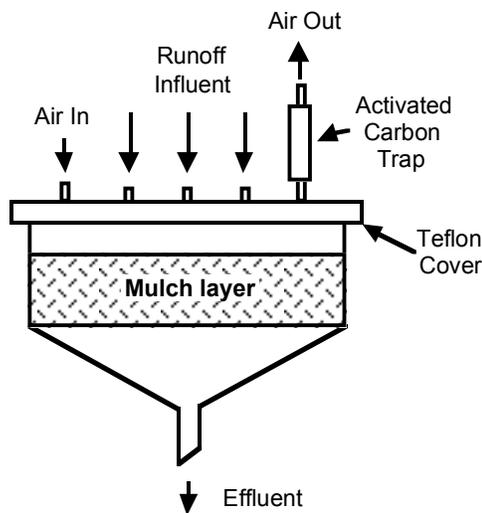


Figure 1. Schematic illustration of the mulch-based bioretention reactor

respectively. For the particulate-associated naphthalene experiments, Berryland Oe soil (Levin, 1994) was added to a naphthalene-water solution to allow sufficient sorption, after which the soil was then removed from the suspension by centrifugation, and subsequently added to synthetic runoff, resulting in total influent naphthalene concentrations of 1.5~1.6 mg/L and total suspended solid (TSS) concentrations of 270~340 mg/L.

All experiments had two phases: Phase 1, which simulated a 6-hour runoff event (4 cm/hr), followed by Phase 2, simulating the time between storm events. During Phase 1, the influent simulated runoff and the reactor effluent were sampled and extracted with hexane, and the hexane was analyzed for the naphthalene or toluene concentration by gas chromatography (GC). This allowed for calculation of the trapped contaminant mass in the mulch. Motor oil concentrations in aqueous samples during Phase 1 were determined by using a solid phase extraction method (Lau and Stenstrom, 1997). Then, a mass balance approach, incorporating monitoring of contaminant levels in the aqueous, gaseous and solid phases, was used to quantify the contaminant mass removal via biodegradation during Phase 2. Specifically, to monitor contaminant loss by degradation, mulch samples were taken everyday for inhibited-control runs and twice per day for biotic runs, and analyzed for the contaminant concentration using hexane extraction and GC. To provide additional evidence supporting that the contaminant removal was due to biodegradation, enumeration of total heterotrophic plate counts (HPC) and naphthalene- and toluene-degrader plate counts (NDPC and TDPC, respectively) and oil-degrader counts was performed using mulch samples during Phase 2. In addition, the activated carbon from the trap (Figure 1) was also extracted with hexane for GC analysis to account for losses by volatilization.

The results of inhibited-control and biotic experiments were compared to distinguish the impact of biodegradation. Mulch for the inhibited-control experiments was amended directly with mercuric chloride (HgCl_2) at a rate of 1.84 mmol/kg and soaked in 1000 ppm HgCl_2 solution for 48 hours. In the same manner, mulch for biotic runs was soaked in 1000 ppm calcium chloride (CaCl_2) solution. The mulch was drained after soaking and packed in the reactor up to a height of 3 cm. HgCl_2 was also introduced to the influent solution for the inhibited-control experiments at a level of 400 mg/L. In the toluene experiments, autoclaved mulch was also used to run another control to better inhibit the microbial activity.

All the samples were taken and analyzed in duplicate. In the figures presented below, the average values are plotted and the standard deviations are shown as error bars; however, in many cases the magnitude of the standard deviations is even smaller than the symbols and, thus not visible in the figures.

Principal Findings and Significance

Experiments performed with ~1.6 mg/L (~3.2 mg/hr surface loading) dissolved naphthalene in the influent simulated runoff demonstrated approximately 90% removal from the aqueous phase via sorption to the mulch layer during the simulated storm event (Figure 2). Subsequently, about 92% naphthalene removal from the solid phase occurred in the mulch layer within 62 hours following the end of the stormwater addition, which was about twice as fast as in the inhibited-control (Figure 3 (a)). In particular, removal of naphthalene in the biotic run proceeded rapidly during the first 48 hours. It was found from analysis of the carbon trap that losses due to volatilization were negligible in experiments with naphthalene, indicating that the fast removal of naphthalene occurred due to microbial activity.

To provide additional evidence confirming that the naphthalene removal was due to biodegradation, the populations of total heterotrophic bacteria and naphthalene-degrading bacteria in the mulch were counted periodically after the stimulated storm event (Figure 3 (b)). From the corresponding results of the microbial plate counts, it was found that the population of the microorganisms in the mulch increased with time, and that the sterilization method inhibited some microbial growth, especially the naphthalene-degraders, causing an approximately four orders of magnitude decrease in the population at 24 hours after Phase 1. Nonetheless, even though the control inhibited the microbial activities, naphthalene-degraders were still present. Thus, the slow decrease of naphthalene with time in the inhibited-control mulch might be explained as being due to biodegradation by the remaining bacteria. The observation of microbial growth in the reactor after introducing the naphthalene supports the hypothesis that the rapid degradation of naphthalene is mainly because of the microbial activities.

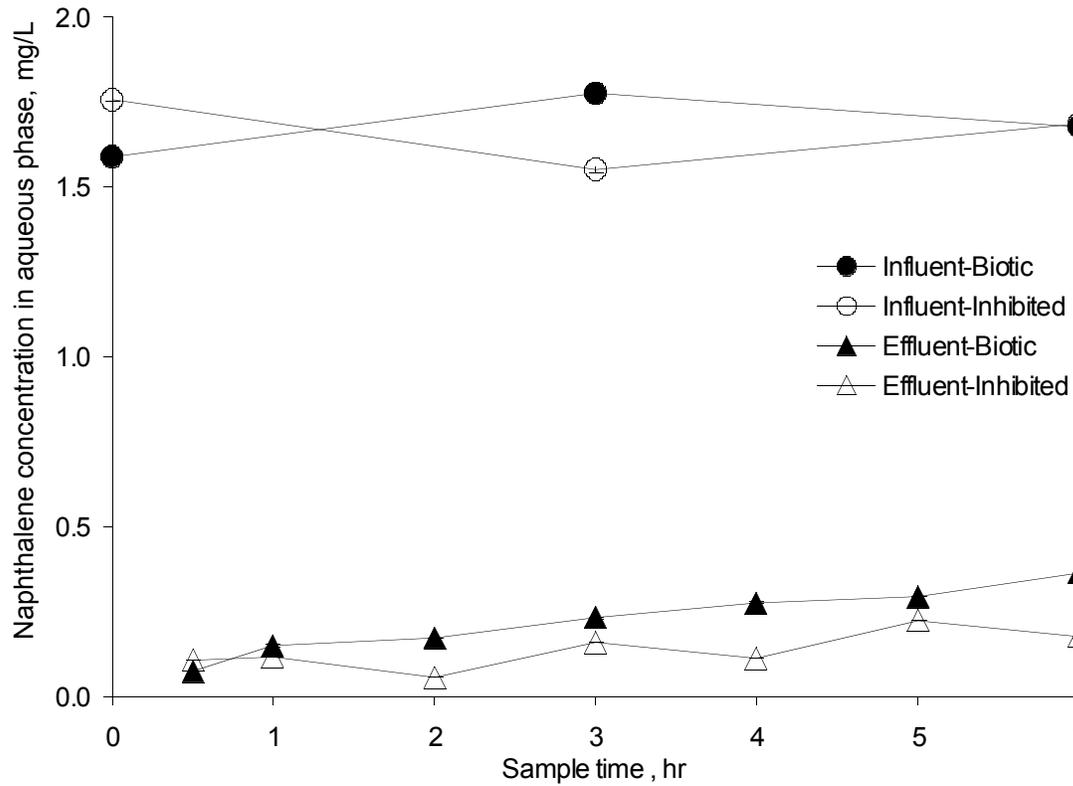


Figure 2. Naphthalene removal from the aqueous phase through the bioretention mulch layer during the simulated storm event. Error bars represent \pm one standard deviation.

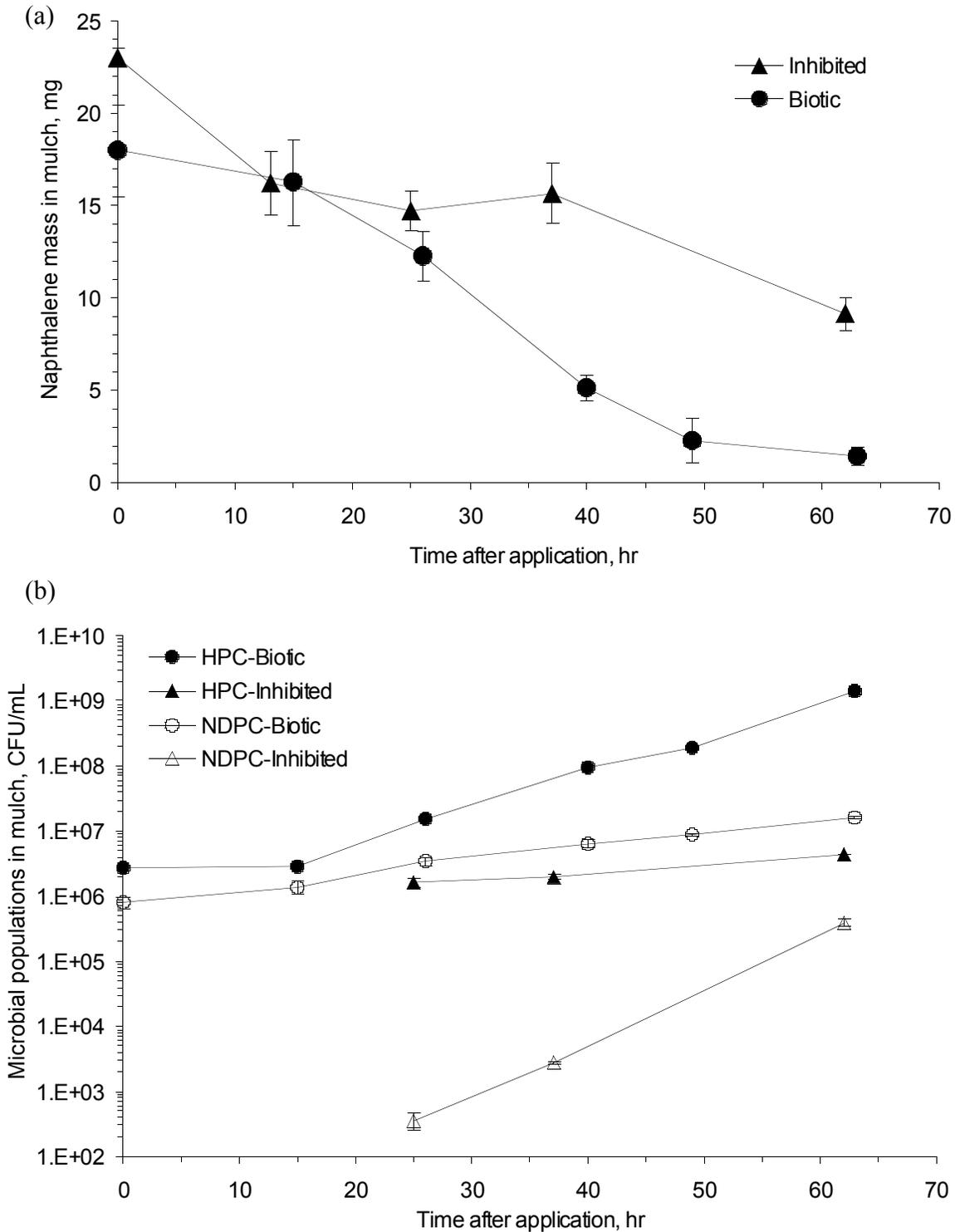


Figure 3. Biodegradation of naphthalene captured on bioretention mulch: (a) Reduction of naphthalene in the mulch, and (b) Microbial growth based on total heterotrophic plate counts (HPC) and naphthalene-degrader plate counts (NDPC) in the mulch. Error bars represent \pm one standard deviation.

Experiments using simulated stormwater runoff contaminated with about 2.7 mg/L dissolved toluene (~5.4 mg/hr surface loading) showed similar results. In this case, biotic and two inhibited control (HgCl₂ amended and autoclaved) experiments were performed. The influent aqueous phase concentration was reduced by approximately 86% during Phase 1 in both the biotic reactor and the control run amended with HgCl₂. However, a lower removal efficiency (~56%) was observed in the autoclaved control experiment (Figure 4). A greater portion of toluene in all experiments (about 8~15% of toluene introduced) was volatilized during storm events compared to the negligible volatilization in the naphthalene experiments. After completion of Phase 1, about 90% removal of toluene from the mulch occurred in the biotic experiments within around 4 days (101 hours) (Figure 5 (a)). Even though the difference between the biotic run and the control run is not very obvious in this case, the more rapid drop in the toluene concentration suggests greater biological activity in the biotic experiment.

Similar to the naphthalene results, corresponding trends between the cumulative amounts of toluene biodegraded from the mulch, and the microbial plate counts provide strong evidence that biodegradation played a major role in the toluene removal from the mulch (Figure 5 (b)). The population of the microorganisms in the mulch appeared to increase gradually with time based on both the HPC and the TDPC.

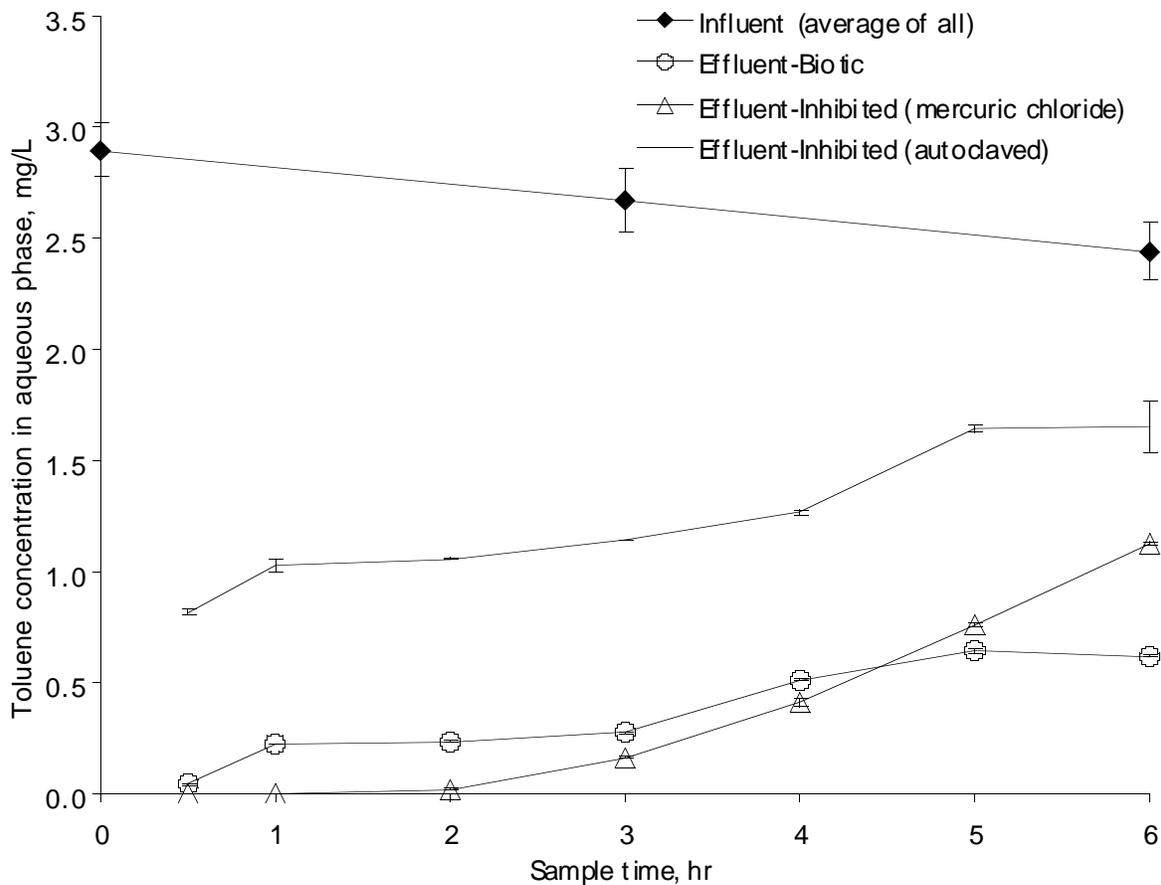


Figure 4. Toluene removal from the aqueous phase through the bioretention mulch layer during the simulated storm event. Error bars represent \pm one standard deviation.

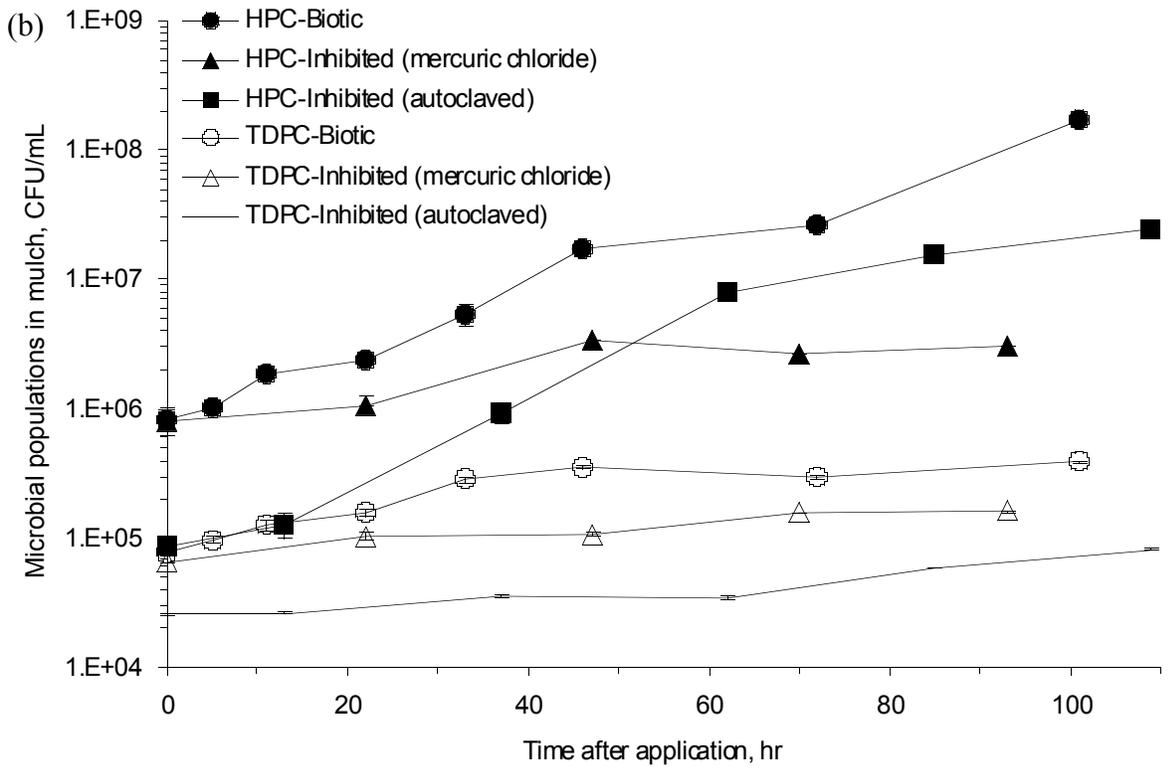
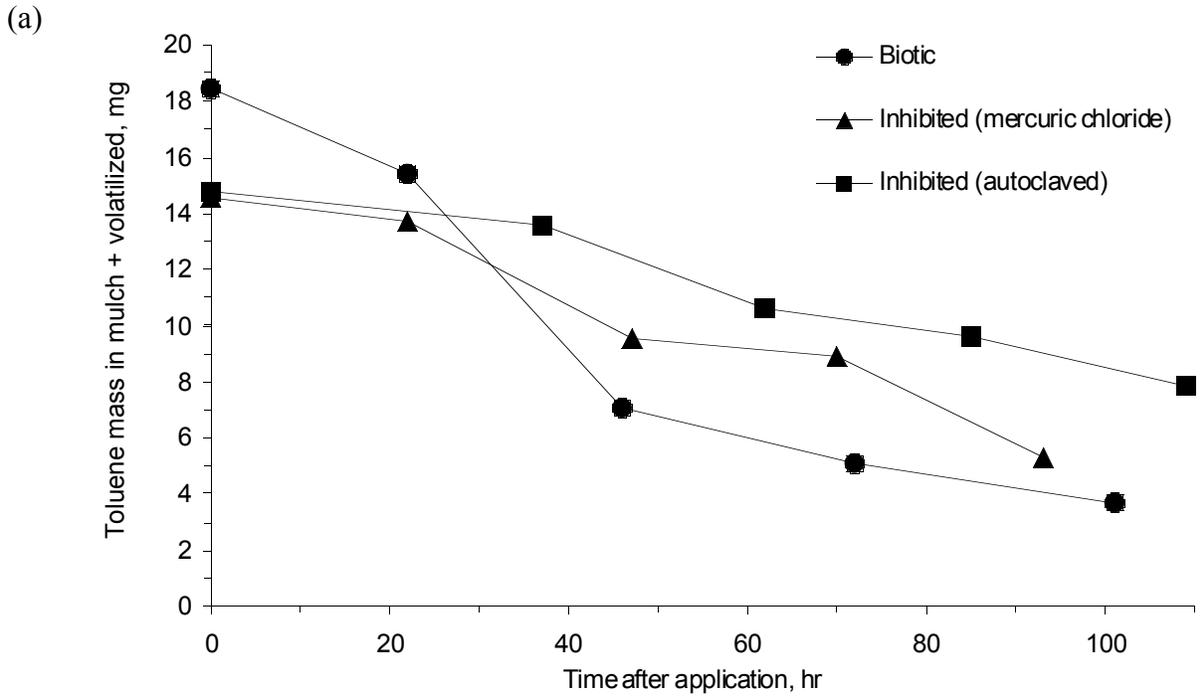


Figure 5. Biodegradation of toluene captured on bioretention mulch: (a) Reduction of toluene in the mulch, and (b) Microbial growth based on total heterotrophic plate counts (HPC) and toluene-degrader plate counts (TDPC) in the mulch. Error bars represent \pm one standard deviation.

Stormwater runoff simulation experiments using motor oil were performed in order to ensure that a bioretention mulch layer could capture and degrade not only a single target compound, but also a complex mixture of hydrocarbons. Experiments performed with an influent concentration of about 27 mg/L dissolved motor-oil hydrocarbons (55 mg/hr surface loading) demonstrated approximately 85% removal from the aqueous phase via sorption to the mulch during the Phase 1 (data not shown). This is comparable to the results in the single contaminant studies with naphthalene and toluene.

Gas chromatograms of the mulch sample hexane extracts can be used to compare the change in the oil content with time during Phase 2 (Figure 6). The heights of the peaks clearly decreased with time in the biotic chromatograms, especially during first two to three days, whereas no significant change in the chromatograms was observed in the inhibited-control experiment throughout Phase 2. Quantitatively, the total mass decrease of oil during Phase 2 was observed by monitoring the total area in the chromatograms (Figure 7 (a)). Although a significant amount of experimental variability is noted, about 92% removal of oil from the mulch occurred in the biotic reactor within around 10 days after the end of Phase 1, whereas only approximately 20% removal of oil was observed in the control reactor after 9 days. Removal of most oil in the biotic reactor was found to occur during the first few days, with more than half of the oil degraded within three days. An increase in the population of the oil-degrading and heterotrophic bacteria in the biotic reactor in the first two to three days correlates well with the initial loss of the majority of oil in that reactor, suggesting microbial activity as a primary removal mechanism (Figure 7(b)).

The time to reach approximately 90% removal of oil (~8 days) in the biotic reactor was much longer than that for naphthalene (~3 days) and toluene (~4 days). This is not unreasonable given that oil is a complex mixture of hydrocarbons, some of which require more time for biodegradation (Yerushalmi and Guiot, 1998). In addition, it is also possible that the longer time needed for degradation is due to the higher concentration of dissolved oil hydrocarbons that was introduced in this experiment compared to the concentrations of the individual target compounds.

Particulate-associated experiments were performed with a total influent concentration of about 1.6 mg/L naphthalene (3.2 mg/hr surface loading). The amount of sorbed naphthalene on the soil particulates in the influent and effluent was determined by the difference between the hexane-extracted naphthalene concentrations of total and centrifuged aqueous samples. The results of biotic and inhibited-control experiments demonstrated approximately 98% removal of total and dissolved naphthalene during Phase 1 (Figure 8 (a)). In both experiments, the influent TSS concentrations increased with time because not all the solids were homogeneously distributed in the influent bottle, even though mixing was provided, causing an accumulation of solids as time elapsed (Figure 8 (b)). All the effluent TSS concentrations, including the control without the input of particulates, demonstrated similar trends, decreasing to very low levels at the end. Even though most particulates appeared to be accumulated on the surface of the mulch, there was almost no water head buildup observed on the mulch during Phase 1. From a practical perspective, this provides a real benefit of using mulch as a top layer material on a bioretention system.

The results for naphthalene loss due to volatilization, naphthalene removal in the mulch, and microbial growth during Phase 2 were very similar to those for the dissolved naphthalene experiments. This indicates that the fast removal of naphthalene observed in Phase 2 of the biotic experiment with particles occurred due to biodegradation (data not shown).

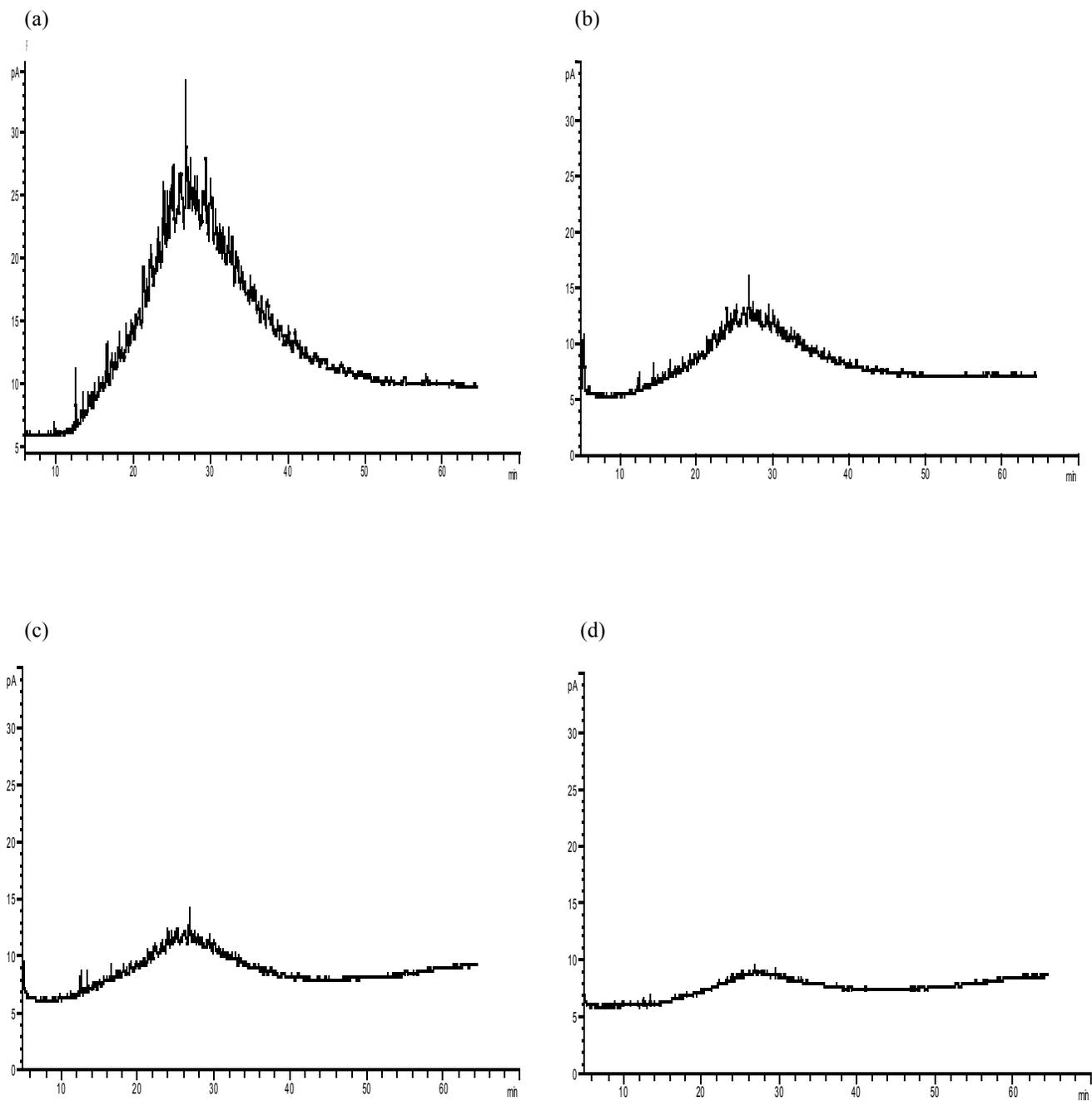
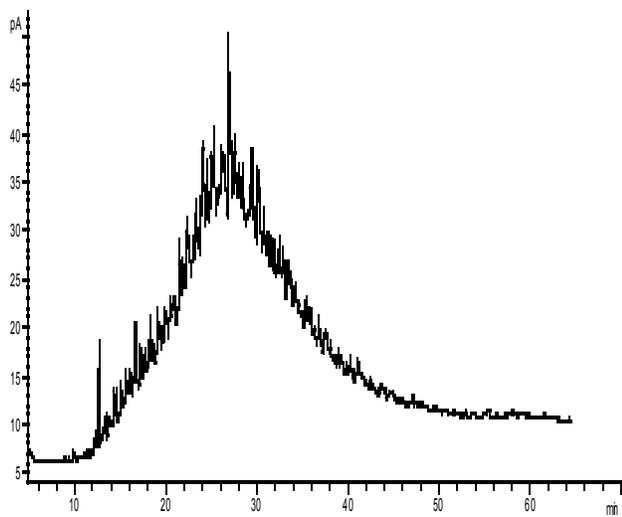
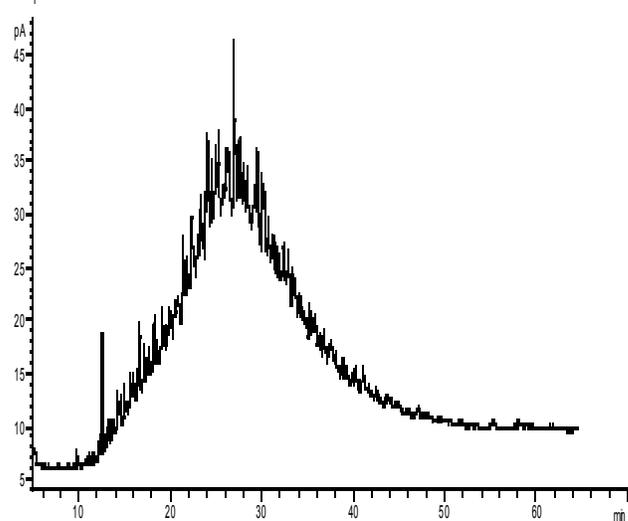


Figure 6. Representative gas chromatograms of oil extracted from the mulch in the biotic experiment at times (a) 0, (b) 2, (c) 3, and (d) 10 days, and in the inhibited-control experiment at times (e) 0, (f) 5, and (g) 11 days

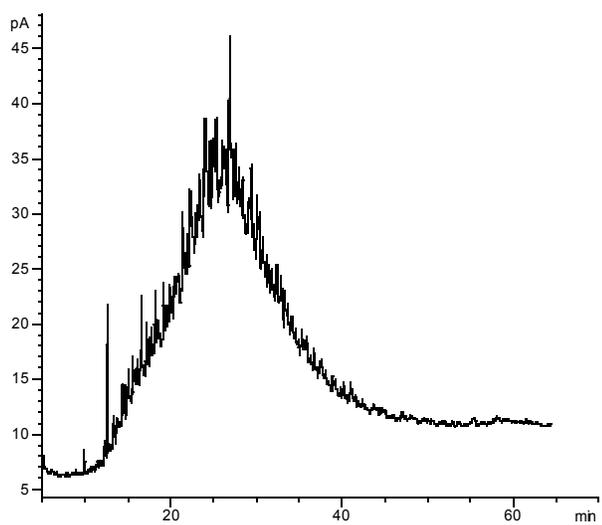
(e)



(f)



(g)



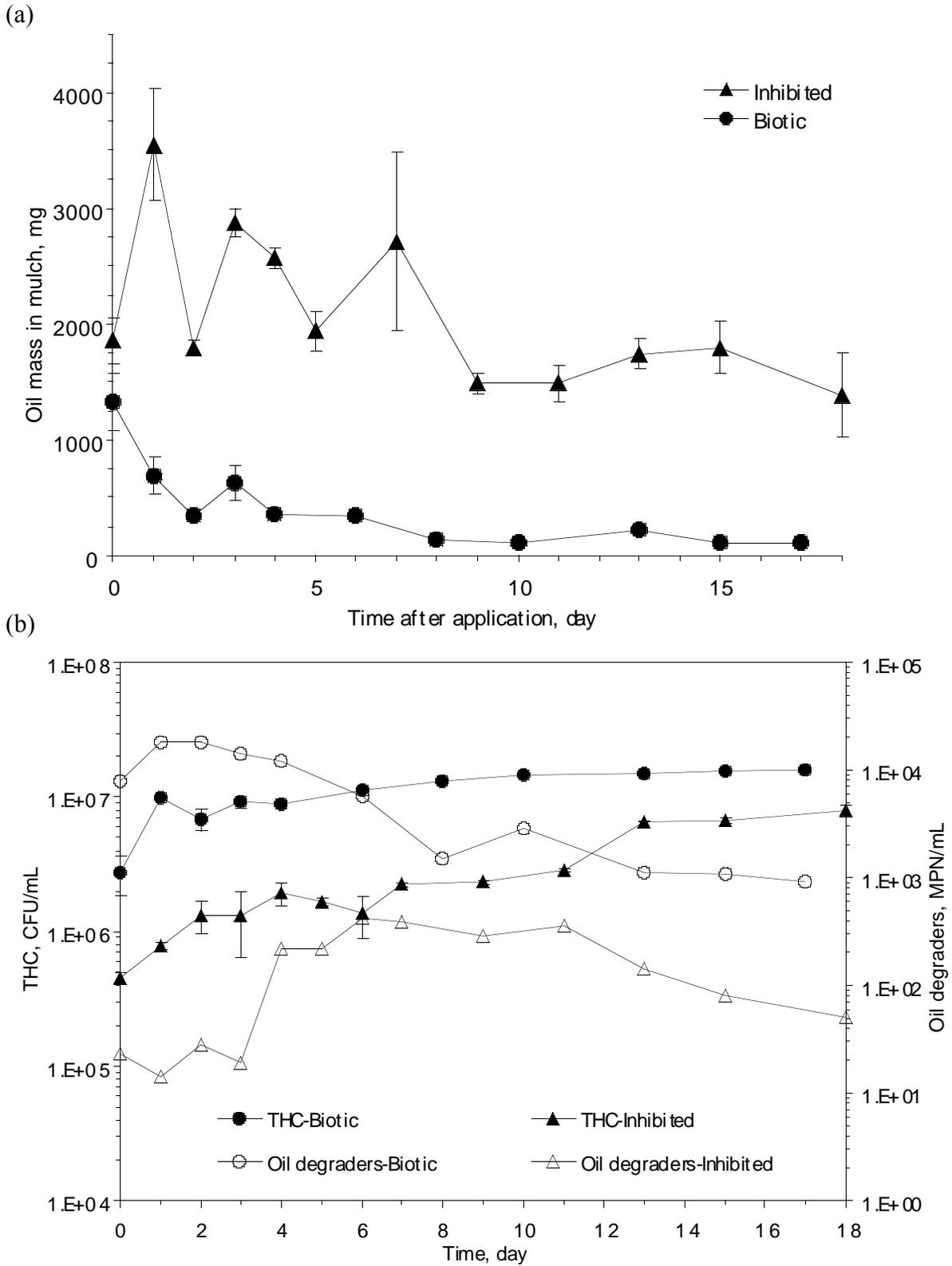


Figure 7. Biodegradation of oil captured on bioretention mulch: (a) Reduction of oil in the mulch, and (b) Microbial growth based on total heterotrophic plate counts (HPC) and oil-degrader counts in the mulch. Error bars represent \pm one standard deviation.

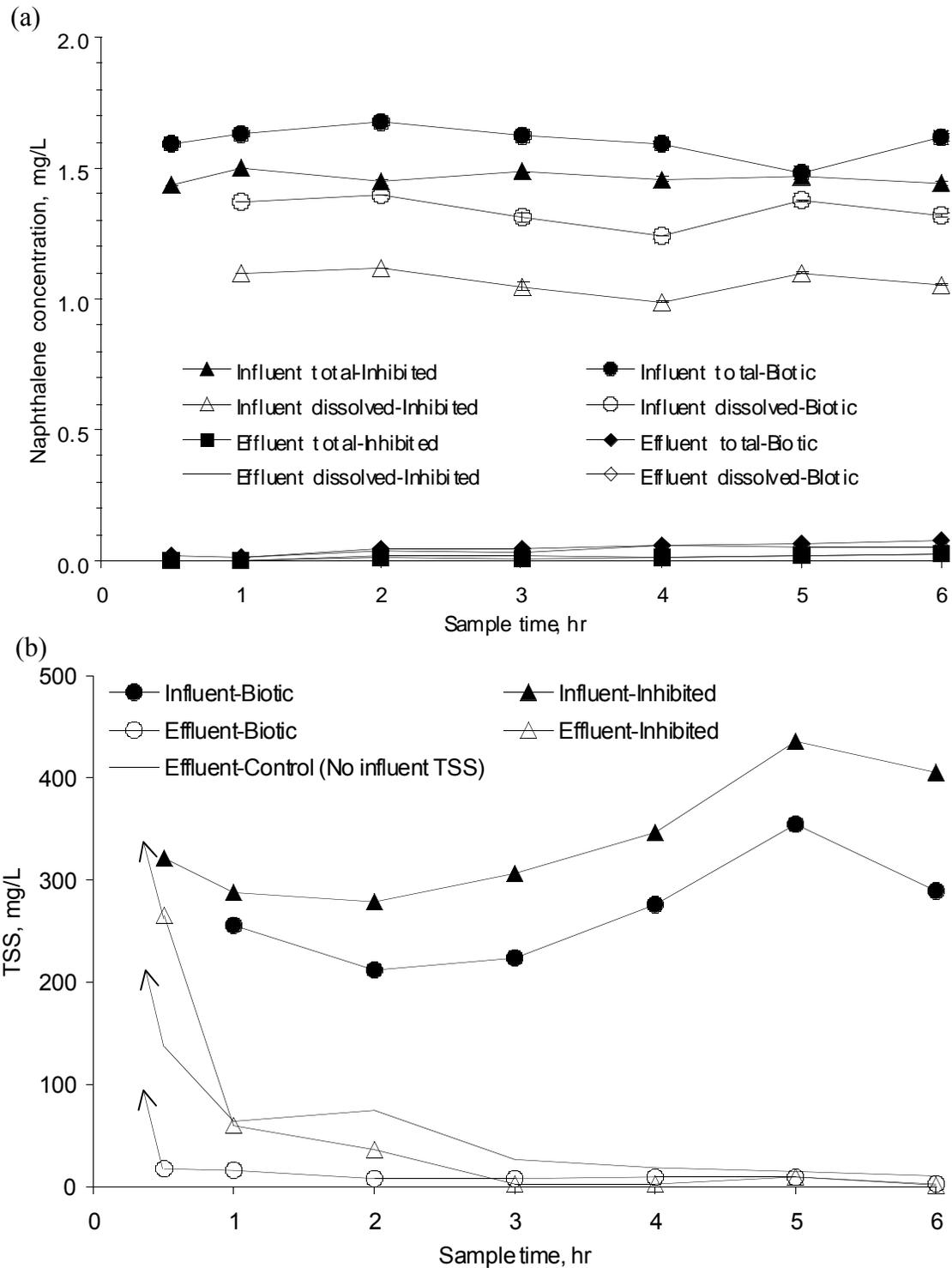


Figure 8. Removal of naphthalene and total suspended solid (TSS) from influent through the bioretention mulch layer during the simulated storm events in particulate-associated naphthalene experiments: (a) Removal of total and dissolved naphthalene, and (b) Removal of TSS. Initial effluent values (at $t \approx 0$) exceeded 1000 mg/L and are not shown. Error bars represent \pm one standard deviation.

Overall, it can be concluded that there are several advantages to placing a surface mulch layer on a bioretention system for O&G removal. First, it appears that high contaminant removal efficiency can be achieved by the placement of a thin (~3 cm) layer of mulch to treat both dissolved and particulate-associated hydrocarbon contaminants. Second, because it only takes a relatively short time (3 to 4 days with single contaminants, and a maximum 10 days with the higher contamination of oil) to degrade the trapped contaminants after the storm event, no accumulation of hydrocarbons occurs, demonstrating that this as a sustainable process. Third, there is no need to inoculate the mulch with specific microorganisms to degrade the O&G contaminants because the native microbial population in the mulch tested has been found to have an appropriate biodegradation capacity. In addition, after exposure of the mulch microorganisms to the contaminants, an increased population of contaminant-degrading microbes is available for biodegradation during a subsequent re-exposure. Fourth, the moisture content of the mulch layer did not decrease drastically after the storm event under an air stream, which will be beneficial for microorganisms in the mulch as well as in the soil below. Fifth, the mulch layer has high permeability; therefore, it should not cause significant head build-up on the surface of bioretention system during the storm event, so that the runoff can readily infiltrate to the soil layer below. Finally, the mulch layer is low cost and is convenient to maintain.

The O&G removal demonstrated in this research, coupled with the pollutant removals shown in previous studies (Davis et al., 2001; 2003), suggests the great potential for water quality improvement via conventional bioretention systems and the possibility for greater pollutant removal through re-engineering.

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