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Influence of environmental parameters on the carbon balance in a biofilter

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Abstract

The fate of pollutants in a biofilter is poorly understood. Quantifying the fate of carbon in the pollutant provides a better understanding of operation and improves modeling of biofilter performance. This study investigated the fate of carbon as influenced by temperature, water tension and pollutant concentrations. Soil biofilters degrading toluene were operated with no supplemental nutrient addition. Rigorous control of inlet concentration, temperature and water content was maintained with a differential biofilter. Temperature experiments were conducted at 20°C, 30°C and 40°C and water tension was varied between 10 cm_{H2O} and 20 cm_{H2O}.

The carbon recovery as CO_2 ranged from 45% to 60% at a tension of 10 cm_{H2O} and an inlet concentration of 170 ± 6 ppm with variable fractions of carbon ending up in the liquid and solid phases as determined by TOC. Further experiments maintaining the temperature at 40°C and varying the tension to 20 cm_{H2O} were done. Fractions of carbon recovered as CO_2 significantly lowered to 32 % at a tension of 20 cm_{H2O}. A third parameter was investigated at 30°C by implementing a lower inlet toluene concentration of 96 ± 4 ppm and 10 cm_{H2O}. The fraction of carbon recovered as CO_2 was 72% illustrating significant variation in the carbon recovery with different environmental parameters. The endogenous respiration of C-CO_2 from the soil bed was corrected for in the net CO_2 produced. This result shows the dynamic variability of the various endpoints and product ratios on system inputs.

Keywords: Biofiltration, non-growth, Toluene, carbon balance

Introduction

Biofiltration is a cost effective biotechnology used to degrade air-borne pollutants. It is effective for large volume air streams with low concentrations of pollutants (< 1000 ppm) and is used widely in industry for both emission and odour control (Devinny, Deshusses, & Webster, 1999) Biofilters are packed bed bioreactors using microbial consortiums to form a pollutant-degrading biofilm. The stable biofilms consume the pollutants because of maintenance energy requirements.The fate of carbon as it is transformed from the pollutant to various end-products in biofilters is poorly understood. Biofilms proliferating in various dynamic environmental conditions are commonly unsaturated, operating at the air/solid interface. Many attempts have been made to close the carbon balance in these systems; however (10-50%) of the degraded carbon often remains untracked (Cox, Sexton, Shareefdeen, & Deshusses, 2001; Deshusses, 1997; Morales, Revah, & Auria, 1998; Song & Kinney, 2000). In spite of the importance of these growth restricted, unsaturated biofilm processes in engineered systems, certain aspects of their activity/metabolism remain unclear, particularly the ultimate fate of carbon entering these systems. Hence this study sets out to find the missing carbon from these bioprocess systems and determine the influence of

various system inputs on the carbon end-points. Quantifying the fate of carbon is required as it provides a context for better understanding and modeling of biofilter performance. This study investigated the various carbon end-points in the gas, liquid and solid phases and the influence of temperature on the various product ratios. By and large, this investigation on end-points, product ratios and influence of system inputs should contribute to understanding the functionality of these unsaturated biofilms in biofilters, all the while elucidating potential environmental concerns.

Experimental Set-up

Desired gas phase toluene concentrations are generated by a diffusion tube apparatus containing liquid toluene (Pure HPLC grade) which adds at a constant mass rate of toluene to a flowing air stream depending on the temperature and dimensions of the diffusion tube. A detailed description of the experimental set up is described elsewhere (Beuger & Gostomski, 2009). Soil (Parkhouse Garden Supplies) was used as a reactor bed material.

Laboratory scale differential biofilters were operated as non-growth systems with no nutrient addition to the soil at different operating temperatures of 20° C, 30° C and 40 °C for about 3 months. Other parameters such as pollutant concentration and water tension was also varied. Biofilters were placed inside an insulated temperature controlled box to maintain the desired operating temperatures. Figure 1 illustrates a depiction of the differential biofilter.

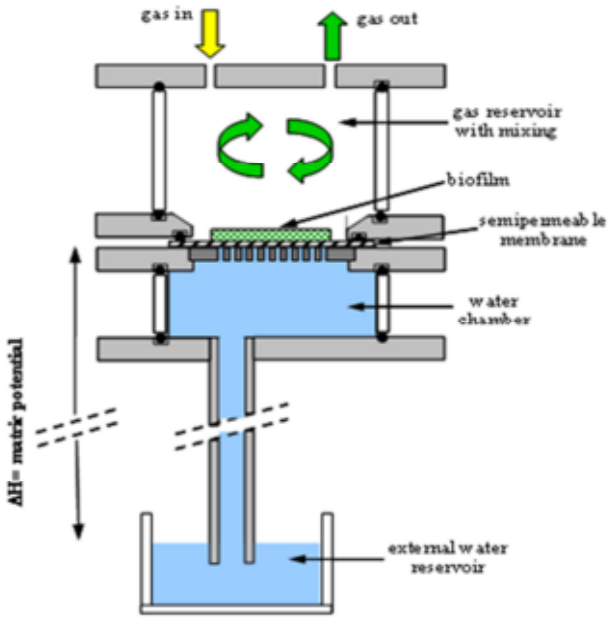

Fig 1: A cut away of the differential biofilter with robust water control.

Materials and Methods

Samples from the inlet and outlet streams were continuously withdrawn via heat traced (outlet) 1/8th inch stainless steel (SS) tubing sampling lines connected to a 10-port valve (Valco, Houston, TX) and injected into a GC/FID (SRI-8610C, SRI instruments). Toluene concentration for the reactor inlet and outlets are measured through the GC and simultaneously CO_2 is measured out of the GC outlet port during the purge time given for each GC measurements using a CO_2 probe (GMP 343, Vaisala Inc.). At standard conditions rector inlet is measured in quadruplicate once a day and outlet in quadruplicate thrice a day. Simultaneously triplicate measurements of CO_2 are taken along with the outlet measurements every day.

Dry matter content of the soil samples are carried out in triplicate from representative samples for 24 hours at 105 °C before start-up of reactors. Soil samples were put in a desiccator after taking out of the oven for 15 minutes prior to gravimetric analysis.

Total organic carbon (TOC) and Total Inorganic carbon (TIC) fraction of the soil samples were initially carried out by Hill laboratories. Nitrogen profile is done by Hill laboratories. The liquid phase TOC, TIC and Total Kjeldahl Digestion (TKN) was done by Hill laboratories. pH of the samples were measured by a pH probe. Subsequent total carbon (TC) analysis for both the soil and liquid samples was done by using model 5050 total carbon analyser (Shimazdu,Kyoto,Japan). The operational parameters for the biofilters are presented in Table 1.

Table 1: Reactor characteristics and Operating parameters

Parameters	***BF1***	***BF 2***	***BF 3***	***BF 1a***	***BF 3a***	***Units***
Inlet concentration	170 ± 6	165 ± 4	170 ± 5	170 ± 5	96± 4	ppm
Flow rate	25	25	25	25	25	ml min^{-1}
Temperature	40	20	30	40	30	°C
Tension	10	10	10	20	10	cm_{H2O}
Elimination Capacity (EC)	83 ± 6	20 ± 8	33 ± 6	45 ± 7	57 ± 4	g m^{-3} h^{-1}
Reactor bed volume	6.6 x 10^{-6}	6.6 x 10^{-6}	6.6 x 10^{-6}	6.6 x 10^{-6}	6.6 x 10^{-6}	m³
Operation period	70	80	97	70	95	days

Results and Discussion

Carbon balance

This work is structured on elemental balance on carbon. The total carbon mass balance on the system is evaluated considering the following equation:

$$C_{\text{Accumulation (Solid)}} = C_{\text{In (Gas)}} - C_{\text{Out (Gas)}} - C_{\text{Out (Liq)}} \quad (1)$$

The carbon balance includes C-toluene degradation, C-CO_2 production, TOC/TIC in the liquid and the TOC/ TIC of the reactor soil. Figure 2 represents the fate of carbon in various phases in the system.

Table 2: Carbon balance over the time scale of biofilter operation degrading toluene.

Fate of carbon	**BF1**	**BF2**	**BF3**	**BF1a**	**BF3a**
Gas phase (%)	58	44	49	32	71
Solid + liquid phase (%)	37	30	51	53	15
Carbon balance (%)	96 ± 9	74 ± 17	97 ± 14	87.5 ± 14	85 ±14

Although these results have tracked the cumulative carbon fate in both the solid and liquid phases, it warrants some critical evaluation through control studies to explicitly define the product ratios as a function of system inputs and environmental parameters.

Influence of temperature on the fate of pollutant

Like any biological system, temperature is a critical operational parameter for biofilter performance. Plethora of microbial communities capable of proliferating at mesophillic to thermophillic range exists which directly influences the biofilter performance (van Lith, Leson, & Michelsen, 1997). Carbon recovery varies as a function of temperature with higher fraction of pollutants being mineralized to CO_2 with increasing temperature (Acuña, Pérez, Auria, & Revah, 1999). Carbon dioxide production pattern is a good indicator of the biological activity happening in the biofilter. Around 58 % of the pollutant was mineralized to CO_2 at 40° C followed by 49% at 30° C and around 30% was mineralized to CO_2 at 20° C. CO_2 production pattern over a wide temperature range gives insightful indication of the physiology of the biological activity of the process.Greater mineralization to CO2 at higher temperatures can be attributed to various phenomena such as increased maintenance energy requirements and temperature induced growth un-coupling (Cox, et al., 2001).This clearly shows greater microbial activity at higher temperatures as illustrated by few other studies previously (Cox, et al., 2001; Wang, Kong, & Zhang, 2012). A reverse trend was found in terms of carbon recovery in the solid and liquid phases with 43% found at 20 °C, 51% at 30 °C and around 37% at 40 °C. This shows the presence of a wide range of microbiota in the soil capable of surviving over a broad range of temperature. However, clearly at lower temperature microbial activity was inhibited which could have led to the production of extracellular polysaccharides (EPS). The physiology of mesophillic toluene degrader could be different from thermophillic degraders as the carbon recovery as CO_2 widely varies. This could essentially alter the fate of carbon endpoints in various phases.

Influence of tension on the fate of pollutant

Optimal water content plays a pivotal role in the effectiveness of the biodegradation process (Devinny, et al., 1999). Too high moisture content could result in the formation of stagnant zones with diffusion limitation for the transport of nutrients and possible anerobic conditions (Nikiema et al., 2005). Little water content also limits the microbial activity (Bohn & Bohn, 1999). To study these parameter two reactors BF1 and BF1a were operated at 40° C at water tensions of $10cm_{H2O}$ and $20cm_{H2O.}$ Significant difference in carbon recovery as CO_2 was found with 58% at $10cm_{H2O}$ as opposed to 32 % at $20cm_{H2O.}$ Holden *et al* (Holden, Halverson, & Firestone, 1997) has previously attributed reduction in growth rates during soil drying to matric potential in the presence of a VOC carbon source. On the other hand a higher fraction of 53% carbon was recovered in the soild and liquid phase at $20cm_{H2O}$ run and 37% was recovered for the $10cm_{H2O.}$ This carbon fraction is most likely a combination of extracellular polysaccharides (EPS), soluble microbial products and dissolved $CO_{2.}$ Response to water stress also results in the production of polysaccharides (Roberson & Firestone, 1992).These kinds of water stress response like production of polysaccharides and solutes involves cellular energy and should decrease the balance for cell synthesis. Since this study was a non-growth system microbes were essentially in maintenance mode and could be a plausible explanation for recovery of carbon at higher tension in the solid and liquid phase due to production of storage polymers and other soluble microbial products (SMP).

Influence of pollutant concentration on the fate of pollutants

One of the important parameters affecting biofilter performance is pollutant concentration. Microbial proliferation is defined by the acclimatization to the optimal pollutant concentration as higher concentration can lead to substrate inhibition. Two identical biofilters BF3 and BF3a was

operated under similar conditions varying only the residual pollutant concentration at 170 ppm and 100 ppm respectively. The recovery of carbon in the gas phase as CO2 accounted for 49% for BF3 while a significant fraction of 71% was recovered for BF3a operating at lower concentration. A greater carbon fraction of 51% was recovered in the solid and liquid phase cumulatively for BF3 as opposed to 15% in BF3a. This significant carbon sink can also be attributed to toluene degraders switching to internal storage polymers like polyhydroxybutyrate (PHB) briefly at higher inlet concentration as viable microbes could be in different physiological states concurrently.

Biofilter Performance

Toluene concentration at the inlet and outlet were tracked throughout the time course of reactor operation. Before starting the toluene feed endogenous CO_2 production of the soil was monitored until it reached a steady state to establish a baseline. These values were corrected for in the net CO_2 produced. Once the toluene feed was started a step change in the CO_2 values was seen as expected and the start-up can be attributed to the acclimatization phase with rapid proliferation of the micro-consortia in the presence of pollutant (carbon/energy source). Figure 2 shows the EC, CO_2 and inlet/outlet concentration profile for the entire period of operation for the biofilters. After the acclimatization phase for all the biofilters BF1 at 40° C had the highest EC of around 83 ± 6 g m^{-3} h^{-1} at steady state around 25 days. BF3 at 30° C had a steady state EC of around 33± 5 g m^{-3} h^{-1}. However BF2 at 20° C never really came to a steady state. The outlet concentration increased over time indicating a decline in degradation process over the course of the experimental run.

BF1a operating at 40° C and 20cm_{H2O} reached a steady state by 25days, about the same time as BF1 at 10cm_{H2O} .But the EC was almost half at 45± 7 g m^{-3} h^{-1}. Both the biofilters were operated identically with tension being the only varying parameter. Although both the biofilters were in steady state with no decline in performance over the course of experimental run but there is apparent differences in the biofilter performance. This implies a significant impact of water tension on the microbial degradation rates.

Biofilter BF3a operating at 30° C at lower pollutant concentration (96± 4ppm toluene) had a very transient EC with a high of 57± 4 g m^{-3} h^{-1} in a brief pseudo steady state (30 days) following an EC of 40± 4 g m^{-3} h^{-1} preceding this phase for 20 days. In contrast BF3 at 170± 6 ppm inlet toluene concentration had a steady state EC of 33± 5 g m^{-3} h^{-1} which gradually declined over the time scale of the experiment. This could be due to substrate inhibition resulting in death of some micro flora or toxic metabolic by products.

Under nutrient limited conditions, the assumption is there is no net biomass growth which indicates a potential carbon sink in the liquid and/or gaseous phase (Cherry & Thompson, 1997). Since the recovery is never 100% as CO_2 or soluble microbial products (SMP) it implies that a fraction of carbon must be accumulating in the reactor as storage polymers or converted into other degradation products. Extracellular polysaccharides(EPS) can be an important carbon sink during nutrient-limited growth (Weber & Hartmans, 1996). Carbon balance results corroborated this assumption

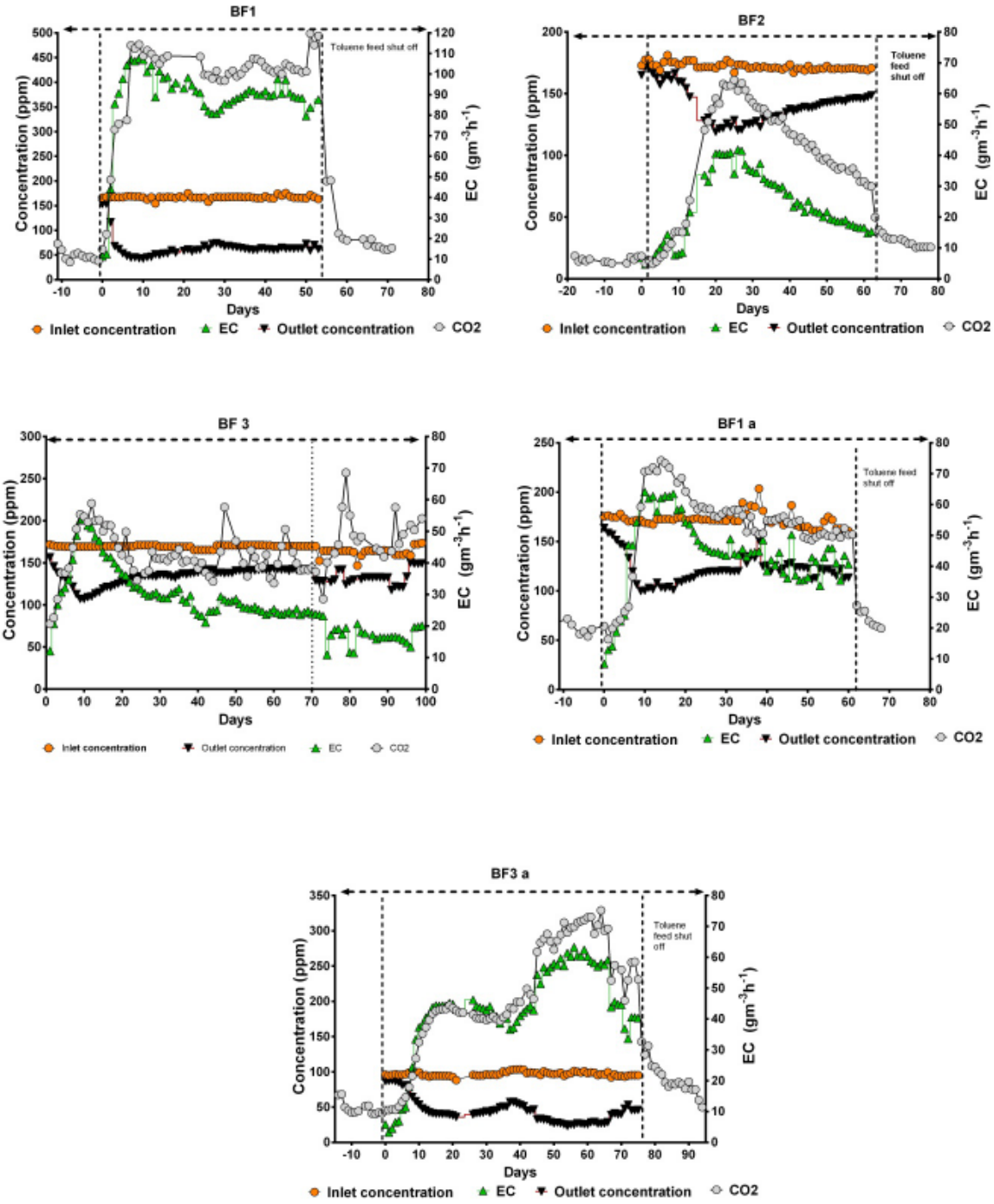

Figure 1. Elimination capacity, CO_2 production and inlet/outlet concentration profile timeline for the biofilters

Conclusions

Overall, the fate of carbon in different phases was tracked conclusively and these results will help in relating the fraction of carbon accumulation to the physiological state of the biofilters. Significant variations were found in the carbon recoveries with changes in environmental parameters.Quantification of the fate of carbon and closure of carbon balance will provide the framework for modelling and predicting the long term biofilter stability and performance. The fractions of carbon recovered in different phases will prove useful for further research to study the influence of environmental parameters and system inputs on various carbon-end points.

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Biography

Achinta Bordoloi obtained his Integrated M.Tech Biotechnology from Amity University, India during 2010. He worked at Riddet Institute, Massey University, New Zealand as a research intern for a year before starting his PhD in Chemical and Process Engineering department at the University of Canterbuty in 2011-ongoing. His research interest lies in environmental bioremediation. His current research focuses on tracking the fate of pollutants being degraded in biofilters and the influence of environmental parameters on various product ratios.

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