

INNOVATIVE EXPERIMENTAL SETUP FOR THE PARALLEL OPERATION OF MULTIPLE BENCH SCALE BIOTRICKLING FILTERS FOR WASTE AIR TREATMENT

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ABSTRACT

A new concept of periodically rotating biotrickling filters was developed for parallel operation of multiple bench scale biotrickling filters without the requirement for expensive equipment such as liquid recycle pumps and air flow regulation. The performance of 20 identically operated rotating biotrickling filters was reproducible with an average toluene elimination capacity of $79.4 \text{ g m}^{-3} \text{ h}^{-1}$ (stand. dev. = 5.7) at an empty bed residence time of 45 s and a toluene inlet gas phase concentration of 1.6 g m^{-3} . At gas and liquid cocurrent operation, the toluene elimination capacity of rotating biotrickling filters was 20 % higher than at countercurrent operation. This was probably caused by greater mass transfer limitation resulting from increased wetting of the biofilm during countercurrent operation. Performance versus load curves of rotating and of conventional biotrickling filters were comparable with non-zero order removal at toluene inlet concentrations lower than 2 g m^{-3} . This multiple rotating biotrickling filters setup provides a new and inexpensive tool for comparative studies in biotrickling filtration for air pollution control.

Keywords

Biotrickling filter, VOC control, Experimental design, Toluene biodegradation

INTRODUCTION

The 1990 Clean Air Act Amendments require US industries to reduce their emission of volatile pollutants into the atmosphere. Amongst the various air pollution control techniques available, biological waste gas treatment is a relatively inexpensive method for the treatment of large volume waste gases with low pollutant concentrations [1, 2, 3]. Two reactor configurations are currently employed in industry: biofilters and biotrickling filters. In biofilters, humidified polluted air is passed through a packed bed of organic materials such as compost and bark. Pollutants are degraded by a natural population of microorganisms immobilized in a biofilm on the packing material [1]. Biotrickling filters use a packed bed of synthetic material over which a liquid phase is circulated. As the packing does not contain an indigenous microbial population nor nutrients, biotrickling filters require inoculation with pollutant degrading organisms and continuous supply of inorganic nutrients. The continuous control of liquid phase parameters such as pH, salinity and nutrient content in biotrickling filters allow biodegradation of a broader range of pollutants and supports higher performance than biofilters [4]. However, industrial deployment of biotrickling filters is still limited [4]. Possible causes include higher treatment costs and more complex operation compared to biofilters. In particular, biotrickling filters suffer from clogging of the bed by growing biomass which affects both the long-term stability and the treatment performance [5, 6, 7, 8]. Further research is needed to optimize the performance and reliability of biotrickling filters.

In biological waste air treatment research, performance studies are mostly done with series of consecutive experiments using one or few biotrickling filters. Performance at certain conditions and at a certain time is generally compared to performance at a reference condition, which is assumed to be constant (steady-state approach). However, it has been shown that microbial populations in vapor phase bioreactors may change even after one year of operation [9] and that the performance depends on the actual amount of biomass present in the biotrickling filter [5, 10, 11]. Consequently, a true steady-state is unlikely to exist in biotrickling filters and the performance during a particular experiment may depend on experiments done

previously. Comparative research would be improved by performing parallel experiments, however, this requires a more complex and more costly experimental setup.

We designed a new, low-cost setup for the parallel operation of twenty biotrickling filters. Such a setup allows for a direct comparison of the performance under selected conditions by performing independent parallel experiments. Construction of conventional biotrickling filters usually requires pumps for liquid recycle and gas flow meters/controllers for the air. Such equipment contributes significantly to the overall construction costs of bench scale units. Hence, the major objective of the new setup was to reduce those costs. This resulted in the concept of periodically rotating biotrickling filter. Details of the experimental design and the cost of construction are presented herein together with a comparison of the performance of the rotating biotrickling filters and conventional biotrickling filters. It should be emphasized here that rotating biotrickling filters have no application for industry; the objective was a low-cost setup for parallel operation of multiple bench scale biotrickling filters to facilitate laboratory research.

MATERIALS AND METHODS

Equipment

The basic concept of the new design is periodical rotation of biotrickling filters with liquid reservoirs attached to both sides of the reactor. In the resting position, liquid from the upper reservoir is allowed to trickle down through the packed bed over a period of 100 s. and is, at the same time, collected in the lower reservoir. The biotrickling filter with the liquid reservoirs at both ends are then rotated 180° to repeat the trickling process. It should be noted that as the gas flows through the reactor in one direction only, periodical rotation results in alternating gas and liquid cocurrent and countercurrent operation. In the following, one cycle of operation (200 s) is defined as two consecutive half-cycles (100 s each) of cocurrent and countercurrent operation.

Design criteria of the rotating biotrickling filters were based on the standard operation of conventional, toluene-degrading biotrickling filters, which have been studied in our laboratory for several years. Details of both systems are summarized in Table 1.

Table 1: Overview of design parameters and standard operating conditions of conventional and rotating toluene-degrading biotrickling filters.

Parameter	Conventional biotrickling filters ^a	Rotating biotrickling filters
Bed dimension (height × ID, cm)	130 × 15.2	50 × 4.0
Bed volume (l)	23.6	0.628
Liquid volume (l)	3	0.35
Amount of packing (g) ^b	2460	144
Gas flow rate (m ³ h ⁻¹)	1.5	0.05
Toluene inlet (g m ⁻³)	1	1.5 - 2
Liquid circulation (l h ⁻¹) ^c	144	12.6
Medium feed rate (ml day ⁻¹)	5,700	60
<i>Normalized conditions of standard operation</i>		
Packing density (kg m ⁻³)	104	229
Interfacial area (m ² m ⁻³)	220	485
Empty bed gas residence time (s)	57	45
Toluene load (g m ⁻³ h ⁻¹)	64	120 - 160
Superficial liquid velocity (m h ⁻¹)	7.9	10
Liquid residence time (day)	0.53	5.8
Reactor to liquid volume ratio	7.9	1.8

^a Cox and Deshusses (1999).

^b 2.5 cm polypropylene Pall rings were broken into smaller pieces for use in rotating biotrickling filters.

^c Continuous liquid circulation in conventional biotrickling filters, semi-continuous trickling of 350 ml liquid per 100 s in rotating biotrickling filters.

Biotrickling filter: The reactors and the liquid reservoirs were made from clear Schedule 40 PVC pipe (ID = 4 cm, Ryan Herco, Burbank, CA) and connected through male and female PVC connectors (Figure 1). The total length of the biotrickling filter including the void space between reactor and liquid reservoirs was 138 cm. The reactor contained 0.63 l of packed bed of crushed polypropylene Pall rings (0.7 - 2 cm, irregular size, Koch Engineering, Wichita, KS) tightly held between two wire mesh plates screwed onto internal supports.

The liquid reservoirs (L = 34 cm) were designed to contain a liquid volume of 0.35 l and to provide an average superficial liquid velocity of approximately 10 m h^{-1} (liquid volume of 0.35 l divided by the cross area of the packed bed and a half-cycle time of 100 s). When the reservoir was in the upper position, liquid was sprinkled over the packed bed through a stainless steel tubing (L \times ID = 5 \times 0.343 cm) which distributed the liquid 5 cm above the packed bed. The reservoir in the lower position collected the recycle liquid through a PVC tube (L \times ID = 31 \times 1.5 cm) until the next reactor rotation. Brass hose barb fittings (Grainger, Riverside, CA) for gas inlet and outlet were located in the plenums between the reactor and the liquid reservoirs as shown in Figure 1.

Frame and rotating mechanism: The mechanical construction included a floor frame (L \times W = 251 \times 91 cm) of steel slotted angle posts (Grainger, Riverside, CA), two standing post (cold-rolled steel angle posts, L = 110 cm) at a distance of 187 cm, a cold-rolled steel shaft (L \times D = 247 \times 1.905 cm) supported by the standing posts at a height of 100 cm using two single row radial ball bearings (Grainger, Riverside, CA), and a biotrickling filter mounting frame (L \times W = 175 \times 45 cm) welded onto the shaft (Figure 2). Back and forth rotation was done by a Craftsman garage door opener (0.5 HP, Sears, Riverside, CA), connected with a chain to a bicycle wheel (D = 57 cm) welded onto the shaft. Adjustment controls on the garage door opener allowed for rotation of exactly 180° , which lasted 4 s to complete. Vertical alignment of the biotrickling filters in resting position was done by adjusting the chain over the sprocket of the garage door opener. The biotrickling filters were rotated once every 100 s using a low-cost, custom-made timer connected to the garage door opener (see <http://www.engr.ucr.edu/~mdeshuss/555timercircuit.gif> for circuit details). Overheating of the garage door opener was prevented by using a 12 W computer fan.

Air supply: We developed an inexpensive method to regulate the gas flow rate using capillaries. According basic fluid dynamics laws, the flow through a capillary depends on the dimensions of the capillary (diameter and length) and on the pressure drop across the capillary. By applying a relatively high pressure (100 cm water column) at the inlet of a battery of capillaries, they act as flow regulators, and will not be significantly influenced by the pressure drop of the biotrickling filter downflow of the capillary (1 - 5 cm of water column).

Toluene-containing air was prepared by mixing compressed air and toluene-saturated air (produced by sparging air into pure toluene) in specific volume ratios using two flowmeters (Fisher Scientific, Pittsburgh, PA). The combined air stream was led to a gas-tight air distribution chamber made of Schedule 40 PVC pipe, equipped with a pressure gauge (0 - 256 cm water column, Grainger, Riverside, CA) and twenty brass hose barb fittings (Grainger, Riverside, CA) corresponding to each of the biotrickling filter air supply. Syringe needles (Fisher Scientific, Pittsburgh, PA), inexpensive and available in many sizes, were used as capillaries and connected to the brass fittings. At a pressure of 102 cm water column in the air distribution chamber, the use of 21G syringe needles provided a stable air flow rate of 50 l h^{-1} to each biotrickling filter.

Medium and microorganisms

The recycle medium contained (l^{-1}): 1.443 g KH_2PO_4 , 1.443 g K_2HPO_4 , 5 g KNO_3 , 1 g NaCl , 0.262 g MgSO_4 , 0.0252 g $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, and 1 ml of a trace-elements solution, pH 6.6. The trace element solution contained (l^{-1}): 12.2 g $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$, 4.09 g $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$, 0.927 g $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, 2.37 g ZnCl_2 , 0.616 g $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$, 0.579 g $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$, 0.16 g H_3BO_3 , 0.148 g KI , 0.067 g $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, and 6.5 g $\text{EDTANa}_2 \cdot 4\text{H}_2\text{O}$. The biotrickling filters were inoculated with a mixed culture of toluene-degrading

microorganisms taken from a biotrickling filter that had been treating toluene-containing gases for over two years [5, 12].

Standard operation of rotating biotrickling filters

All biotrickling filters were operated in an identical manner over a period of 10 days to investigate the reproducibility of performance during the start-up and pseudo steady-state at nutrient-sufficient conditions. On day 0, 0.35 l of the medium and 0.01 l of the inoculation culture were added to each biotrickling filter and standard operation was initiated. Air containing 1.5 - 2 g m⁻³ toluene was supplied at a flow rate of 50 l h⁻¹, corresponding to an empty bed gas residence time of 45 s. The biotrickling filters were rotated 180° once every 100 s. On a daily basis, 0.06 l of the recycle liquid was replaced by fresh medium in order to supply nutrients throughout operation. Once every 2 - 3 days, distilled water was added to compensate for evaporation losses (about 0.02 l day⁻¹ reactor⁻¹). Performance during standard operation was determined once every two days by analyzing toluene inlet and outlet concentrations, gas flow rates, liquid volumes and liquid trickling times. Biomass accumulation in the packed bed was determined on day 9. In a second experiment with five biotrickling filters only, biomass accumulation was analyzed on a more frequent basis. Operation of the latter biotrickling filters was as described above.

Specific experiments

Toluene elimination capacities at various toluene loadings were determined by step increments of the toluene inlet concentration from 0.532 to 3.589 g m⁻³ while maintaining a constant gas flow rate of 50 l h⁻¹. Toluene outlet concentrations were determined at least 1 h after increasing the inlet concentration, when the outlet concentration was constant. Experiments were done with one biotrickling filter after 26 - 27 days of standard operation.

The influence of the trickling liquid on toluene degradation during cocurrent and countercurrent operation was investigated in three series of experiments (one biotrickling filter, after 28 days of standard operation): 1) with the culture liquid, 2) with fresh water instead of the culture liquid, and 3) with no liquid at all. In all series, toluene outlet concentrations at cocurrent and countercurrent operation were determined over three consecutive cycles.

Analyses

Toluene gas phase concentrations were determined in triplicate by direct injection of 0.16 to 0.5 ml gaseous samples into a flame ionization detector, model 8860 from SRI Instruments (Las Vegas, NV) and integration of the response by a Hewlett Packard 3390 A integrator. The time required for taking and analyzing a gas sample was 25 s; triplicate analysis was done during one half-cycle of either cocurrent or countercurrent operation. Gas flow rates were determined at the outlet of the biotrickling filters with a flowmeter (Manostat model 125, New York, NY). For the determination of the amount of wet biomass immobilized on the packing, the rotation of the biotrickling filters was stopped and the liquid was allowed to drain for at least 15 min, the liquid reservoirs were then removed and the packed bed section was weighed. Wet biomass was calculated as the increase in weight from the clean and dry packed bed section.

Construction costs

The total cost for the experimental setup was estimated at \$1600 which is very reasonable (\$80/biotrickling filter). There is a potential saving of about \$300 if opaque PVC pipe is used instead of clear PVC for the trickling filters. Labor costs for assembly (about 8 days) were not included in the above cost estimate. Most work did not require special skills, and can be done in a small workshop. Special help from the department's workshop was required for precision work and welding (about 12 hours). The electronics workshop designed and assembled the timer for operation of the garage door opener.

RESULTS AND DISCUSSION

Standard operation of rotating biotrickling filters

Operating parameters were regularly determined to track fluctuations as they may affect biotrickling filter performance. The toluene inlet concentration fluctuated between 1.5 and 2 g m⁻³ (Figure 3A). Gas flow rates through the biotrickling filters showed little variation and the average remained constant throughout the experiment (Figure 3A). In some reactors a reduction of the gas flow rate was occasionally observed after weeks of operation when large amounts of biomass had accumulated on the packing. This resulted in higher pressure drops over the bed. A constant air flow rate in all reactors, irrespective of the degree of clogging, can easily be maintained by selecting a syringe needle with a smaller diameter to control the air flow while increasing the pressure in the air distribution chamber.

Recycle liquid volumes decreased over time as a result of evaporation and some liquid loss via the air outlet. By regular addition of water and extra medium, a liquid volume between 0.275 and 0.350 l was maintained (Figure 3B). Actual superficial liquid velocities were high directly after rotation when the liquid volume in the upper liquid reservoir was at its maximum and decreased to zero when the upper reservoir became empty. With 0.32 l pure water in clean reactors and liquid reservoirs, it took 55 s (n = 40, standard deviation = 5.2) for the entire volume to trickle down from the upper reservoir. Trickling times were the same during cocurrent and countercurrent operation. Liquid trickling times in inoculated biotrickling filters during standard operation depended on the actual volume of liquid present, but appeared to increase at prolonged operation (Figure 3B). Two factors were considered to be the cause. First, microbial growth in the recycle liquid caused an increase in viscosity. Second, fouling of the liquid distribution tubing caused lower liquid flow rates. Although superficial liquid velocities were not constant, no effect was observed on the toluene degradation rate. Preventive maintenance should consider cleaning the distribution tubing on a regular basis. Toluene outlet concentrations remained constant during the entire duration of one half-cycle of either cocurrent or countercurrent operation as found by analyzing the outlet gas once every 10 s (not shown) for several cycles.

Performance of rotating biotrickling filters

Figure 4 shows the average toluene elimination capacity of twenty biotrickling filters as a function of time. Toluene degradation started one day after inoculation and reached a maximum of about 80 g m⁻³ h⁻¹ after 2 - 4 days. Such a rapid start-up can be directly linked to the effective inoculation with an adapted culture. Similar findings have been reported by Schönduve *et al.* [6] and Pederson *et al.* [13]. Accumulation of immobilized wet biomass showed an approximately linear increase at a rate of 11.6 g wet biomass reactor⁻¹ day⁻¹ (Figure 4). Despite the continuous accumulation of biomass, the toluene elimination capacity remained unchanged during the 10-day experiment, a fact also observed by Schönduve *et al.* [6] and Zuber [14]. This is because the relatively constant depth of penetration of the pollutant, oxygen and possibly other nutrients into the biofilm which limits biodegradation to the regions of the biofilm exposed to the gas phase. Biomass growth occurs only on top of an increasingly thicker biofilm with deeper layers composed of dead and/or inactive biomass. In general, excessive biomass growth over an extended period of time causes increasing pressure drops and decreasing pollutant elimination capacities. This has been reported by others [5, 10] and has also been observed with the present setup, however only after several weeks of operation. This is consistent with the results of our larger scale systems. Cost effective solutions to manage excess biomass growth are currently being researched in our laboratory.

At a mineral medium supply rate of 0.06 l reactor⁻¹ day⁻¹, the elemental composition of the medium (except nitrogen) was designed to allow for a toluene elimination capacity of 155 g m⁻³ h⁻¹ assuming a dry biomass to C-toluene yield of 0.59 g_{dry weight} g⁻¹_{C-toluene} [12] and yield coefficients on other elements as

reported by Pirt [15]. A corresponding supply rate of nitrogen would have required $19 \text{ g l}^{-1} \text{ KNO}_3$ in the medium, a concentration which appeared to be growth-inhibiting in batch experiments with toluene degrading mixed cultures (results not shown). The KNO_3 concentration in the medium was therefore decreased to 5 g l^{-1} , which would theoretically have resulted in N-limitation at a toluene degradation rate of $40 \text{ g m}^{-3} \text{ h}^{-1}$. The observed elimination capacity was however substantially higher (Figure 4). Clearly, secondary processes such as predation recycle essential nutrients in biotrickling filters [12, 16], thus increasing nutrient availability and pollutant elimination capacity.

A summary of the standard performance of rotating biotrickling filters over day 8 - 9 is presented in Table 2. Toluene elimination capacities were determined for each filter during half-cycles of both cocurrent and countercurrent operation. Small differences existed in the amount of packing, in the amount of immobilized biomass or in gas flow rate, but without any apparent correlation with the toluene elimination capacity. The low standard deviation in the determination of the elimination capacity proved that experiments were reproducible when parallel biotrickling filters were operated under identical conditions. This contrasts with unpublished reports by several investigators using sequential experiments.

Table 2: Overview of the performance over day 8 - 9 of rotating biotrickling filters ($n = 20$) with a packed bed volume of 0.628 l .

Parameter	Average	Stand. dev.	Minimum	Maximum
Bare packing (g)	144	10.4	131.9	164.7
Wet biomass (g)	92.5	11.4	77.9	113.4
Gas flow rate (l h^{-1})	50.2	1.7	47.8	52.7
Elimination capacity ($\text{g m}^{-3} \text{ h}^{-1}$) ^a				
- Cocurrent	87.1	7.6	74.1	98.1
- Countercurrent	71.7	7.4	58.4	86.4
- Average co- countercurrent	79.4	5.7	66.6	91.4

^a Toluene inlet concentration of 1.59 g m^{-3} .

Detailed examination of the biotrickling filter performance revealed that for 18 out of 20 reactors, the toluene elimination capacity was higher during cocurrent (air in downflow mode) than during countercurrent operation (Table 2). A two-tailed student T-test indicated that the difference between co- and countercurrent was significant at the highest probability level (probability higher than 99.9%). Higher elimination capacities at cocurrent operation of conventional biotrickling filters are predicted by mathematical models [14, 17] even if experiments have usually found only slight variations between the two modes of operation [4, 17]. In conventional biotrickling filters, cocurrent is usually preferred since countercurrent operation may result in stripping of the pollutant from the recycle liquid near the air outlet, causing a lower overall elimination capacity. For rotating biotrickling filters, a similar reasoning reveals however that countercurrent operation should be more efficient. This was contradicting our observations and further investigations were warranted to find an explanation to the observed phenomenon.

An experiment was conducted with one of the biotrickling filters after 28 days of standard operation in which the recycle liquid was 1) replaced by water and 2) removed. The results in Table 3 show that the elimination capacity was 18 - 25% higher during cocurrent operation in the presence of either the culture liquid or the same volume of fresh water. As expected, the elimination capacity in cocurrent and countercurrent position was the same when the recycle liquid was removed. A plausible explanation is that during countercurrent operation, the biofilm wetting was greater than during cocurrent operation and thus greater pollutant mass transfer limitations were encountered. This is further supported by: 1) the high elimination capacity without trickling indicates a high mass transfer coefficient for direct gas to biofilm mass transfer; 2) the higher elimination capacity while trickling water compared to the original liquid which indicates some degree of mass transfer limitation in the liquid; and 3) the liquid culture was relatively viscous and higher dynamic liquid hold-up were observed with the liquid culture. Even so, the air flow direction had only a small effect on the performance which did not affect the usefulness of the rotating biotrickling filter setup. Overall, the results stress the importance of understanding the fundamentals of any potential rate limiting process in biotrickling filters.

Table 3: Toluene elimination capacity (average of three consecutive cycles (three measurements per cycle) with one biotrickling filter; n = 3) during cocurrent or countercurrent trickling of the recycle liquid, clear water or with no liquid at all. The biotrickling filter contained 184 g wet immobilized biomass (28% of bed volume).

Experiment	Cocurrent		Countercurrent	
	Average	Stand. dev.	Average	Stand. dev.
Culture liquid (0.23 l)	77.8	1.7	62.2	2.8
No liquid ^a	79.6	2.1	78.0	2.1
Water (0.23 l)	86.5	3.1	72.8	1.9

^a Periodical rotation after removal of all liquid was maintained in this series; elimination capacities were determined at air upflow (=countercurrent) and downflow (=cocurrent) reactor positions as if liquid was present.

Comparison of rotating and conventional biotrickling filters

Toluene removal performance versus load curves for rotating (29% wet biomass in the packed bed) and conventional (38% wet biomass) biotrickling filters are compared in Figure 5. Data for the conventional biotrickling were previously reported [12], while the elimination capacity of the rotating biotrickling filter is the average value during cocurrent and countercurrent operation. Both curves show non-zero order removal kinetics at low toluene concentration with the elimination capacity reaching a maximum at a toluene concentration of about 2 g m^{-3} and higher. At all toluene concentrations, the rotating biotrickling filters showed a slightly higher elimination capacity, which may be attributed to the higher interfacial area of the crushed packing (Table 1). A maximum elimination capacity of about $80 \text{ g m}^{-3} \text{ h}^{-1}$ was observed for the rotating biotrickling filters. This value is in the higher range of elimination capacities reported for toluene-degrading biotrickling filters as summarized by Pedersen and Arvin [18]. While the rotating biotrickling filters exhibited a slightly higher performance than the conventional biotrickling filters, one can reasonably conclude that both systems had the same general behavior, and that rotating biotrickling filter data can be extrapolated to conventional systems, both for design and research purposes.

CONCLUSIONS

The present paper introduces the new concept of periodically rotating biotrickling filters. Rotating biotrickling filters allow for the parallel operation of multiple bench scale reactors at a minimum cost. Experimental results presented herein demonstrate that the behavior of rotating and conventional biotrickling filters is comparable. Further the performance of the rotating biotrickling filters is reproducible when the reactors are operated under identical conditions. Detailed examination of toluene biodegradation revealed that degree of wetting of the biofilm probably influences the pollutant mass transfer rate and may have an effect on the overall pollutant elimination. Overall, the results show that rotating biotrickling filters provide a new and useful tool for applied or for fundamental research in biological waste air treatment.

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FIGURE CAPTIONS (see separate file for Figures, Tables were in the text)

Figure 1. Schematic (not to scale) of one rotating biotrickling filter: 1) bed section; 2) reservoir sections; 3) location of the bed/reservoir connection; 4) wire mesh grid; 5) recycle liquid distribution tubing; 6) liquid collection pipe, 7) air inlet; 8) air outlet; 9) liquid sampling port.

Figure 2. Picture of the finished biotrickling filter equipment: 1) floor frame; 2) standing posts; 3) shaft with bearings; 4) rotating mechanism with motor, chain and wheel; 5) biotrickling filters; 6) synthetic waste air preparation; 7) air distribution chamber; 8) outlet air collection.

Figure 3. Short term stability of the operating parameters for the rotating biotrickling filters over time: average inlet toluene concentration and average gas flow rate (3A), and recycle liquid volume and trickle time (3B). The error bars show the standard deviation (N = 20).

Figure 4. Performance of the rotating biotrickling filters over time: toluene elimination capacity and wet biomass accumulation rate. The error bars show the standard deviation (N = 20).

Figure 5. Comparison of toluene elimination capacity vs. load characteristics for rotating and conventional biotrickling filters. The reactors were operated at a volumetric loading of $65 \text{ m}^3 \text{ m}^{-3} \text{ h}^{-1}$. The dashed line represents 100% removal of he toluene.

Figure 1

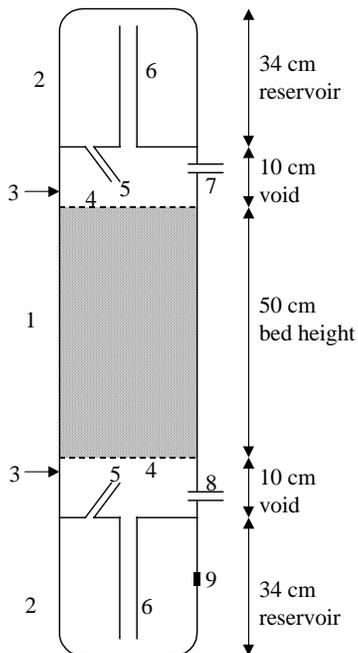


Figure 2 (please use electronic version or email mdes Huss@enr.ucr.edu if printout is not of sufficiently high quality)

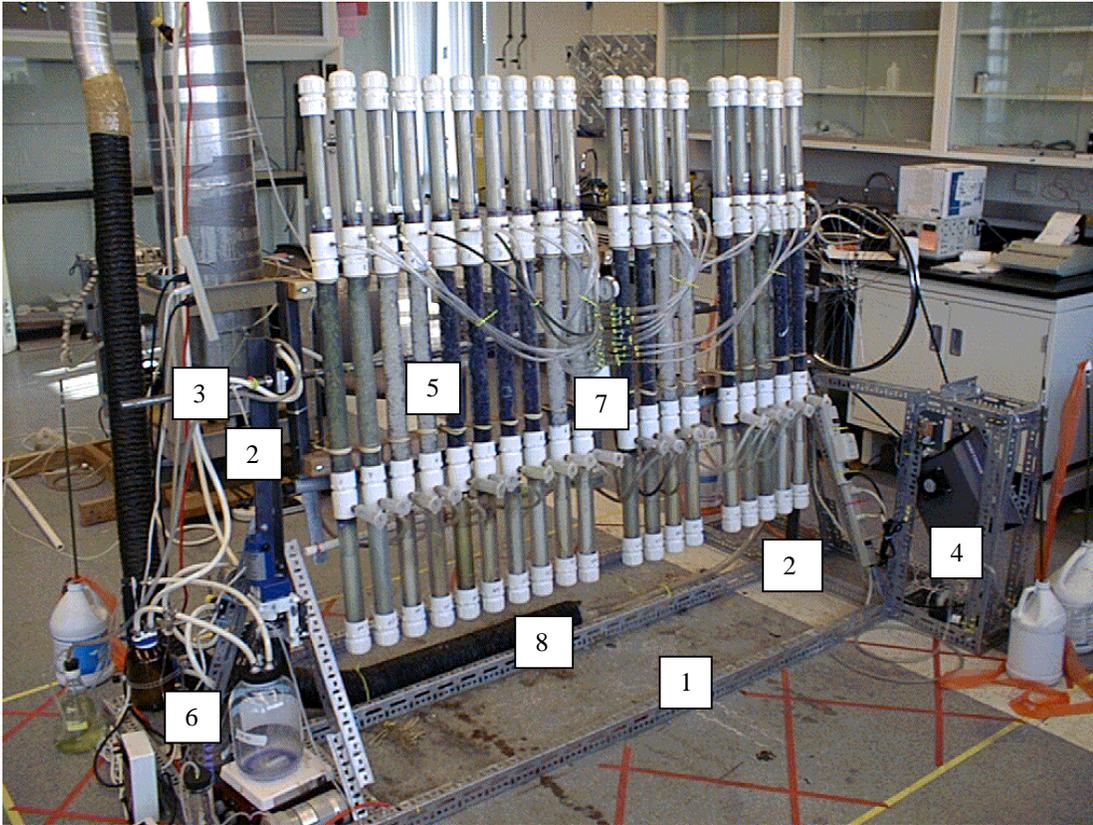


Figure 3

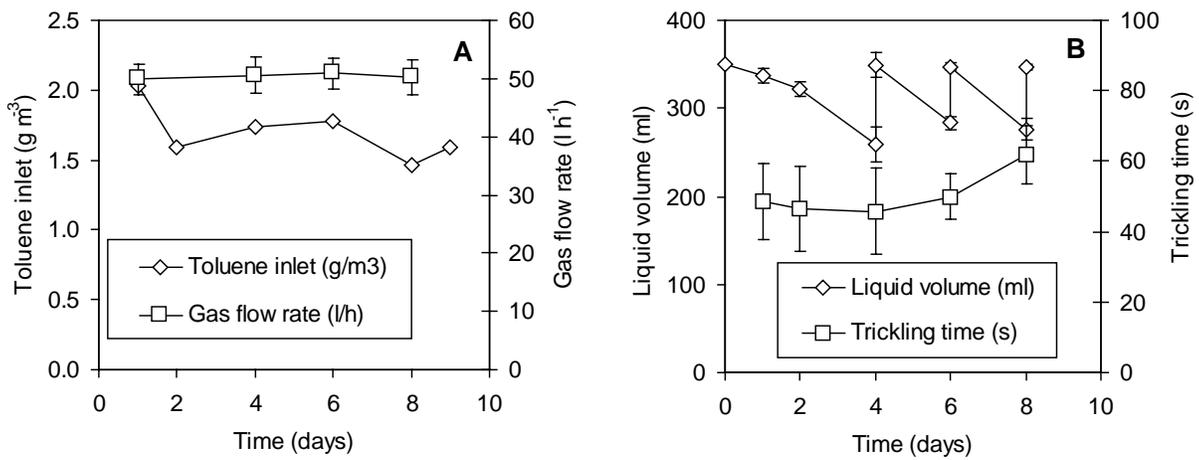


Figure 4

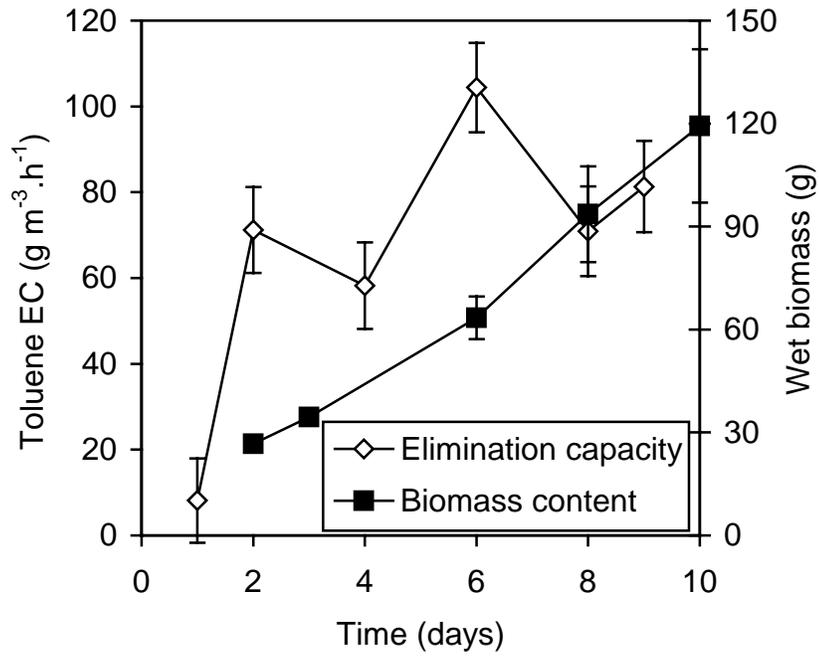


Figure 5

