A Cost Benefit Approach to Reactor Sizing and Nutrient Supply for Biotrickling Filters for Air Pollution Control

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In the present paper, a general model was developed that allows the selection of the most cost-effective operation of biotrickling filters for air pollution control. The model was demonstrated for a typical case of industrial pollution: 10,000 $m^3 h^{-1}$ airstream contaminated with 1.5 g m^{-3} toluene. The effects of nitrogen (as nitrate) loading on the pollutant elimination capacity and on the rate of biomass growth were considered. Using model simulations, the influence of the nitrate loading on the overall treatment cost was quantified and an optimum nitrate loading was determined. The results suggest that biotrickling filtration is very competitive compared to conventional treatment technologies. For the case studied, a treatment cost optimum was obtained at a nutrient loading of 8 g N-nitrate per cubic meter bed volume per day. This represents a relatively severe nutrient limitation. The range of nutrient loading for cost effective treatment was about 4 to 30 g N-nitrate $m^{-3} d^{-1}$. Overall, the approach presented herein is widely applicable for the determination of the best reactor design and the optimum reactor operating conditions.

INTRODUCTION

Biological waste air treatment is an emerging technology for controlling emissions from manufacturing processes. It is particularly cost effective for the treatment of high air flow rates and low contaminant concentrations [1]. Biotreatment of waste air offers an attractive alternative to conventional air pollution control technologies such as incineration, or adsorption.

Two types of bioreactors for air pollution control can be distinguished: biofilters and bioscrubbers. Biofilters are efficient and cost effective and have been increasingly used in industries for several decades [1]. Bioscrubbers differ from biofilters in that they include a free water phase. The most promising bioscrubber is the biotrickling filter setup. In biotrickling filters, a liquid is trickled over an inorganic packing on which a biofilm of pollutant degrading organisms grows. Biotrickling filters often offer superior performance over biofilters [2, 3]. Even so, only few industrial-scale biotrickling filters have been installed for air treatment [4-7]. The main obstacle for the deployment of biotrickling filters in industries is the growth of biomass and subsequent clogging of the packed bed over time. Existing large biotrickling filters have therefore mostly been deployed for applications with low potential for biomass growth. This includes the removal of hydrogen sulfide and carbon disulfide [6], odors [5], very low loading of volatile organic compounds [7], or intermittent medium VOC loadings [4] where weekdays biomass growth was partially offset by biomass decay during weekend recesses.

In this context, resolving the problems caused by excessive growth of biomass has recently received much attention [8-10]. Various approaches have been proposed by different investigators. Some have argued that one should starve or stress the process culture to the extent that no net biomass growth occurs over the entire reactor(s), and thus avoid the problems of clogging. This approach implies a low volumetric pollutant elimination, hence large and costly reactors. Others advocate that operating conditions should support the highest rate of pollutant elimination possible, so that small biotrickling filters can be installed. This implies dealing with the issue of biotrickling filter clogging by a fast growing process culture.

Curiously, no one has looked at this problem in terms of global treatment costs. Obviously, a large reactor implies a large capital investment, while a small but very effective reactor will be less costly but be expensive to operate because of frequent clogging. There might be an optimum between these two extremes. In the present paper, we first establish the baseline of a cost benefit method which allows for the determination of the best design and reactor operation. Then, a case study of a toluene-degrading biotrickling filter is discussed. In the case study, the

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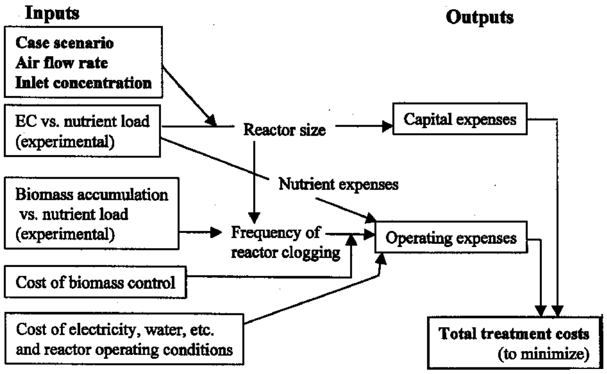

FIGURE 1. Schematic approach for the determination of the total treatment cost (not all relationships are shown). EC = pollutant elimination capacity.

supply of nitrogen limited biomass growth and controlled the reactor performance. Hence, the overall treatment cost was optimized with respect to the nitrogen supply. The interest of the general approach is that it can be modified to suit various operating modes and/or biomass control strategies and is thus widely applicable to optimize the cost effectiveness of biotrickling filters used for air pollution control.

GENERAL MODEL DEVELOPMENT

A major objective in the design of any pollution control equipment is to minimize the overall treatment costs. The overall treatment costs are the sum of the annualized capital costs and the yearly operating costs. In the case of a biotrickling filter for air pollution control, the capital costs include the purchase of the reactor, ducting, controls, reactor installation, etc. These will all increase with the size of the reactor, and because operating costs are often low, capital costs can be a significant part of the overall treatment costs. Operating costs include electricity, water, nutrients, labor and, last but not least, the costs associated with controlling the growth of biomass. Capital and operating costs both depend on the reactor design and on the reactor operating conditions. Figure 1 schematically describes these interrelationships and outlines the model approach to jointly minimize these costs to find the most cost-effective reactor design and operational mode. The model development is described below.

Let f, g, and h be mathematical functions depending on various parameters. Note that the numerical parameters in f, g, and h do not need to have a physical meaning, but should rather allow for a good representation of the various costs. For a given problem, defined by its flowrate of contaminated air, inlet concentration of contaminant and target pollutant removal, the annual capital costs for the biotrickling filter can be described as in Equations (1) and (2).

$$\text{Annual Capital Costs} = f\left(\text{Investment Costs, Interest Rate, Plant Life}\right) \quad (1)$$

in which

$$\text{Investment Costs} = g\left(\text{Reactor Size, Reactor Type and Complexity}\right) \quad (2)$$

It should be recognized here that the required elimination capacity of the target pollutant in the biotrickling filter is the principal factor determining the size of the reactor.

Annual operating costs are described by function h in Equation (3).

$$\text{Annual Operating Costs} = h\begin{pmatrix}\text{Electricity Costs, Water Cost,}\\ \text{Labor and Maintenance Costs,}\\ \text{Nutrient Costs, Cost of Controlling Biomass}\end{pmatrix} \quad (3)$$

The total treatment costs (calculated for example on a yearly basis) are given by the sum of capital costs and operating costs as in Equation (4).

$$\text{Total Yearly Treatment Costs} = f + h \quad (4)$$

Designing the most cost effective biotrickling filter is equivalent to minimizing f + h with respect to the leading parameter(s), say p. For example, in the next section, the nitrogen loading was chosen as the leading parameter for further development. The most optimum design and operating condition defined by f, h, and p, should satisfy the conditions given by Equation (5), where the function f + h reaches a minimum when plotted against p.

$$d(f+h)/dp = 0$$
$$\text{and } d^2(f+h)/dp^2 > 0 \text{ for } p = p_{optimun} \quad (5)$$

The challenge of reducing this model to practice is to select the most appropriate leading parameter p and obtain reliable biotrickling filtration experimental data for a wide range of p values, and to make reasonable assumptions on cost functions so that f, g, and h predict reliable cost estimates.

RESULTS

Case Study Conditions

For the purpose of demonstrating the applicability of the general approach proposed above, the following case was chosen:

- Air flow rate: 10,000 $m^3 h^{-1}$ (5,900 cfm)
- Pollutant: toluene; inlet concentration: 1.5 g m^{-3} (404 ppmv)
- Continuous operation, 24 hours per day, 365 days per year
- Leading parameter: nitrate supply to the biotrickling filter
- High pollutant removal efficiency (strictly defined in the model: 100% removal)

This case represents a medium air flow rate, and a relatively high inlet concentration. The inlet concentration was chosen because it matches some of our

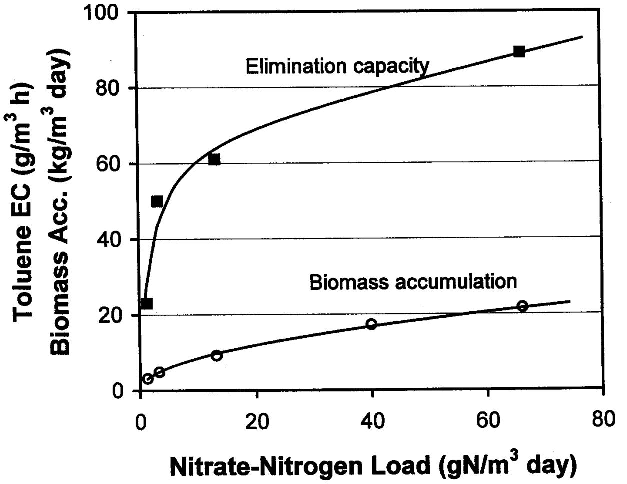

FIGURE 2. Experimental results of toluene elimination capacity and biomass accumulation as a function of the N-nitrate loading to the reactor. Each point is the average of two duplicate biotrickling filter reactors. The lines represent the best fit.

experiments on biomass accumulation and toluene elimination at various nutrient loadings. In the particular case presented below, nitrate was the limiting nutrient since it had been shown in a number of studies to impact both the rate of biomass accumulation and the performance of the system.

Biomass Accumulation and Elimination Capacity

Experimental data on the toluene elimination capacity and the rate of biomass accumulation in laboratory scale biotrickling filters as a function of the nitrate loading are shown in Figure 2. Details of the methods and of the experimental setup are presented elsewhere [11] and will not be discussed in great details in this paper. In summary, toluene-containing air (1.5 to 1.7 g m^{-3}) was fed to 20 small biotrickling filters (4 cm ID, 50 cm bed height) operated in parallel in a comparable manner to our larger laboratory-scale biotrickling filters [9,11]. Previous experiments had demonstrated that pollutant removal data in small (4 cm ID) and in larger (15 cm ID) biotrickling filters were comparable (11). The air flow rate through each biotrickling filter was 50 L h^{-1}, corresponding to a volumetric loading of 80 m^3 m^{-3} h^{-1} and a toluene loading of 120 to 136 g m^{-3} h^{-1}. The packing was crushed polypropylene Pall rings (0.7-2 cm, irregular size, Koch Engineering, Wichita, KS) with a surface area of 485 m^2 m^{-3} and a basic mineral nutrient formulation with potassium nitrate as the limiting nutrient was circulated over the packing. A portion of the recycling liquid was removed daily and fresh mineral nutrient containing various concentrations of potassium nitrate (0.1, 0.25, 1, 5 g L^{-1}) was added to the system. The N-nitrate loading was calculated based on the daily supply of nitrate and the bed volume. The reactors were initially inoculated with a toluene-degrading consortium [9] and were monitored for toluene elimination capacity by direct injection of grab gas samples into a flame ionization detector (SRI Instruments, Las Vegas, NV) and for biomass growth by off-line weighing of each reactor.

The data of Figure 2 show that both elimination capacity and biomass accumulation in the biotrickling filter depend strongly on the load of nitrate to the reactor. For modeling purpose, fitting of these experimental results was needed. It was obtained with the following mathematical functions [Equations (6) and (7)], where EC is the toluene elimination capacity (g m^{-3} h^{-1}), and N_{load} is the nitrogen-nitrate loading to the reactor in gN m^{-3} day^{-1}. It should be stressed that constants in Equations (6) and (7) have no physical meaning. Instead, these functions were chosen for their ability to fit the data best. These equations are valid for the experimental conditions listed above, and for the range of nitrate loading shown in Figure 2.

$$\begin{aligned}&\text{Wet Biomass Accumulation Rate}\\&= 2.729 \times N_{\text{load}}^{0.4926}\left(kg\ m^{-3}\ \text{day}^{-1}\right)\end{aligned} \qquad (6)$$

$$EC = \frac{67.7 \times N_{\text{load}}}{1.94 + N_{\text{load}}} + 0.347 \times N_{\text{load}}\left(g\ m^{-3} h^{-1}\right) \qquad (7)$$

Reactor Size and Investment Costs

Equation (7) together with the problem definition (10,000 m^3 h^{-1}, 1.5 g m^{-3}) allows calculation of the reactor volume using Equation (8). In doing so, two assumptions are made. First that the elimination capacity is constant over the height of the reactor. This is a simplification, but a more accurate relationship could be introduced without problems. Second, that the elimination capacity is not influenced by the growth of biomass over time. While it has been shown recently that this is not entirely true [12-14], including changes in elimination capacity with biomass accumulation would require including a time variable in the model. This was clearly beyond the scope of this paper.

$$\begin{aligned}&\text{Reactor Bed Volume}\\&= \text{Inlet Concentration} \times \text{Gas Flow Rate}/EC\left(m^3\right)\end{aligned} \qquad (8)$$

where the elimination capacity (EC) is a function of the nitrate loading given by Equation (7).

From the reactor volume, the cost of the biotrickling filter plant can be determined. For this, one should consider the costs of designing, building and installing the biotrickling filter. Our best estimate for the installed cost as a function of the bed volume is Equation (9). It is not exactly linear because large reactors are, on a per volume basis, less expensive to build than small reactors. We estimated these costs with a margin of error of about ± 20%. Based on 20 years plant life and 7% interest, the yearly capital costs are given by Equation (10).

$$\begin{aligned}&\text{Total Reactor Investment Cost}\\&= 13{,}000 \times \text{Reactor Volume}^{0.757}(\$)\end{aligned} \qquad (9)$$

$$\begin{aligned}&\text{Yearly Capital Costs}\\&= \text{Total Reactor Investment Cost}/10.75(\$/\text{year})\end{aligned} \qquad (10)$$

Yearly Operating Costs

The following operating costs were considered: nutrient, water, electricity, labor, and costs of biomass control. Maintenance costs, permitting, insurance, etc. were not included in the model because they either represent a minor fraction of the total costs or are assumed to be lumped in other costs.

The yearly nutrient expenses were calculated pro rata of the nitrogen usage [Equation (11)]. The cost of nutrients mix (fertilizer grade chemicals) was about \$1.7 kg^{-1} which comprised 26% by mass of nitrogen [15]. As expected, nutrient costs increase with the nutrient loading and the reactor volume.

$$\text{Yearly Nutrient Costs} = \text{Reactor Volume} \times N_{\text{load}} \times 1.7 \times 365 / (0.26 \times 1000)(\$ / \text{year}) \tag{11}$$

Water usage was estimated at a pro rata of nutrient usage and reactor volume [Equation (12)] and costs were calculated using a water rate of \$1.3 m^{-3} water. This is a relatively high rate, but it includes sewer discharge expenses. Note that function 12 is not linear [see last term in Equation (12)] because large reactors requiring low nutrient loadings need a minimum of water to compensate for evaporation and to purge possible salts accumulating in the recycle water. A detailed examination of the water costs reveals however, that water expenses are almost insignificant compared to other fixed or variable costs.

$$\text{Yearly Water Costs} = N_{\text{load}} \times \text{Reactor Volume} \times \frac{365}{1000} \times 1.3 \times \frac{1}{2.5 - 0.002 \times \text{Reactor Volume}}(\$ / \text{year}) \tag{12}$$

Electricity consumption for the plant was estimated at 30 kWh^{-1} for all size biotrickling filters. The rationale for a constant value is that a small reactor will offer a higher pressure drop because of the shorter empty bed retention time, and will therefore need a more powerful blower (e.g., 25 HP) but they will require less power for trickling the recycle liquid. Larger reactors will require a less powerful blower but more pumps for keeping the packing wet. This will result in approximately an equal power consumption, independent of the biotrickling filter size. As above, considering increasing power consumption over time due to higher pressure drop caused by growing biomass was not justified. Using \$0.05 kWh^{-1}, the yearly electricity expenses for all reactors amounts to \$13,140.

Based on our prior experience with a pilot/full-scale biotrickling filter (4), we estimated that 35 hours per month were needed for monitoring and general maintenance of the reactor. This excludes costs of removing excess biomass. Using a fully burdened salary of \$40 per hour, the yearly labor expenses amount to \$16,800 per year. It is assumed that these costs do not greatly depend on the size of the unit which is a reasonable assumption for general maintenance.

Yearly Cost of Controlling Biomass Growth

Over time, the biotrickling filter will experience clogging caused by biomass growth and will require some remedial actions. The frequency of clogging can be calculated using the rate of biomass accumulation [Equation (6)] assuming biomass removal will be needed when the biomass will fill 50% of the reactor volume. The time required for reactor clogging is given by Equation (13). Note that it depends solely on biomass accumulation rate and not on reactor volume.

Evaluating the yearly costs of controlling or removing the biomass for an industrial biotrickling filter is not an easy task because of the lack of field data. Clearly, the costs of controlling excess biomass will depend on the technique chosen and will be case and reactor size dependent. Based on our experience both in the laboratory and in the field using chemical washes to remove excess biomass [10], we estimate that, per declogging event, two days of labor (20 person hours x \$40 h^{-1}), 3 reactor volumes of water, and \$20-40 chemicals per cubic meter of reactor volume are needed. The flat labor per event is an oversimplification, but it can easily be changed if deemed necessary. The three reactor volumes of water assumption is based on a maximum suspended biomass concentration of about 140 g L^{-1} in the wash water, if all the biomass was to be detached. The chemical costs requires more careful consideration since, as discussed further in the paper, it is one of the highest charge. In prior studies, we found that sodium hypochlorite (bleach) was one of the most effective chemicals that we tested to rapidly remove large amounts of biomass. Sodium hydroxide was slightly less effective [10]. An approximate amount of 30-60 kg

TABLE 1. Estimated Chemical Costs of Removing Biomass (50% of the Reactor Volume) Using Sodium Hypochlorite.

Reactor volume (m^3)	Chemicals Cost (\$/event)[1]	Chemicals Cost (\$/m^3 reactor)	Cost per ton biomass removed (\$/ton)	Chemicals per ton biomass removed (kg/ton)
200	5260	26	52	42
400	12500	31	62	49
800	29800	37	74	59
1000	39400	39	78	62

[1] Calculated according to the formula: Reactor Volume$^{1.25}$ x 7 (see Equation 14).

of sodium hypochlorite is needed per ton of biomass removed (Cox and Deshusses, unpublished results). We believe that larger reactors will require more chemicals (per unit volume) than smaller reactors because of the reactor configuration, volume of piping etc. This was taken into account in the model [note the exponent 1.25 on Reactor Volume in Equation (14)] and is illustrated in Table 1. Industrial grade bleach (12.5%) costs about \$0.16 L^{-1} in the U.S. Hence, the total costs associated with biomass control translate into Equation (14), where n is the number of times the reactor will require biomass removal per year given by Equation (15).

$$\text{Time for Clogging} = 500 / \text{Biomass Accumulation Rate} \; (\text{days}) \qquad (13)$$

$$\text{Yearly Costs for Biomass Control} = n \times \left(\begin{array}{l} 800 + 3 \times \text{Reactor Volume} \\ \times 1.3 + \text{Reactor Volume}^{1.25} \times 7 \end{array} \right) (\$ / \text{year}) \qquad (14)$$

$$n = \text{Number of Clogging Events per year} = 365 / (\text{Time for Clogging} + 2) (\text{year}^{-1}) \qquad (15)$$

Total Yearly Treatment Costs

The total yearly treatment costs can be calculated adding capital costs [Equation (10)] to the nutrient, water, labor, electricity and biomass control costs. The result is shown in Figure 3 and selected cases are detailed in Table 2.

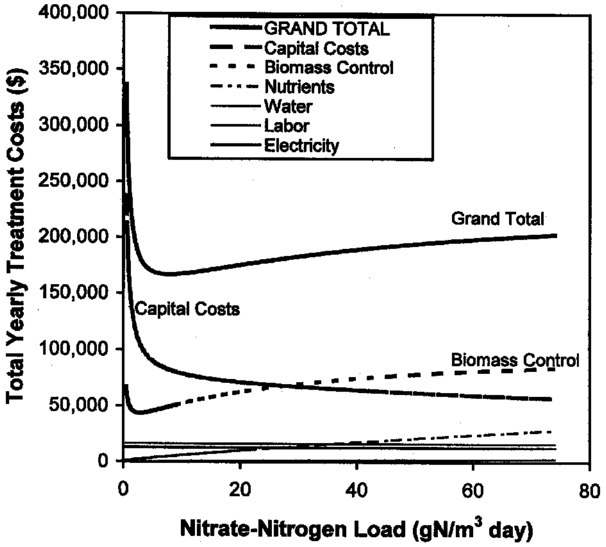

FIGURE 3. Model estimates for the total yearly treatment costs for a 10,000 m^3 h^{-1} airstream contaminated with 1.5 g m^{-3} toluene as a function of the nitrate loading.

DISCUSSION

Examination of Figure 3 shows that a cost optimum is obtained for a nitrate loading of about 8 g N-nitrate m^{-3} d^{-1} for the particular case studied. At this nutrient load, the toluene elimination capacity is 57 g m^{-3} h^{-1}, which is about half of the maximum elimination capacity, and excess biomass removal is required every 66 days [Equations (7) and (13), respectively]. Detailed examination of Figure 3 reveals that the cost effectiveness of operating biotrickling filters at low nutrient loadings drops drastically below the optimum nutrient supply. This is because the toluene elimination decreases rapidly at very low nutrient loadings (Figure 2), hence that very large reactors are needed. On the other hand, the sensitivity of the treatment costs to changes in nutrient loadings is very low above the optimum nutrient load. In the particular case studied, this leaves a wide window of opportunity for cost-effective treatment (about 4 to 30 g N-nitrate m^{-3} d^{-1}).

TABLE 2. Model Computed Costs for the Biotrickling Filtration of a 10,000 m^3 h^{-1} Airstream Contaminated With 1.5 g m^{-3} Toluene as a Function of the Nitrate Loading. Not shown in the table: labor (\$16,800/year) and electricity (\$13,140/year).

N-nitrate load (gN $m^{-3}d^{-1}$)	Reactor Bed Volume (m^3)	Reactor Investment Cost (\$)	Capital Costs (\$/year)	Nutrients (\$/year)	Water (\$/year)	Biomass Control (\$/year)	Gand Total (\$/year)	\$ per 1000 m^3 air treated
0.5	1068	2,550,000	237,000	1,300	700	67,000	336,000	3.84
1	642	1,734,000	161,000	1,500	300	51,000	244,000	2.79
2	428	1,276,000	119,000	2,000	200	44,000	195,000	2.23
4	319	1,022,000	95,000	3,000	300	44,000	173,000	1.97
8	262	880,000	82,000	5,000	500	50,000	167,000	1.90
11	244	835,000	78,000	6,400	600	53,000	168,000	1.92
15	230	798,000	74,000	8,200	800	58,000	171,000	1.95
20	218	767,000	71,000	10,400	1,000	63,000	175,000	2.00
30	203	725,000	67,000	14,500	1,400	70,000	183,000	2.09
50	182	667,000	62,000	21,700	2,000	79,000	194,000	2.22
70	166	624,000	58,000	27,800	2,600	84,000	202,000	2.30

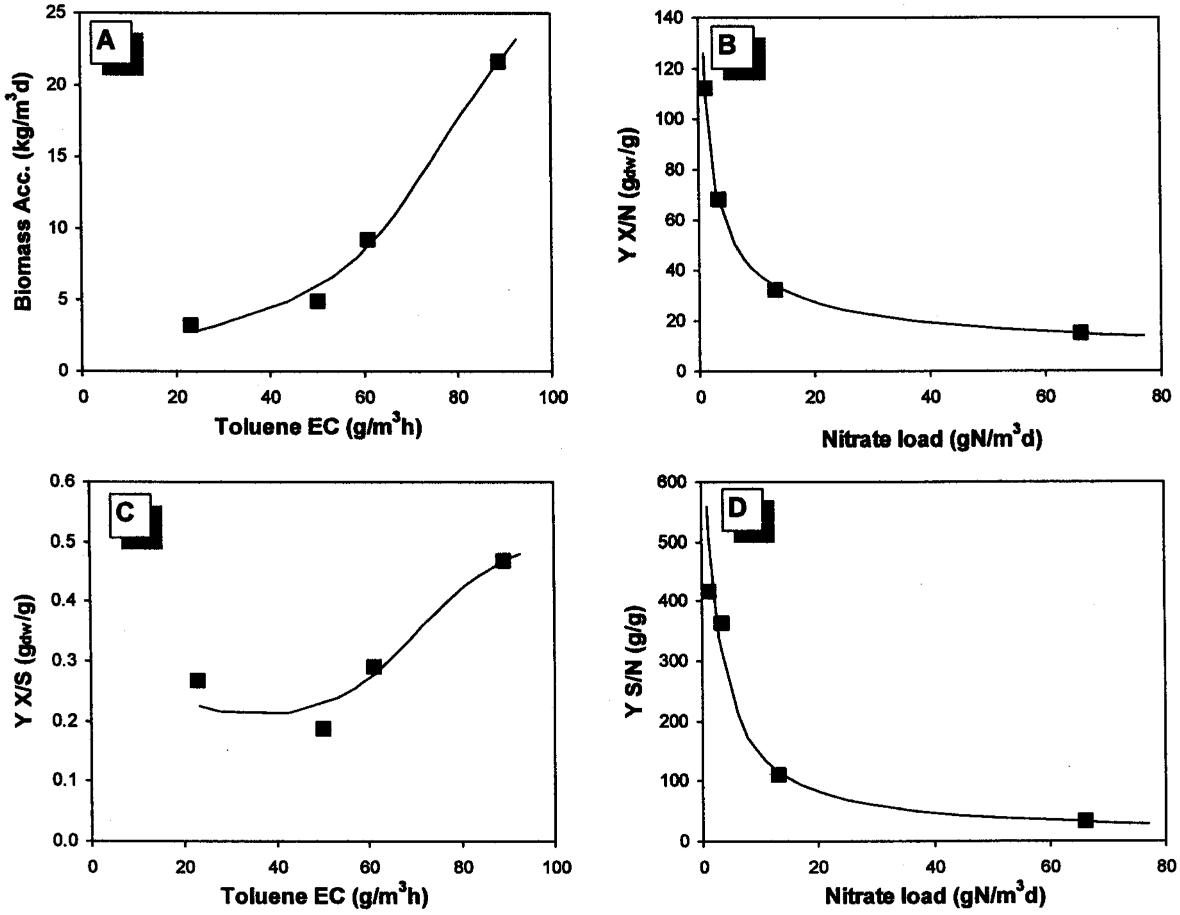

FIGURE 4. Experimental (symbols) and calculated (from Equations 6 and 7) values for process culture and bioreactor operating parameters. 4A: Biomass accumulation vs. toluene elimination capacity; 4B: biomass formed to nitrogen load yield; 4C: biomass formed to toluene degraded yield; 4D: toluene degraded to nitrogen load yield. For biomass yields, a conversion factor of 0.0462 g dry biomass/g wet biomass was used (9).

The optimum nutrient loading of about 8 g N-nitrate m^{-3} d^{-1} represents a relatively severe case of nutrient limitation from a traditional microbiology point of view. While a detailed discussion of the process culture microbiology and physiology is beyond the scope of this paper, selected parameters are plotted in Figure 4. They allow for a better understanding of the interrelationship between pollutant elimination or nutrient loading and biomass growth (Figure 4A), biomass yields (Figures 4B and 4C), and carbon to nitrogen ratio (4D). At the lowest cost conditions (8 g N-nitrate m^{-3} d^{-1}), the substrate to biomass

Table 3. Breakdown of biomass control costs.

N-nitrate load (gN m^{-3} d^{-1})	Time for Clogging (days)	Number of Clogging Events ($Year^{-1}$)	Labor Costs ($/year)	Water ($/year)	Chemicals ($/year)	Total Biomass Control ($/year)
0.5	258	1.4	1,100	5,900	60,000	67,000
1	183	2.0	1,600	4,900	44,600	51,100
2	130	2.8	2,200	4,600	37,600	44,400
4	93	3.9	3,100	4,800	36,500	44,400
8	66	5.4	4,300	5,500	39,700	49,500
11	56	6.3	5,000	6,000	42,400	53,400
15	48	7.3	5,800	6,500	45,600	57,900
20	42	8.3	6,700	7,100	48,900	62,600
30	34	10.1	8,000	7,900	53,800	69,800
50	27	12.7	10,200	9,000	59,500	78,700
70	23	14.8	11,900	9,600	62,100	83,600

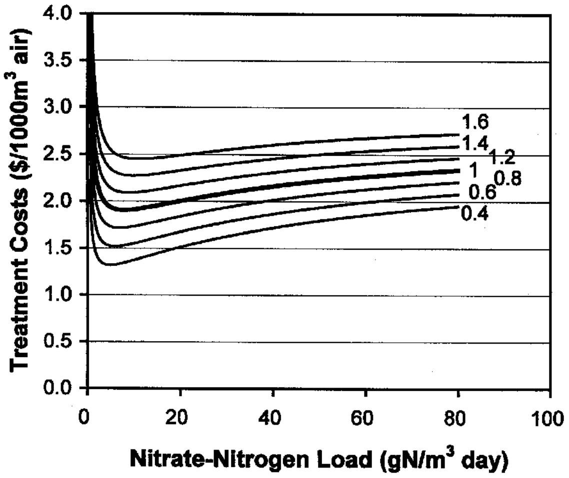

FIGURE 5. Sensitivity of specific treatment costs model estimations to the capitals costs. The yearly capital costs (Equation 10) were multiplied by factors (see legend) ranging from 0.4 to 1.6. Airflow rate 10,000 m3 h^{-1}, inlet toluene concentration: 1.5 g m^{-3}.

yield is low (4C), and the ratio of the mass of toluene degraded to the nitrogen load is 170 (Figure 4D). The latter value corresponds to a C/N ratio 6 to 20 times higher than in conventional cultures (16, 17) and suggests that in biotrickling filters, nutrients are recycled by the action of secondary degraders and/or predators. These complex conditions certainly affected the process culture metabolism, and probably lowered cell synthesis and increased mineralization of the pollutant to carbon dioxide. At higher nutrient loadings, i.e., high toluene elimination capacities, both the biomass yield coefficient and the rate of biomass accumulation increase very rapidly (Figures 4A and 4C). This had profound implications as far as the determination of the most cost effective treatment conditions is concerned. Clearly, the challenge of obtaining high performance biotrickling filters with very little or no net biomass growth will be to engineer the system parameters to minimize the biomass yield coefficient at high elimination capacities (Figure 4C) while maximizing nutrient utilization (Figure 4D).

A breakdown of the treatment costs is presented in Table 2. Not unexpectedly, most of the treatment costs for large reactors (low nitrate loadings) are the capital expenses. On the other extreme, a large part of the treatment costs for small but very effective biotrickling filters (high nitrate loading) are those of biomass control. These costs constitute up to 40% of total treatment costs. Electricity, labor, nutrient and water costs are minor (less than 30% of total) in all cases. Details of the biomass control costs are reported in Table 3 for selected designs. As mentioned earlier, most of the biomass control costs are towards the purchase of chemicals used to remove excess biomass. Clearly these costs are sensitive to the model assumptions. Other techniques for biomass control might be preferred and model equations will need to be adjusted.

Figures 5 and 6 show the sensitivity of the treatment costs to the investments costs and to the biomass control costs, respectively. Here the treatment costs are reported per 1000 m^3 air treated, a common way to compare various treatment technologies. Either the investment costs (Figure 5) or the biomass control costs (Figure 6) were multiplied by a factor (see legend) and the specific treatment costs per 1000 m^3 of air treated were plotted. Figure 5 shows that for high capital expenses (upper curves), there is no clear minimum in treatment costs, and a low sensitivity to high nutrient loadings is obtained. On the other hand, when investment costs are low (lower curves), a clear minimum in the treatment costs is obtained. This reflects that there is no incentive to build high performance reactors (high N loadings) if the construction costs are low. In a similar manner, the sensitivity of the specific treatment costs to the biomass control costs is reported in Figure 6. As expected, the specific treatment costs decrease with decreasing biomass control costs, and this effect is more pronounced at higher nutrient loadings where rapid biomass accumulation occurs. Also, with decreasing biomass control costs, the treatment costs become less sensitive to nutrient loadings (above N loads of 5 gN m^{-3} d^{-1}). A comparison of Figures 5 and 6 reveals that low performance/high volume reactors are sensitive to capital costs, whereas high performance/low volume reactors are sensitive to biomass control costs. Overall, the sensitivity of the total treatment costs to either investment costs or to biomass control costs is approximately the same. However, it is interesting to speculate that as progress is made in methods to remove/control excess biomass, the costs associated with the control of biomass may significantly be reduced, while the costs of building biotrickling filters will remain approximately the same. The data of Figures 5 and 6 suggest that such progress, will over the next decade, push the optimum design and operation of biotrick-

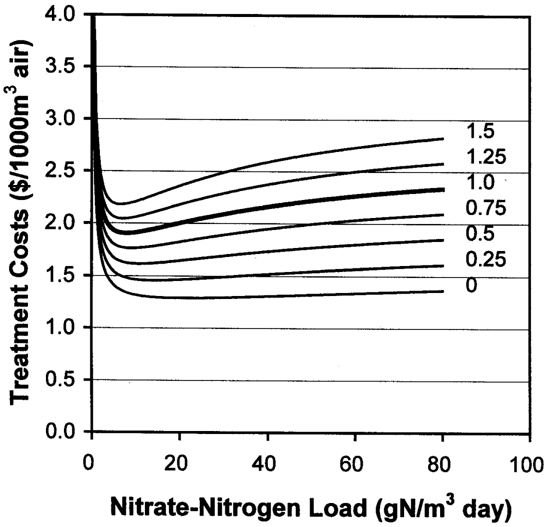

FIGURE 6. Sensitivity of the specific treatment costs to the cost of biomass control. The costs of biomass control (Equation 14) were multiplied by factors (see legend) ranging from 0.4 to 1.6. Airflow rate 10,000 m^3 h^{-1}, inlet toluene concentration: 1.5 g m^{-3}.

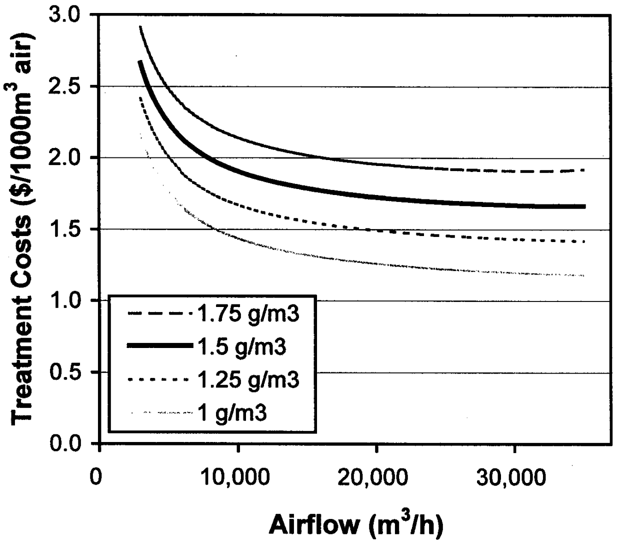

FIGURE 7. Sensivity of the optimum treatment costs as a function of the airflow rate for toluene inlet concentrations ranging from 1 to 1.75 g m^{-3}. Airflow rate 10,000 m^3 h$^{-1.}$

ling filters towards smaller and more effective biotrickling filters. Further, it is plausible that future progress in microbiology or in process engineering will significantly change the shape of the biomass accumulation vs. nutrient load graph (Figure 2) and the related culture/reactor characteristics (Figure 4). One can speculate that biotrickling filters will require less nutrients, degrade more pollutant, and produce less biomass. While such improvements will be easy to implement in the model, it will change the outcome of Figures 3, 5, an 6, and consequently the way biotrickling filters are designed and operated.

The present model also allows to evaluate the effects of the airflow rate and of the inlet pollutant concentration on the specific treatment costs. While doing this, one must ensure that all model equations remain applicable. Equations 9 through 15 assume a reactor volume of 50 to 1000 m^3. Strictly, Equations 6 and 7 are only valid for a toluene inlet concentration of 1.5 g m^{-3}, but within ±20% they will reasonably apply for inlet concentrations ranging from about 1 to 1.75 g m^{-3}. The only suggested modification to the model equations is a correction for the electricity consumption by a factor Air Flow Rate/10,000 to compensate for the different air flow than the case study. In Figure 7, the influence of the air flow rate on the specific treatment costs is shown. Only the minimum of the specific cost curve vs. nutrient loading is reported (see Equation 5). It is interesting to note that in all cases, the model predicts that the optimum nitrate loading is around 8 gN m^{-3} d^{-1}, however as stressed earlier, a large window of opportunity (about 5-30 gN m^{-3} h^{-1}) exists for cost effective treatment. Figure 7 further illustrates that the competitiveness of biotrickling filtration increases with increasing air flow rate and with decreasing inlet concentration. Overall, the values obtained range from \$1.9 to \$3.8 per 1000 m^3 of air treated, which is very competitive compared to conventional treatment techniques.

CONCLUSIONS

With the increasing use of biological techniques for waste air treatment, new decision tools are needed to help engineers design and operate biotrickling filters in the most cost-effective manner. The merit of our approach is that it is widely applicable to all biotrickling filtration situations. The challenge is to include correct assumptions and pertinent experimental data into the model to obtain reliable cost estimates. Further, the general model can be expanded easily to include more complex parameters such as a decrease of pollutant removal due to biomass growth or more complex pollutant elimination kinetics. Of course, the final selection of the actual design and of the actual operating conditions should only be made after careful evaluation of all possible options. This may include refinement of the model assumptions and possible pilot studies to verify key modeling results. Hopefully, this approach will result in a wider and better use of biotrickling filtration for air pollution control.

NOTATION AND UNITS

Unless specified otherwise, the units used in all equations are as follows:

All yearly costs		(\$ year^{-1})
Elimination capacity	= EC	(g m^{-3} h^{-1})
Frequency of clogging	= n	(year^{-1})
Gaseous pollutant concentration		(g m^{-3})
Gas flow rate		(m^3 h^{-1})
N-nitrate load	= N_{load}	($g_{nitrogen\ nitrate}$ m^{-3} d^{-1})
N-nitrate to biomass yield	= $Y_{X/N}$	($g_{dry\ biomass}\ g^{-1}{}_{N\text{-}nitrate}$)
Reactor volume		(m^3)
Substrate to biomass yield	= $Y_{X/S}$	($g_{dry\ biomass}\ g^{-1}{}_{toluene}$)
Time for clogging		(days)
Toluene degraded to N-nitrate load	= $Y_{S/N}$	($g_{toluene}\ g^{-1}N\text{-}_{nitrate}$)
Total reactor investment costs		(\$)
Wet biomass accumulation	= X_{acc}	($kg_{wet\ biomass}$ m^{-3} day^{-1})

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