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SCALE-UP AND COST EVALUATION OF A FOAMED EMULSION BIOREACTOR

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ABSTRACT

In the present paper, the potential of the foamed emulsion bioreactor (FEBR), a novel biological reactor for air pollution control was evaluated. Experimental data obtained on a laboratory-scale prototype were used to scale-up the process for a hypothetical case consisting of a contaminated air flow rate of 10,000 m^3 h^{-1}, a toluene inlet concentration of 1 g m^{-3} and minimum required treatment efficiency of 92%. Reactor design and operating issues for the full-scale FEBR were identified. They included the requirement for stable foam generation with appropriate air distributors, and recycling of the auxiliary organic phase, surfactants and cells from the discharge of the reactor. The capital and operating costs for the concept full-scale FEBR were evaluated and compared to those of competing technologies, namely biofiltration, biotrickling filtration and catalytic and thermal oxidation. All three biological techniques had significantly lower capital and operating costs. Among the biological techniques, the FEBR had the lowest estimated capital cost since its greater effectiveness allowed a smaller reactor to meet the treatment objectives. The operating costs for the FEBR were higher than those of biofilters and biotrickling filters because of the requirements for nutrients and auxiliary chemicals. Overall, the results highlight that biotreatment is much more cost effective than thermal and catalytic oxidation. They further suggest that the FEBR may an interesting alternative to biofilters and biotrickling filters where the available space for air pollution control equipment is limited

Keywords: Foamed emulsion bioreactor, air pollution control, biofilter, scale-up, cost evaluation

INTRODUCTION

Biological treatment is a cost-effective and safe technology for air pollution control and increasingly selected as an alternative to physical and chemical treatment techniques, especially for the control of odors and volatile organic compounds in high flow rates – low concentrations cases [1]. The most widely utilized bioreactors for air pollution control are biofilters and biotrickling filters [1, 2]. Biofilters are reactors in which a humid polluted air stream is passed through a porous packed bed on which a mixed culture of pollutant-degrading organisms is naturally immobilized [1]. In biotrickling filters, a distinct free water phase containing various nutrients is trickled over a packed bed [3, 4, 5]. Both biofilters and biotrickling filters have some limitations of performance. Biofilters typically have low pollutant elimination capacities, due to the low cell activity of essentially resting cells in the reactors, while biotrickling filters have often experienced clogging from excessive biomass growth, which results in high pressure drop and process instability [6,7,8].

Recently, we have developed a new vapor phase bioreactor named the foamed emulsion bioreactor (FEBR) that overcomes some of the limitations of biofilters and biotrickling filters [9, 10]. The FEBR consists of an emulsion of a highly active pollutant-degrading bacterial culture and a water-immiscible organic phase which is made into a foam with the air being treated (Figure 1). After the desired treatment is achieved, the foam is continuously collapsed, and the cells with the emulsion are reused. In order to promote growth and flush excess biomass, continuous feeding of a mineral nutrients solution and purge of the spent emulsion are required. The FEBR has high oxygen and pollutant mass transfer rates due to the large interfacial area between gas and liquid of the fine foam and the favorable partitioning of pollutants into the organic phase. Rapid biodegradation of the pollutants is achieved by a high density bacterial culture actively growing. Bed clogging and associated pressure drop problems are prevented by using a moving foam rather than an immobilized culture growing on a support. We demonstrated a higher performance for toluene removal in the FEBR than in most current bioreactors. FEBR lab scale prototypes reached toluene elimination capacities of 210-280 $g_{toluene}$ $m^{-3}_{reactor}$ h^{-1} with removal efficiency up to 95% at a gas residence time of 15 seconds and toluene inlet concentration of 1-1.2 g m^{-3} [9, 10].

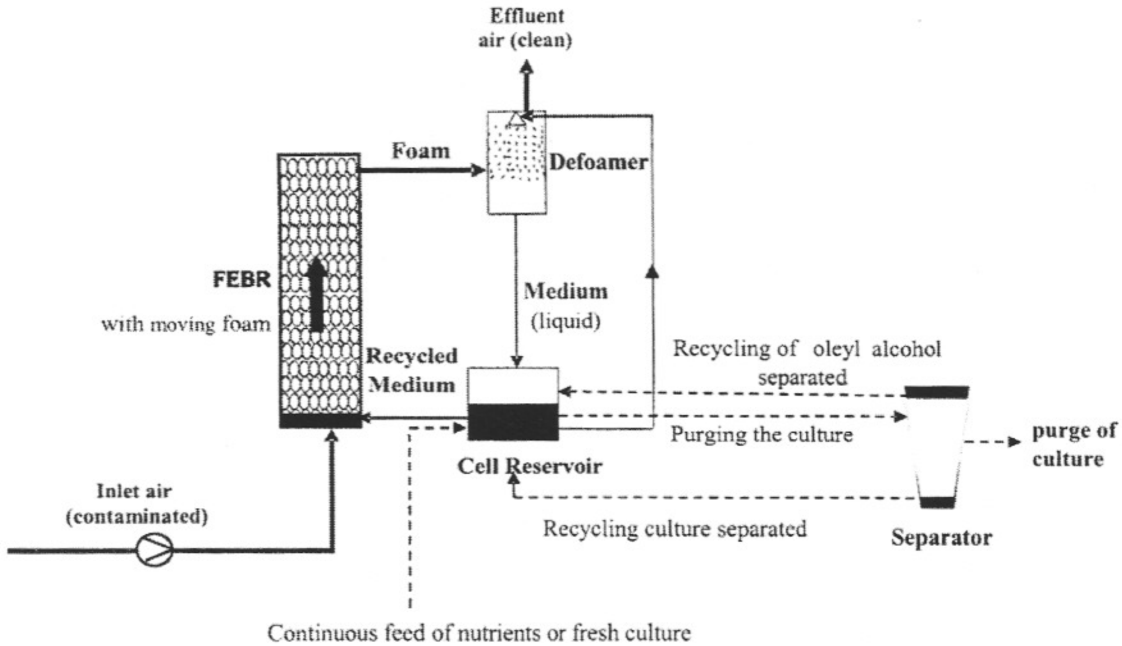

Figure 1. Configuration of the FEBR. The solid lines describe the batch operation of the FEBR, and the dash line flows are needed for the continuous operation when feeding nutrient and recycling oleyl alcohol and cells separated by a separator. See the text for details.

Scale-up and comparative cost evaluation is an important task in the development and evaluation of a new process. In the present paper, the optimum design of the FEBR obtained through detailed experiments in the laboratory was scaled-up and the overall treatment cost of a hypothetical full-scale foamed emulsion bioreactor treating toluene vapors was compared to the treatment costs of current technologies for air pollution control.

SCALE-UP OF THE FOAMED EMULSION BIOREACTOR

The operating variables for the foamed emulsion bioreactor are empty bed retention time of gas (EBRT), oleyl alcohol (the auxiliary liquid phase) concentration and culture density. The criterion for reactor scale-up is that these operating variables remain constant, so that the same treatment performance can be expected in the full-scale FEBR. It should be stressed that the foam properties (diameter and liquid film thickness of the foam) on which mass transfer depends are affected by the foam rising velocity, hence the geometry of the bed (depth and height for a given volume) will need to be within a range of acceptable conditions.

For the purpose of the present study, a generic case of air pollution control was selected and laboratory data served to support the scale-up of the FEBR. The case consisted of the following:

- Air flow rate: 10,000 $m^3 h^{-1}$
- Pollutant nature and inlet concentration: toluene, 1 g m^{-3}
- Inlet air temperature and relative humidity: 25°C, 100%
- Required minimum toluene removal (RE %): 92%

The most important scale-up issue is the reactor size, which can be calculated using Equation i, in which the elimination capacity (EC) is determined based on the knowledge acquired in laboratory experiments.

$$\text{Reactor Volume } (m^3) = \frac{\text{Inlet concentration } (g\ m^{-3}) \times \text{Gas Flow Rate } (m^3\ h^{-1}) \times RE\%}{EC\ (g\ m^{-3}\ h^{-1})} \quad \text{(i)}$$

It was determined in laboratory experiments that the toluene EC and removal efficiency at an inlet concentration of 1 g m^{-3} was 226 g m^{-3} h^{-1} and 92%, respectively [10]. The foam bed volume of the FEBR for these conditions will be 44 m^3. The foam bed was assumed to be constructed in four identical layers through which the stream of toluene-contaminated air will be distributed. The dimension of the hypothetical full-scale FEBR (3.5 m (L) x 3.5 m (W) x 3.6 m (H)) was determined by considering 10% of the FEBR volume as a headspace (not filled with foam) and reasonable gas velocity (5.6 cm s^{-1})

ensuring good foam stability. An alternative to determining the foam bed volume would be to use a mathematical model, and give input parameters, and let the model find the appropriate reactor volume for the case. This was not done here as experimental data at the conditions required for scale-up were available [11]. In addition to sizing the main bed of the FEBR, the volumes of the cell reservoir and of the defoamer need to be calculated. The cell reservoir is merely a holding tank for the cell culture emulsion, while the defoamer serves to collapse the foam -usually using a spray- to separate the treated air from the cell culture emulsion. It was shown previously [9] that pollutant removal and biodegradation principally occurs in the foam riser, rather than in the defoamer or in the cell reservoir. The sizes of these units were not optimized in the laboratory experiments. Hence, in the absence of a better basis for the scale-up, the defoamer and cell reservoir volumes were simply pro-rated to the volume of the FEBR bed, i.e., 12.5% of the FEBR bed volume for the defoamer and 25% of the FEBR bed volume for the cell reservoir. The pro-rated volume fractions are consistent with demister and sump volume fractions in conventional scrubber design. It is very possible that these can be built smaller, but this was not investigated. The total volume of the FEBR system thus includes the FEBR and any air plenum, the defoamer, the cell reservoir, the centrifuge for cell and organic phase recycling and ancillary tanks for nutrients. A summary of the volumes of the conceptual full-scale FEBR is presented in Table 1.

For the full-scale FEBR to function properly, operation should be similar to that of the lab scale unit described earlier [10]. A high cell concentration should be maintained, and continuous feeding of nutrients and withdrawal of part of the culture should be conducted. The resulting dilution rate and cell growth rate can be determined by the pollutant load, the biomass yield and the specific growth rate of the culture. For economical operation of the FEBR, separation of the purged culture is required so that recycling of oleyl alcohol, and to a lesser extent of the surfactant, and partial recycling of cells can be accomplished. A realistic and adequate recycling ratio is 95% for oleyl alcohol, and 50% of the aqueous phase with cells and surfactant. The unit operation that was selected is centrifugation which provides efficient performance with easy maintenance. It will be discussed in detail later in this section.

During the conceptual scale-up of the FEBR, several issues surfaced, which deserve further consideration. These include foam generation, and recovery of cells and of the organic phase. First of all, large-scale generation of stable foam is required. Ideally, the foam should be able to travel at high gas velocity in the FEBR, so that tall beds can be constructed. Within the biocompatibility limits of the surfactant, increasing concentration of the surfactant could be one possible solution for improving foam generation. While fine foams are easily produced by common air spargers or air stones in a bench scale, large scale production of fine foam in a full-scale reactor requires a more elaborate system. The mass production of foam for full-scale FEBRs is an issue that has not been resolved. Possible solutions include membrane diffusers and fine sieves which are not expensive and can most probably produce a fine and stable foam for large scale application. However, both systems have a risk of biofouling over the long term. Therefore, the feasibility of those air distributors should be evaluated through a series of foam generation/foam stability tests before detailed design and construction of a pilot or full-scale FEBR. For economical and environmental reasons, recycling of oleyl alcohol, the surfactant and a fraction of the cells from the effluent of the FEBR is necessary. As mentioned above, the design calls for recycling oleyl alcohol (> 95%), the surfactant (> 50%) and cells (>50%) to the cell reservoir. The remaining fraction of oleyl alcohol and surfactant will probably be hard to recover and will end as a waste, with the liquid effluent. The waste cells from the process can either be sent to the sewer, or where the amount of cells produced warrants it, the cells can be recovered and used as a single cell protein for animal feed, or for another beneficial use yet to be defined. A simple calculation based on the experimental biomass yield coefficient of 0.6 g_{dw} $g^{-1}_{toluene}$, which was obtained from the continuous laboratory operation [10], shows that for the 10,000 m^3 h^{-1} and 1 g m^{-3} case 130-140 kg of dry biomass will be produced daily. Forward thinking is to view this stream as a resource, rather than a waste.

Table 1. Characteristics of the scaled-up FEBR.

Total bed volume of the FEBR (m^3)	44
Bed volume of each layer (m^3)[a]	11
Dimension of the FEBR (m x m)	3.5 (W) x 3.5 (L) x 3.6 (H)
Volume of the defoamer (m^3)	5.1
Volume of the cell reservoir (m^3)	10.2
Total volume of the FEBR system (m^3)	59.3

*Conditions: Air flow rate, 10,000 m^3 h^{-1}; toluene inlet concentration, 1 g m^{-3}; removal efficiency of toluene, 92 (%); elimination capacity, 226 g m^{-3} h^{-1}; empty bed residence time, 15 s.
* a: The FEBR is assumed to have four identical foam layers (see text)

COST EVALUATION FOR A FULL-SCALE FOAMED EMULSION BIOREACTION

A key aspect for any new technology is its cost compared to competing technologies. Thus, the objective of the present section is to estimate the overall treatment costs, i.e., the monthly capital costs and the monthly operating costs for the case considered, and compare them with those of conventional technologies. In doing so, one should keep in mind that all numbers presented below are estimates, with a degree of uncertainty probably approaching 20-30%. This was deemed sufficient to evaluate whether the FEBR is a potentially competitive technology.

Capital costs of the FEBR

The capital costs include the costs of designing, building and installing the FEBR. These costs will be influenced by the type and materials of construction, the size of the units determined by the air flow rate, the degree of instrumentation and controls [12, 13]. Capital cost evaluation of the FEBR is difficult as no such full-scale system exists. Alternatively, capital costs for the FEBR can be obtained by modifying a rule of thumb developed for full-scale biofilters (Equations ii and iii) designed with a 30 s EBRT and packed permanent synthetic media [14].

a) \$30-36 per 1 $m^3 h^{-1}$ of air for air flow rates less than 25,000 $m^3 h^{-1}$ (ii)

b) \$15-21 per 1 $m^3 h^{-1}$ of air for air flow rates greater than 25,000 $m^3 h^{-1}$ (iii)

The initial rule of thumb for biofilters (Equations ii, iii) was modified to suit the high-tech nature of the FEBR. For FEBRs, the estimated gas contact time for the required treatment of 92% of 1 g m^{-3} toluene is 15 s. The initial rule of thumb for biofilters can be pro-rated to determine the capital cost of a FEBR at an EBRT of 15 s since the criteria shown in Equations ii and iii were obtained on the basis of EBRT of 30 s. Therefore, the following rule of thumb can be used for calculating capital costs for the FEBR (Equations iv, v).

a) \$15-18 per 1 $m^3 h^{-1}$ of air for air flow rates less than 25,000 $m^3 h^{-1}$ (iv)

b) \$7.5-11 per 1 $m^3 h^{-1}$ of air for air flow rates greater than 25,000 $m^3 h^{-1}$ (v)

The upper value of \$18 per $m^{-3} h^{-1}$ of Equation iv was used, and multiplied by 1.33 to account for the greater complexity of the FEBR. This should provide a relatively conservative estimate. The result is a capital cost of \$120,000 for the FEBR. In addition to this cost, an industrial centrifuge (0.6 m (D) x 0.6 m (H), vol. 0.17 m^3 – throughput up to 15 m^3 per day) estimated at \$10,000 (Matches Ltd, Edmond, OK) needs to be included in the total capital cost. Thus, the total capital cost of the FEBR will be about \$130,000. Based on 20 year reactor life and 7% interest, the monthly capital costs will be about \$1,000.

Operating Costs for the FEBR

The operating costs are based on continuous operation 365 days a year. They include the costs of chemicals (nutrients, oleyl alcohol, surfactant, water), electricity (liquid pumps, air blower) and labor for maintenance. As shown in Figure 1, the process liquid is made of mineral medium [9] with 3% (v/v) oleyl alcohol, 0.2% (v/v) silicone surfactant and the bacterial culture.

The costs of chemicals and utilities are listed in Table 2. They also apply to the other technologies evaluated later. The costs of the mineral medium, oleyl alcohol, a surfactant and the tap water were calculated based on the feed composition [9] and its dilution rate (here, 0.2 day^{-1}). Recycling of 95% of oleyl alcohol and 50% of the surfactant is assumed (see text above). Evaluation of energy consumption considers that the FEBR includes four liquid pumps (each ~0.5 HP) and one 20 HP air blower for 10,000 $m^3 h^{-1}$. The maintenance cost is mostly labor for the personnel who will monitor the daily operation of the reactor. After calculating the monthly capital costs and the monthly operating costs, the overall treatment costs for the FEBR is calculated as the sum of both costs.

COMPARISON OF THE OVERALL TREATMENT COST FOR THE FEBR WITH OTHER TECHNOLOGIES

The overall treatment cost for the FEBR was compared with the costs of current biological techniques (biofilters and biotrickling filters), and thermal and catalytic oxidation. The capital costs listed in the rule of thumb (Equations ii and iii) for biofilters at EBRT of 30 s were also pro-rated to obtain the cost of biofilters and biotrickling filters designed at different EBRT. For biofilters, the estimated gas contact time for the required treatment of 92% of 1 g m^{-3} toluene was 83 s, or a biofilter with a bed volume of 231 m^3.

This assumes an elimination capacity of 40 g $m^{-3} h^{-1}$ [7]. By prorating the capital costs from the rule of thumbs by the EBRT (i.e., 83/30 s), the capital cost of the biofilter is estimated as about \$277,000. For biotrickling filters, the estimated gas residence time assuming a realistic elimination capacity of 70 g $m^{-3} h^{-1}$ was 47 s [2,3], or a bed volume of 131 m^3. In a similar manner, the capital cost of the biotrickling filters was estimated to be \$252,000. Next, the operating costs for

Table 2. Estimated overall treatment costs for the FEBR.

	Item	Unit cost	Usage	Cost ($ per month)
Operating Cost				
	Tap water	1.3 ($ m^{-3})[a]	122 m^3 $month^{-1}$	160
	Mineral salts	1.7 ($ kg^{-1})	489 kg $month^{-1}$	830
	Oleyl alcohol	3.6 ($ kg^{-1})	147 kg $month^{-1}$	530
	Surfactant	5 ($ kg^{-1})	24 kg $month^{-1}$	120
	Electricity (liquid pump)	0.1 ($ kWh^{-1})	1,070kWh $month^{-1}$	107
	Electricity (air blower)	0.1 ($ kWh^{-1})	10,700 kWh $month^{-1}$	1,070
	Personnel	40 ($ h^{-1})	10 h $month^{-1}$	400
	Monthly operating cost ($ $month^{-1}$)			3,220
Capital Cost				
	Total capital cost ($)			130,000
	Monthly capital cost ($ $month^{-1}$)			1,010
Overall estimated treatment costs ($ $month^{-1}$)				4,230

a: This water cost includes estimated sewer charges

treatment in the biofilter and in the biotrickling filter were evaluated. The operating costs for the biotrickling filter are costs of chemicals (nutrients, biomass controlling agents) and electricity for air blower, while O&M costs of the biofilter mainly depend on costs for air blowers and packing replacements. Both the reactors require a blower with about 20 HP to force the 10,000 m^3 h^{-1} air through the beds. For biofilters, they will need replacement of the packing every 6 months to 2 years (an average of once per year is used for further calculation). The average cost for packing replacement is estimated to be $400/month based on packing costs of $60 per cubic meter [14]. The costs associated with biomass control for biotrickling filters are greatly unknown. An estimate (Equation vi) was proposed [12], though those costs have never been confirmed by actual experience and should probably be considered as the worst possible case. Therefore, for the present estimate, the cost determined by Equation vi was divided by 2.

Yearly cost for biomass control ($/yr)

$$= n \times \left(800 + 3 \times \text{Reactor Volume} \times 1.3 + \text{Reactor Volume}^{1.25} \times 7\right) \quad \text{(vi)}$$

where n ($year^{-1}$) = number of clogging events per year = 365/(time for clogging + 2), time for clogging (days) = 500/biomass accumulation rate.

Based on application of Equation vi at the given case conditions, the yearly cost for biomass control will be about $2,500 / year.

The details of the estimated operating costs of biofiltration and biotrickling filtration are presented in Table 3. From Table 3, it is found that biotrickling filters have lower capital costs but greater operating costs, mostly due to nutrients and chemicals to control biomass.

Thermal and catalytic oxidizers are also widely used to treat VOC contaminated air [15-17]. Thermal oxidation usually occurs at 700-1400 °C, while catalytic oxidation is conducted at 300-700 °C.

Table 3. Estimated costs for treatment using a biofilter or a biotrickling filter.

Cost	Item	Biofilters	Biotrickling filters
Capital cost			
	Total capital cost ($)	277,000	252,000
	Monthly capital cost ($ $month^{-1}$)	2,150	1,950
Operating cost			
	Packing replacement ($ $month^{-1}$)	400	-
	Tap water ($ $month^{-1}$)	negligible	160
	Mineral salts ($ $month^{-1}$)	negligible	210
	Biomass control ($ $month^{-1}$)	-	210
	Electricity ($ $month^{-1}$)	1,070	1,120
	Personnel ($ $month^{-1}$)	400	400
	Monthly operating cost ($ $month^{-1}$)	1,870	2,100
Overall treatment cost ($ $month^{-1}$)		4,020	4,050

Both techniques are energy intensive processes, but are quite reliable and are able to achieve very high contaminant destruction efficiency (>99%). For the estimation of the capital costs of thermal or catalytic oxidation, a value of $325,000 per 10,000 m^3 h^{-1} of air being treated for thermal or catalytic oxidizers was obtained from a vendor (Duur Environmental, Plymouth, MI). Consequently, the monthly capital costs would be $2,520 for both thermal and catalytic oxidizers. Typically, operating costs are high for the treatment of dilute pollutants as additional fuel is required to bring the calorific value of the air undergoing treatment in the correct range. Thus, the operating costs for thermal and catalytic oxidation are mostly natural gas or electricity. It is interesting to realize that since 1 g m^{-3} toluene is about 38 times lower than the lower explosive limit (LEL) of toluene (1.1%), thermal and catalytic oxidation is really about burning fuel rather than the pollutant. This will result in an additional emission of 5,000 to 10,000 tons of CO_2 per year and all the associated environmental consequences. From a treatment cost perspective, previously published data [15] allow one to estimate that for 10,000 m^3 h^{-1} and 1 g m^{-3} toluene or 1% LEL, the required energy costs (natural gas or electricity) would be about $6.6 h^{-1} for catalytic oxidation and $13.6 h^{-1} for thermal oxidation. This totals to monthly operating costs of $9,800 for thermal oxidation and $4,800 for catalytic oxidation, or $10,200 for thermal oxidation and $5,200 for catalytic oxidation after adding $400 per month for labor cost. Table 4 shows the capital, operating and overall treatment costs for thermal or catalytic oxidizers. The overall treatment costs are estimated as $12,700 per month for thermal oxidizers and $7,700 per month for catalytic oxidizers.

A summary of the costs of the various technologies is shown in Figure 2. Clearly, biological techniques are much more advantageous than conventional treatment, with total treatment costs roughly a third or a half of those of thermal or catalytic oxidation. The capital cost for the FEBR is the lowest of all the technologies. This is because of the small size of the FEBR allowing shorter gas retention time. The operating cost for the FEBR is also much lower than thermal or catalytic oxidation which requires natural gas or electricity, however, the FEBR is more expensive to operate than biofilters and biotrickling filters, since the FEBR requires chemicals such as oleyl alcohol and surfactant. The current evaluations show that the overall treatment cost for the FEBR is very similar to the estimated cost of biofiltration and biotrickling filtration. A more detailed economical evaluation would probably be needed to decrease the uncertainty of the costs reported in Figure 2. The FEBR has several advantages over biofilters and biotrickling filters: these include a smaller footprint, absence of clogging issues, the possibility of a rapid startup or restart after shut down or after a starvation period and the flexible operation resulting from the use of a distinct liquid culture. In any case, a complete evaluation of the pros and cons of the competing technologies is a necessary step in the selection of a treatment method. The cost figures presented in this study for the newly developed FEBR suggest that this technique may be cost competitive.

CONCLUSIONS

Biological treatment is an increasingly accepted technology for air pollution control, especially in those cases where the concentration of air pollutants is low. In the present paper, the cost-effectiveness of the FEBR, a novel biological reactor for air pollution control was evaluated and compared to treatment in biofilters, biotrickling filters and thermal and catalytic oxidation. The evaluation considered a hypothetical case consisting of an air flow rate of 10,000 m^3 h^{-1}, a toluene inlet concentration of 1 g m^{-3} and a minimum required treatment efficiency of 92%. The results highlight that conventional treatment in oxidizers is not competitive for diluted air streams. This is because of the requirement to significantly raise the calorific value of the treated air stream so that oxidation can be sustained. Today, with rising energy costs and concerns about CO_2 emissions, the choice of thermal or catalytic oxidation for such an application would be highly questionable. On the other hand, biological treatment was found to be very cost effective and differences in the capital and operating costs between FEBR, biofilters and biotrickling filters were identified. The current evaluation shows that the FEBR maybe an interesting alternative to biofilters and biotrickling filters, especially where space is limited and flexible operation is desired.

Table 4. Estimated treatment costs for thermal or catalytic oxidation.

Cost	Item	Thermal oxidizer	Catalytic oxidizer
Capital cost			
	Total capital cost ($)	325,000	325,000
	Monthly capital cost ($ $month^{-1}$)	2,520	2,520
Operating cost			
	Electricity + natural gas ($ $month^{-1}$)	9,790	4,750
	Personnel ($ $month^{-1}$)	400	400
	Monthly operating cost ($ $month^{-1}$)	10,190	5,150
Overall treatment cost ($ $month^{-1}$)		12,710	7,670

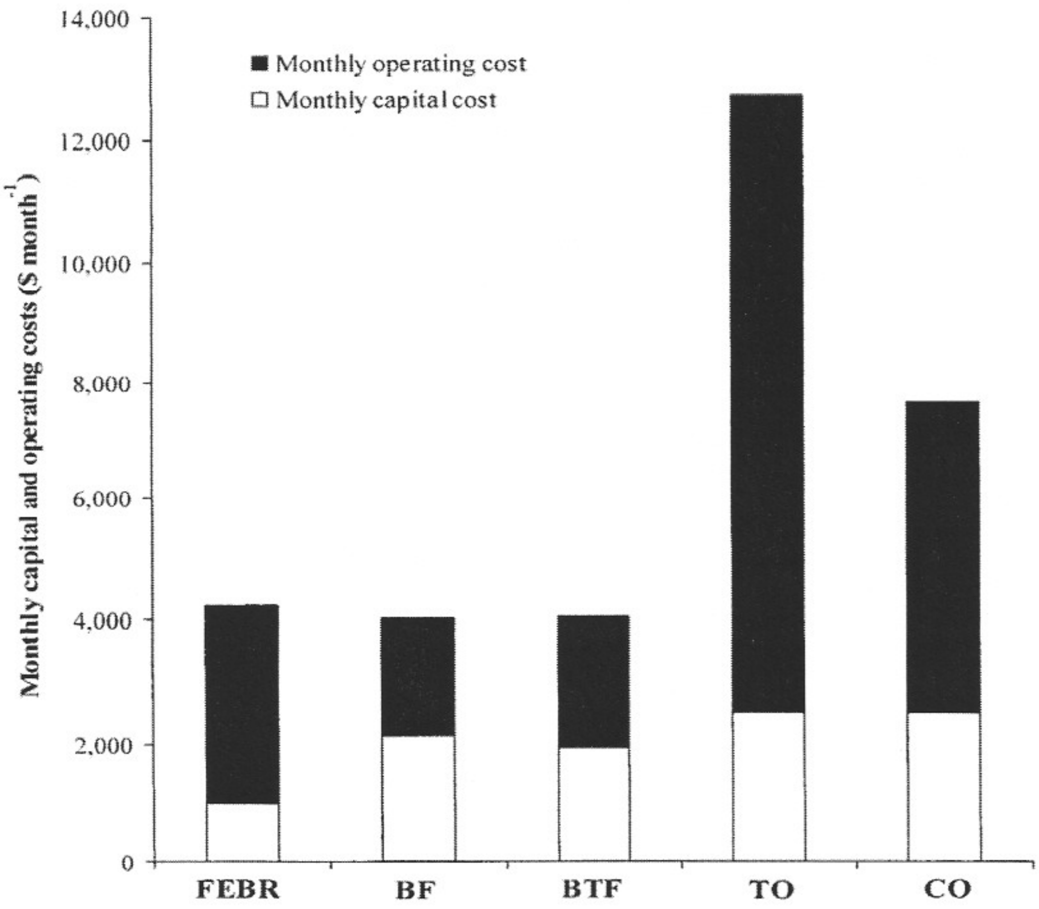

Figure 2. Comparison of the capital and operating costs for the FEBR and competing technologies. Conditions: 10,000 m^3 h^{-1} air, 1 g m^{-3} toluene, or 1% LEL (lower Explosive limit). FEBR: foamed emulsion bioreactor, BF: biofilter, BTF: biotrickling filter, TO: thermal oxidizer, CO: catalytic oxidizer. See the text for details.

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