

Evaluating odour control technologies using reliability and sustainability criteria – a case study for water treatment plants

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ABSTRACT

Technologies for odour control have been widely reviewed and their optimal range of application and performance has been clearly established. Selection criteria, mainly driven by process economics, are usually based on the air flow volume, the inlet concentrations and the required removal efficiency. However, these criteria are shifting with social and environmental issues becoming as important as process economics. A methodology is illustrated to quantify sustainability and robustness of odour control technology in the context of odour control at wastewater treatment or water recycling plants. The most commonly used odour abatement techniques (biofiltration, biotrickling filtration, activated carbon adsorption, chemical scrubbing, activated sludge diffusion and biotrickling filtration coupled with activated carbon adsorption) are evaluated in terms of: (1) *sustainability*, with quantification of process economics, environmental performance and social impact using the sustainability metrics of the Institution of Chemical Engineers; (2) *sensitivity* towards design and operating parameters like utility prices (energy and labour), inlet odour concentration (H_2S) and design safety (gas contact time); (3) *robustness*, quantifications of operating reliability, with recommendations to improve reliability during their lifespan of operations. The results show that the odour treatment technologies with the highest investments presented the lowest operating costs, which means that the net present value (NPV) should be used as a selection criterion rather than investment costs. Economies of scale are more important in biotechniques (biofiltration and biotrickling filtration) as, at increased airflows, their reduction in overall costs over 20 years (NPV_{20}) is more extreme when compared to the physical/chemical technologies (chemical scrubbing and activated carbon filtration). Due to their low NPV and their low environmental impact, activated sludge diffusion and biotrickling filtration are in general the most cost-effective, and probably the technologies to be considered first for odour treatment in a wastewater treatment or water recycling plant. When, in an economical and risk evaluation, the reliability is counted to be as relevant as the overall costs, a hybrid technology (biotrickling filtration with activated carbon polishing) would be comparable to biotrickling filtration and activated sludge diffusion as the most preferred technologies, when all technologies are designed to have a 99% reduction of H_2S and a 95% reduction of the odour concentration.

Key words | economics, odour abatement, operating costs, robustness, sensitivity analysis

INTRODUCTION

With residential areas encroaching on odour sources and environmental legislation becoming more stringent, there is an increasing need for odour management. Malodours not only are a direct threat for human health and welfare, but also represent a significant contribution to photochemical

smog formation and particulate secondary contaminant emission (Sucker *et al.* 2008). Moreover, most companies are increasingly aware of their public image.

A sustainability analysis recently carried out quantified the environmental and social impacts, and the net present

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value (NPV₂₀), of the most commonly used odour abatement technologies, confirming the more sustainable performance of biological technologies and the key relevance of the operating costs in the overall process economics (Estrada *et al.* 2011). However, this study also revealed the high uncertainty in the evaluation of the operating costs due to their high dependence on utility prices, wages and process design parameters (Estrada *et al.* 2012).

The robustness of each technology towards typical process fluctuations and operational upsets is also important. Quantifying the robustness identifies and analyses how to avoid failures, and/or mitigate the effects of the operational risks inherent to the system. It can be used to set requirements for control, monitoring and backup equipment, and criteria for performance testing as well as maintenance schedules.

This paper demonstrates how to quantify the sustainability and robustness of odour control technology in the context of odour control at water treatment plants. It also quantifies the influence of the most important utility prices and process design parameters on process economics, which today still constitutes the main selection criterion despite the recent increased attention on sustainability.

METHODS

Model malodorous emission

For this evaluation, a model for malodorous emission was selected and consisted of the odour composition typically emitted from municipal wastewater treatment systems.

This includes many different volatile organic compounds (VOCs) and volatile organic sulphur compounds including hydrogen sulphide (H₂S) and mercaptans. The assessment was based on a compilation of real data from full-scale facilities. All the systems evaluated were based on designs capable of coping with typical daily and seasonal fluctuations in odour concentration, which often requires the over-sizing of the reactor.

Odour abatement technologies

The technologies evaluated are described elsewhere (Estrada *et al.* 2011) and their designs are based on a minimal 99% reduction of the H₂S concentration (outlet concentration <0.1 ppm_v) and a 95% reduction of the odour concentration (outlet concentration <1,000 OU (odour unit)). The design and costing parameters for the different technologies are summarised in Table 1 below.

Costs, sustainability and robustness of odour abatement technologies

The energy consumption (kW) for gas circulation was calculated as $Q \text{ (m}^3 \text{ s}^{-1}) \times \Delta P \text{ (kPa)} \times \text{blower efficiency (0.6)}$. All costs in this paper are given in US dollars. The operating costs are based on a price of \$0.15 kW⁻¹ for energy, \$1.50 kL⁻¹ for potable water, \$0.50 kL⁻¹ for secondary effluent water, \$6 kg⁻¹ for impregnated activated carbon with a density of 0.5 g kL⁻¹, \$0.54 L⁻¹ for 50% (w/w) NaOH, \$0.34 L⁻¹ for 12.5% (w/w) NaOCl, media disposal costs of \$500 kL⁻¹ (BTF, CS, AC) and \$250 kL⁻¹ (BF),

Table 1 | The summary of the design and costing parameters for the odour control technologies evaluated in the context of odour control at wastewater treatment or water recycling plants.

Technology	Gas contact time (sec)	Pressure drop (Pascal)	Lifespan media (years)	Costs media (US\$)	Remarks
Biofiltration (BF)	60	1000	5	\$250 kL ⁻¹	Organic/inorganic media mix; includes a pre-humidification unit
Activated carbon filtration (AC)	3	1000	Defined by H ₂ S load	\$6 kg ⁻¹	Caustic impregnated carbon with 13% (w/w) adsorption capacity; includes prefilter for grease
Biotrickling filtration (BTF)	16	800	10	\$2000 kL ⁻¹	Two-stage (autotrophic/heterotrophic)
Hybrid (BTF + AC)	9 + 2	1250	10 (BTF) + 2 (AC)	See above	Single-stage BTF + AC
Chemical scrubbing (CS)	3	600	10	\$1800 kL ⁻¹	Two-stage (caustic/hypo)
Activated sludge diffusion (ASD)		52000			4.5 m deep aeration tank

and a cost for labour of \$100 per hour. The investment costs shown include only direct equipment costs of the odour abatement unit and does not include costs for transport of the abatement unit to site, installation and commissioning and site-specific costs like the costs for site preparation, the air extraction system (covers, ductwork and fans), industrial plant control integration, access platforms, performance testing, contractor mobilisation, engineer and client costs for detail design work, tendering and project management. All these indirect costs are considered to be relatively independent and similar regardless of the type of odour treatment system.

The comparison of sustainability was based upon the triple bottom-line concept, which includes the assessment of environmental performance, social responsibility, and process economics using the sustainability metrics of the Institution of Chemical Engineers (ICHEME 2002). A green house emissions factor of 250 kg CO₂-equivalents per GJ of energy consumed (ICHEME 2002), 1,376 and 1,065 kg CO₂-equivalents per dry tonne of caustic and sodium hypochlorite, respectively, consumed (Owen 1982), and 1,000 kg CO₂-equivalents per dry tonne activated carbon (Agentschap 2012) is used. The greenhouse gas (GHG) emissions are only operation and maintenance (O&M) related and exclude the GHG for manufacturing and transportation of new media (BF media is usually natural and requires minimal processing; AC and BTF media is a relatively small amount and usually has a long life span) and exclude the transportation costs for delivery of chemicals and activated carbon as they have only a relatively small contribution.

The robustness of a technology (R) can be quantified by determining the risk of negative effects on the performance of the technology for each possible disorder (process fluctuation or operational upset), multiplied by its frequency of

occurrence, and adding all possible disorders according to Kraakman (2003) as show in Equation (1)

$$R = \sum p \times E \quad (1)$$

where p is the probability of occurrence of a disorder and E the effect of a disorder. In this paper both the probability of occurrence and the effect are semi-quantified on a scale of 1 to 5 based on operator field experiences and other studies (Estrada *et al.* 2012).

RESULTS AND DISCUSSION

The investment costs per amount of air treated decreased exponentially with increased design airflow for all the odour abatement technologies evaluated, which highlights the relevance of the economies of scale (Figure 1). The odour treatment technologies with the highest investments are biotrickling filtration and biofiltration and with the lowest investment are the physical/chemical technologies (chemical scrubbing and activated carbon filtration). The selected configuration in chemical scrubbing (one stage versus two stages) significantly influences the investment costs, with two-stage chemical scrubbers presenting higher costs than their one-stage counterparts. Nowadays, odour removal at typical design efficiencies of 95% demands at least two stages for higher odour loads whereas one stage is enough when only H₂S abatement is required. The investment costs in activated sludge diffusion are not shown as they would be minimal, because all equipment required is already present in the wastewater treatment line. Additional investments for activated sludge diffusion would derive from

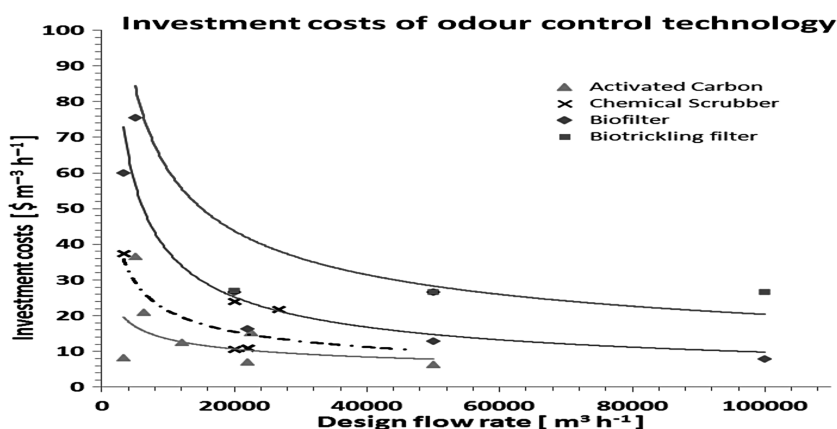


Figure 1 | The investment costs for activated carbon filtration, chemical scrubbing, biofiltration and biotrickling filtration (adapted from Estrada *et al.* 2011).

the installation of moisture traps and dust and grease aerosol filters and from the use of corrosion-resistant materials in blowers and air piping. In this context, a survey from 30 wastewater treatment plants in the USA showed that these corrosion concerns were not well founded, but, in most cases, corrosion-resistant materials must be installed in filters, moisture traps and blowers (Bowker & Burgess 2001). Despite its limitation in air volume and foul air loading, activated sludge diffusion is the cheapest of all technologies selected. The maximum air volume that can be treated by activated sludge diffusion is determined by the aeration requirements of the activated sludge tank at the wastewater treatment plant, while the foul air loadings are limited by its degradation/adsorption capacity as discussed in Kieseewetter et al. (2012).

During evaluation and selection of odour abatement systems, the NPV rather than the initial investment cost should be used as the economic selection criterion. For a relatively low ($7,500 \text{ m}^3 \text{ h}^{-1}$) odorous emission containing less than 7.5 ppm_v of H_2S , activated carbon filtration is the cheapest technology, but the dearest when the H_2S exceeds approximately 20 ppm_v . (Figure 2(a)). For higher airflows ($75,000 \text{ m}^3 \text{ h}^{-1}$) it reveals that the biotechniques (biofiltration, biotrickling filtration as well as the hybrid technology) become increasingly less expensive (NPV₂₀) with increased air flows (Figure 2(b)).

The cost of secondary effluent water is assumed to be less than that of potable water (as secondary effluent is often used as plant service water), which favours the operational costs and the overall costs (NPV₂₀) of the biotechniques. Nearly complete (>99%) H_2S degradation in the BTF stage was assumed for the hybrid technology. The effect of higher H_2S

concentrations on biofiltration is typically a reduction of biofilter media lifespan due to an increased acidification of the BF media, which reduces its abatement performance. Therefore a biofilter media lifespan of 5 years at an average H_2S concentration of 5 ppm_v , and a media lifespan of 2 years at 40 ppm_v were used here in this evaluation.

A single-stage chemical scrubber offers for relatively low concentrations an opportunity to reduce the capital costs of chemical scrubbing. A single-stage chemical scrubber could reduce the investment cost by about 40% (data not shown). This cost saving on investment will result in an approximately 10% saving from the total costs (NPV₂₀) at an airflow of $7,500 \text{ m}^3 \text{ h}^{-1}$ and an inlet concentration of 20 ppm_v H_2S (approx. 5% at $75,000 \text{ m}^3 \text{ h}^{-1}$) and an approximately 15% saving from the total costs (NPV₂₀) at an inlet concentration of 5 ppm (approx. 10% at $75,000 \text{ m}^3 \text{ h}^{-1}$). To obtain the assumed minimum required reduction of 95% in odour concentration, both caustic and hypochlorite dosing are still needed, which typically results in slightly higher chemicals consumption in the single-stage scrubber compared to a two-stage scrubber. In summary, although capital cost savings for a single-stage scrubber is significant, the overall cost savings (NPV₂₀) are not as large compared to a two-stage scrubber to obtain 95% odour removal, because the total costs of chemical scrubbing are mainly determined by the operating costs.

The influence of the utility prices (energy and labour) and design parameters (media life and reactor size) on the NPV₂₀ of the odour abatement technologies are evaluated. Figure 3(a) shows that at 50% higher energy prices compared to the currently used \$0.15 per kW, activated carbon is the least affected as energy is only a very small

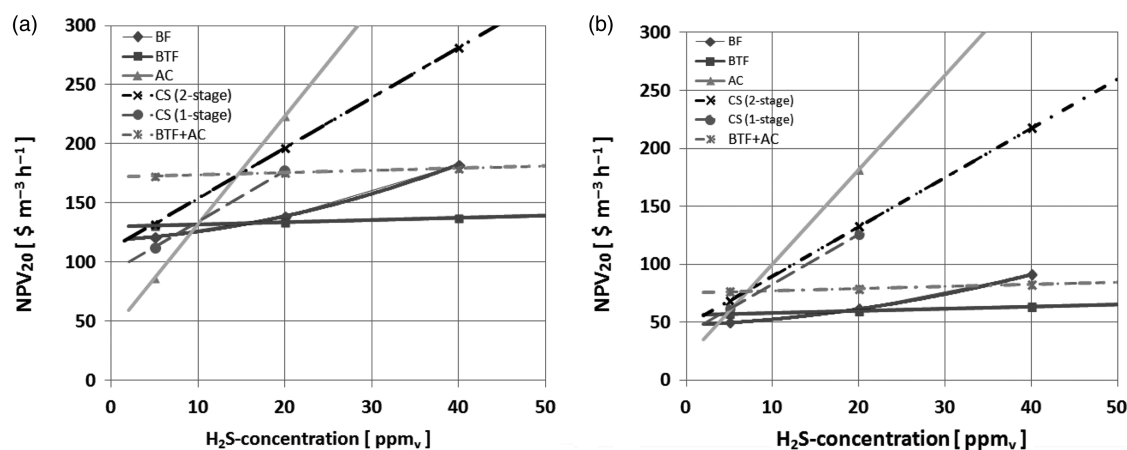


Figure 2 | The NPV over 20 years (NPV₂₀) evaluated for a $7,500 \text{ m}^3 \text{ h}^{-1}$ odorous emission (a) and evaluated for a $75,000 \text{ m}^3 \text{ h}^{-1}$ odorous emission (b) at different H_2S -concentrations. CS is chemical scrubber, AC is activated carbon, BF is biofiltration, BTF is biotrickling filtration, BTF + AC is biotrickling filtration with activated carbon polishing.

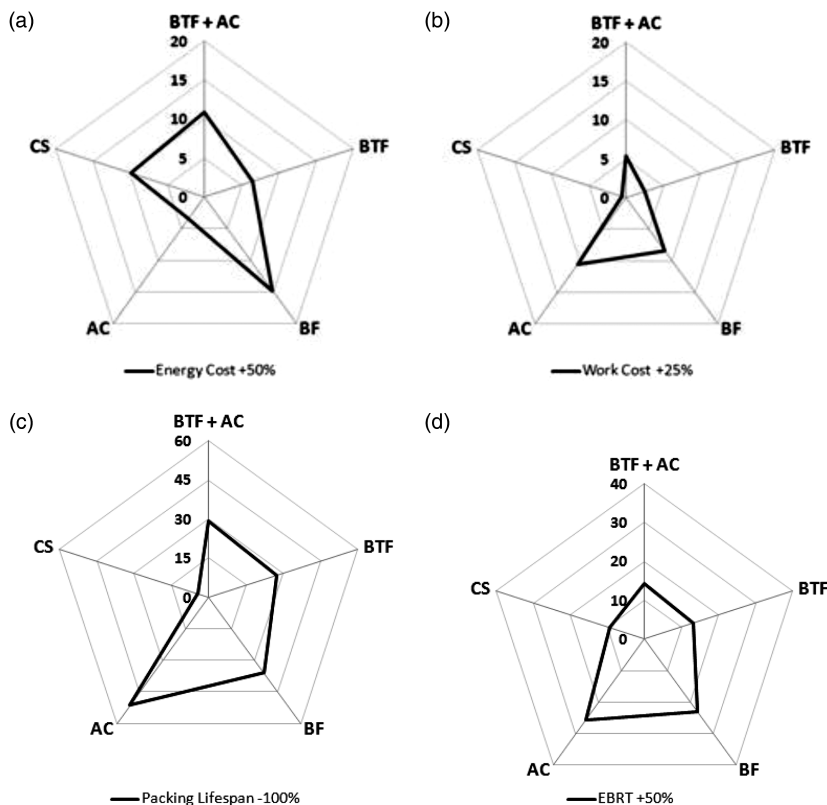


Figure 3 | The influence of the utility prices and design parameters on the NPV₂₀ of five odour abatement technologies evaluated for 75,000 m³ h⁻¹. The results are shown as percent increase of the NPV₂₀ when the energy cost is increased by 50% (a), the labour costs increased by 25% (b), the lifespan of the media is decreased by a factor of 2 (c) and the reactor size is increased by 50% (d) (Estrada *et al.* 2012). CS is chemical scrubber, AC is activated carbon, BF is biofiltration, BTf is biotrickling filtration, BTf + AC is biotrickling filtration with activated carbon polishing.

part of all operating costs, while biofiltration is most affected followed by chemical scrubbing and the hybrid technology. Figure 3(b) illustrates that when the labour cost is increased by 25%, activated carbon and biofiltration are most affected due to their relatively low media lifespan and large volumes of packing material that require disposal, transport and handling. Nevertheless, the cost of labour for operations is between 5 and 20% for all odour treatment units and therefore not a key parameter (Estrada *et al.* 2012). Figure 3(c) shows that if lifespan of the media is reduced, the activated carbon is most affected, as well as biofiltration, as a significant amount of the operating costs are related to the renewal of the packing material. The NPV of biotrickling filtration is also significantly affected due to the high price of packing material. The relatively expensive packing material for biotrickling filtration is often provided with a guarantee of a minimum 10-year lifespan durability. When an extra design safety factor is applied for the reactor size, the hybrid technology as well as chemical scrubbing are hardly affected (Figure 3(d)). Chemical scrubbing is hardly affected due to the relatively small packing volume and

the fact that most costs come from chemical usage. Biofiltration is significantly affected as packing material is a significant operating cost. The reactor size (gas contact time) and the cost of the packing material often constitute the key parameters determining the initial investment cost in biofiltration. When the land available is limited (Figure 4) or the price of land is relatively high, biofiltration can come with an additional cost.

The operational related GHG emissions of the different odour control technologies treating 50,000 m³ h⁻¹ at

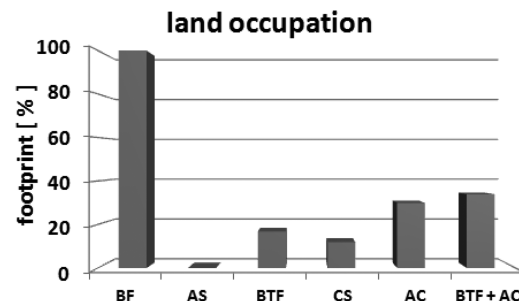


Figure 4 | The footprint of odour control technology relative to each other.

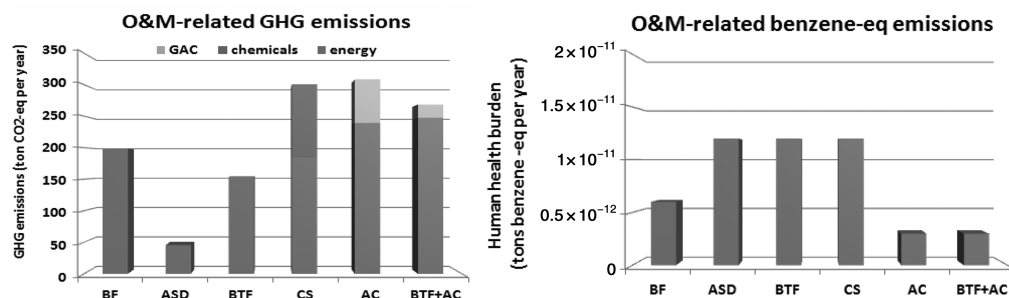


Figure 5 | The atmospheric impact burdens according to IChemE sustainability metrics: (a) the operational (O&M) related GHG emissions (in tons per year of CO₂ equivalents) and (b) the human health burden (in tons of benzene equivalents per year) for treating 50,000 m³ h⁻¹ containing 15 ppm_v of H₂S. GAC is granular activated carbon.

15 ppm_v H₂S are illustrated in Figure 5(a) and are mainly determined by the energy consumed for fans, pumps and instrumentation. At 15 ppm_v, chemical scrubbing leads to the highest GHG emissions, while biotrickling filtration and especially activated sludge diffusion results in significantly lower GHG emissions. The GHG emissions of the activated sludge diffusion are considered nearly zero as aeration for the activated sludge bioreactor will already be present. It should be noted that the application of activated sludge diffusion is restricted especially by the aeration capacity of the activated sludge bioreactor, which usually means that activated sludge diffusion can only be applied for relatively small odorous airflows.

The residual emissions of all the different compounds in the treated odorous air stream are calculated and evaluated for the different technologies elsewhere (Estrada *et al.* 2011). activated carbon and the hybrid technology will provide the lowest human health effect (a measure for the carcinogenic effect) and expressed in benzene equivalents (IChemE 2002), as illustrated in Figure 5(b). Besides legislation to eliminate odour nuisance from wastewater treatment plants, additional regulations for specific compounds like benzene can be present. In California, for example, some locations require additional treatment to obtain high removal of specific VOCs like benzene.

Table 2 illustrates the robustness of the different technologies for typical operation at a wastewater treatment or wastewater recycling plant, and includes process fluctuation and operational upsets. The robustness of a technology can be quantified by determining the risk of negative effects on the performance of the technology for each possible disorder (process fluctuation or operational upset), multiplied by its frequency of occurrence, and adding all possible disorders. Here both the probability of occurrence and the effect of a disorder are semi-quantified on a scale of 1 to 5 based on multiple operator field experiences and other studies (Estrada *et al.* 2012). The robustness evaluation conducted showed

that activated carbon filtration and the hybrid technology are the most robust technologies, while biotechnologies exhibited robustness comparable to that of chemical scrubbers. The robustness of biofiltration, biotrickling filtration and chemical scrubbing is about half of the robustness of activated carbon and the hybrid technology. Activated carbon filtration together with the hybrid technology is the most robust technology. For activated carbon filtration this assessment of robustness is correct only for the restricted situations where the inlet H₂S concentrations are relatively low (probably less than 10–15 ppm_v). For higher H₂S concentrations the breakthrough of the activated carbon will be much faster, leading to possibly unexpected odour emissions that might require a major action of replacement of the activated carbon to restore performance.

When, in an economical and risk evaluation, the robustness is counted as relevant as the overall costs (NPV₂₀), the hybrid technology would move up next to biotrickling filtration and activated sludge diffusion as the most preferred technologies.

CONCLUSIONS

From a process economics viewpoint, odour treatment technologies with the highest investments presented the lowest operating costs, which means that the NPV (NPV₂₀) should be used as a selection criterion rather than investment costs.

Economies of scale are more important in biotechniques (biofiltration and biotrickling filtration), as at increased airflows their overall cost (NPV₂₀) reduction is more extreme when compared to the physical/chemical technologies (chemical scrubbing and activated carbon filtration).

The physical/chemical technologies (chemical scrubbing and activated carbon filtration) were highly impacted in economic terms by the concentration of H₂S, which

Table 2 | A semi-quantitative robustness evaluation for the different odour abatement technologies evaluated according to the methodology proposed.

Technology	Disorder / upset	Possible cause	Chemical Scrubbing			Biofiltration			Biotrickling Filtration			Activated Sludge Diffusion			Activated Carbon			Biotrickling + Act. Carbon Polishing			Recommended control (protection / detection)
			p	E	p · E	p	E	p · E	p	E	p · E	p	E	p · E	p	E	p · E	p	E	p · E	
Water supply disorder		Failure of supply or recirculation pumps; control failures (e.g. valves); changing conditions inlet air (temp., rel humidity)	3	-4	-12	4	-3	-12	3	-3	-9	2	-1	-2	1	-1	-1	3	-1	-3	Duty-standby pumps / back-up water supply / spare parts / flow and level transmitter alarms
Electricity supply		Power outage	2	-3	-6	2	-2	-4	2	-3	-6	2	-2	-4	2	-1	-2	2	-1	-2	Back-up / alarms
Chemical dosing disorder		Pump or control failures; empty chemical storage tank	2	-4	-8	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	Duty-standby pumps / spare parts / flow and level transmitter alarms
Foul air supply interruption		Fan failure; blockage extraction ductwork; production stops	2	-1	-2	2	-2	-4	2	-2	-4	2	-2	-4	2	-1	-2	2	-1	-2	Duty-standby fans / flow and pressure transmitter alarms
Fluctuation of inlet concentrations		Changing or discontinuous production; diurnal or seasonal changes; production stops	4	-2	-8	4	-2	-8	4	-2	-8	4	-2	-8	4	-1	-4	4	-1	-4	Combine foul air from sources / continuous pollutant detection transmitter alarms
Higher inlet concentrations		Changing conditions or production; inaccurate design	1	-1	-1	1	-2	-2	1	-1	-1	1	-3	-3	1	-4	-4	1	-1	-1	Redundancy in design or layout
Fluctuation of inlet temperature		Changing or discontinuous production; diurnal or seasonal changes; production stops	3	-1	-3	3	-2	-6	3	-1	-3	3	-1	-3	3	-1	-3	3	-1	-3	Combine foul air from sources / temperature transmitter alarms
Robustness of performance (K)			-40			-37			-32			-25			-17			-16			

Probability (p): 1. Very unlikely or not possible. 2. Low. 3. Occasional. 4. Probable. 5. Frequent (it is certain that it will happen).

Effect (E): 1. Minor. 2. Marginal. 3. Moderate. 4. Critical. 5. Catastrophic.

constitutes an important drawback for these technologies. Also the GHG emissions are relatively high and directly impacted by the odour load.

Due to their low NPV (NPV₂₀) and their low environmental impact, activated sludge diffusion and biotrickling filtration are in general the most cost-effective, and probably the technologies to be considered first for odour treatment in a wastewater treatment plant. However, the odorous air flow volume treated with activated sludge diffusion is usually restricted by the aeration tank capacity.

When, in an economical and risk evaluation, the reliability is counted to be as relevant as the overall costs (NPV₂₀), hybrid technology (biotrickling filtration with activated carbon polishing) would be comparable to biotrickling filtration and activated sludge diffusion as the most preferred technologies, when all technologies are designed to have a 99% reduction of H₂S and a 95% reduction of the odour concentration.

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