



Review of Sewer Odour Assessment Techniques

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Executive Summary

Abatement of odours from sewerage networks is of high importance due to potential impacts on surrounding communities. While the wastewater industry and researchers have focused much effort on addressing sewer odour issues, key knowledge gaps remain with regards to the specific odorants present in sewer emissions as well as in the design and operation of odour abatement processes. Key members of the Australian wastewater industry have committed to enhancing the understanding of sewer odour related issues and improve the design, operation and monitoring of odour abatement processes under the Australian Research Council Sewer Corrosion and Odour Research (SCORe) linkage project.

Towards this end, one of the objectives of the experimental and field components of the *Odour measurement and assessment, evaluation of odour treatment technologies subproject* (SP3) is to benchmark and standardise analytical/monitoring techniques to provide information to support the improvement of the design, operation and monitoring of odour abatement processes. To support this objective, a review of existing sewer odour monitoring techniques was conducted to establish the current status of these techniques and identify knowledge gaps to provide additional focus for SP3.

Existing and emerging odour/odorant assessment techniques were reviewed to assess their current status and identify knowledge gaps. With the range of strengths and limitations, along with the variability in chemical character of odorous emissions, no single analytical technique can be applied universally for the measurement of odours from sewers and abatement processes. The sensory and analytical techniques currently used to characterise odours must instead be regarded as complementary rather than mutually exclusive.

A summary of key knowledge gaps identified during the review is provided as **Table i**. Regardless of the monitoring techniques employed, the sampling component of the analysis chain remains a source of weakness due to the continued existence of significant knowledge gaps. The need exists for standardisation of sampling methodologies, enhancement of sampling

campaign design, and greater knowledge of the fate and transformation of odorants in sample containers as well as odorant transformation during analysis.

Table i Summary of odour/odorant assessment technique knowledge gaps.

Technique	Knowledge Gaps
Specific Gas Sensors	<ul style="list-style-type: none"> • Sensor cross sensitivity and interferences • Impact of moisture poorly understood • Dependence on manufacturer data, no independent reviews of instruments (calibration requirements, operating costs, maintenance, reliability)
Field Olfactometers	<ul style="list-style-type: none"> • Activated carbon filter effectiveness
Online Sensors (Specific Gas)	<ul style="list-style-type: none"> • Sensor cross sensitivity and interferences • Impact of moisture poorly understood • Dependence on manufacturer data, no independent reviews of instruments (calibration requirements, operating costs, maintenance, reliability)
Non-specific gas sensor arrays	<ul style="list-style-type: none"> • Standardisation of data analysis • Techniques to compensate for environment parameters, sensor ageing, sensor drift, and wastewater matrix changes
Qualitative Sensorial Odour Analysis (OPM)	<ul style="list-style-type: none"> • Database of observations and linkage of key odorants/descriptors to common sources for the wastewater industry
Quantitative Sensorial Odour Analysis (Dynamic Olfactometry)	<ul style="list-style-type: none"> • Limited information on odorant transformation/loss during sample collection and storage • Guidelines for sample collection and storage
Gas Chromatography	<ul style="list-style-type: none"> • Degradation and transformation of odorants during analysis • Sorbent performance (range of odorants captured and capture efficiency) • Limited information on odorant transformation/loss during sample collection and storage • Guidelines for sample collection and storage
Combined Gas Chromatography and Olfactory Analysis	<ul style="list-style-type: none"> • Degradation and transformation of odorants during analysis • Sorbent performance (range of odorants captured and capture efficiency) • Limited information on odorant transformation/loss during sample collection and storage • Guidelines for sample collection and storage • Standardised analysis methodology

Overall, there has been substantial development in recent years with regards to analytical techniques for odour analysis. It is anticipated that these techniques will be further enhanced as the result of continued technological development, and their adoption to allow the identification

of key odorants will play a significant role in future improvements in the selection, design and management of odour abatement processes. To promote adoption, these information rich monitoring techniques need to be provided in a cost effective manner, and their value must be demonstrated through practical application.

SP3 will focus on addressing several of the knowledge gaps associated with quantitative sensorial odour analysis (dynamic olfactometry) and GC-based analysis (including combined GC and olfactory analysis). Experimental work conducted in SP3 will lead to several deliverables that will contribute to addressing these knowledge gaps, in particular:

- characterisation of odour/odorant transformation/loss during sample collection and storage;
- evaluation of the degradation and transformation of odorants during analysis;
- assessment of sorbent performance (range of odorants captured and capture efficiency);
- development of a standardised analysis methodology for GC based analysis; and
- preparation of guidelines for sample collection and storage for both dynamic olfactometry and GC-based analysis.

Addressing the knowledge gaps related to specific sensors and online sensors (sensor cross sensitivity and interferences, the impact of moisture, and lack of independent instrument reviews) is beyond the existing scope of SP3. Given that these parameters can have a strong impact on the accuracy/quality of monitoring data and that these instruments are widely used in the wastewater industry for H₂S monitoring, the industry would benefit from these knowledge gaps being addressed.

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1.0 Introduction

Abatement of odours from sewerage networks is of high importance due to potential impacts on surrounding communities. While the wastewater industry and researchers have focused much effort on addressing sewer odour issues, key knowledge gaps remain with regards to the specific odorants present in sewer emissions as well as in the design and operation of odour abatement processes. Key members of the Australian wastewater industry have committed to enhancing the understanding of sewer odour related issues and improve the design, operation and monitoring of odour abatement processes under the Australian Research Council Sewer Corrosion and Odour Research (SCORe) linkage project.

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Sewer odour emissions are complex mixtures of volatile chemicals discharged to sewers and volatile by-products derived from biochemical reactions occurring under anaerobic conditions (Vincent 2001; Zarra et al. 2008). These emissions (**Table 1**) are mainly composed of volatile organic and inorganic sulfur compounds such as hydrogen sulfide (H_2S), methyl mercaptan (CH_3SH), dimethyl sulfide ($CH_3)_2S$ and dimethyl disulfide ($CH_3)_2S_2$, organic and inorganic nitrogen derivates such as ammonia (NH_3), amines, indole and volatile organic compounds such as aromatic, aliphatic and chlorinated hydrocarbons, fatty acids, aldehydes, terpenes and ketones (Van Langenhove et al. 1985; Zarra et al. 2008). Similar compounds are also formed during the anaerobic decomposition of urban and agricultural solid waste and residual activated sludge (Bruno et al. 2007; Srivastava et al. 2004).

Table 1 Odour descriptor and threshold concentration of the main odorants present in emissions from wastewater treatment plants (Suffet et al. 2004 and Rosenfeld et al. 2007).

Odorant	Odour Descriptor	Odour Threshold (ppmv)
<i>Sulfur Compounds</i>		
H ₂ S	Rotten eggs	0.0005
Ethyl mercaptan	Rotten Babbage	0.00001
Carbon disulfide	Disagreeable, sweet	0.007
Dimethyl sulfide	Decayed cabbage	0.001
Dimethyl disulfide	Rotten cabbage	0.000026
<i>Nitrogen Compounds</i>		
Ammonia	Pungent	0.038
Trimethylamine	Fishy, pungent	0.0004
Indole	Faecal, nauseating	0.0001
Skatole	Faecal, nauseating	0.001
<i>Volatile Fatty Acids</i>		
Acetic acid	Vinegar	1.1
Butyric acid	Sour, perspiration	0.0003
Isovaleric acid	Unpleasant	0.0006
Propionic acid	Rancid, pungent	0.028
<i>Ketones</i>		
Butanone	Sweet, minty	0.25
Acetone	Fruity, pungent	20
Methyl ethyl ketone	Sweet, minty	0.25
<i>Aldehydes</i>		
Acetaldehyde	Green Sweet	0.0001
Propionaldehyde	Sweet, ester	0.011
Valeraldehyde	Pungent	0.028
<i>Hydrocarbons</i>		
Toluene	Rubbery, mothballs	2.1
Benzene	Sweet, solventy	1.4
Phenol	Medicinal, sweet	46
Styrene	Solventy, rubbery	0.047

Most volatile compounds are malodours and exhibit very low odour thresholds (**Table 1**). Thus, despite being present at trace level concentrations, they can still induce a serious annoyance to

nearby receptors (Sucker et al. 2008). With over 70% of air pollution complaints in the United States being odour related (Pandey and Kim 2009), the public is obviously sensitive to these issues and expects them to be addressed in a timely manner.

Detailed characterisation of odorous emissions (in terms of composition and concentration) is the fundamental basis for environmental engineers and researchers to understand the mechanisms of odour formation and degradation, and to optimise the design and management of odour abatement processes (Cheng et al. 2007; Turkmen et al. 2004). Furthermore, an accurate characterisation of odorous emissions is the cornerstone for policy makers and environmental regulatory agencies to objectively legislate and monitor these emissions (Frechen 2001).

Unlike other wastewater parameters such as dissolved organic carbon (DOC) or inorganic nitrogen species, odours have both a sensorial and a chemical component, and as a result the characterisation of odorous emission is a challenging task. The sensorial component, involving both physiological reception by the olfactory system and psychological interpretation (Gostelow et al. 2001), can be highly subjective in nature, complicating analysis (Bliss et al. 1996). In addition, the combination of the large number of chemical compounds present in odorous emissions with their relatively low concentrations (typically in the ppbv and pptv levels) severely challenges the detection limits and separation capacities of the most advanced instrumental techniques (Dewulf and Van Langenhove 1999; Dewulf and Van Langenhove 2002).

Despite significant advances in the recent years in the standardisation of dynamic olfactometry and gas chromatographic analyses of volatile compounds, odour measurement is still regarded as more of an art rather a scientific discipline (Gostelow et al. 2001). This is likely due to the lack of standardised protocols for sampling, analysis and monitoring (Sharma et al. 2008), along with the fact that odour assessment is often approached in an independent and disconnected manner by a wide range of research groups and commercial laboratories. While reviews of odour assessment techniques have been previously published (Delahunty et al. 2006; Dewulf

and Van Langenhove 2002; Gostelow et al. 2003; Gostelow et al. 2001), there has been limited comparison of the different approaches to odour assessment.

This review assesses the current status of existing approaches for the sensorial and chemical characterisation of odorant emissions from sewers. While the focus will be on odorant analysis for sewers, many similarities and parallels to odorant analysis conducted at wastewater treatment plants (WWTPs) exist, and knowledge from this area will also be leveraged to support the review. The following categories of monitoring techniques will be assessed:

- portable instruments (**Section 2.0**);
- online monitoring instrumentation (**Section 3.0**);
- laboratory based assessment of gaseous samples (**Section 4.0**); and
- laboratory based assessment of liquid phase samples (**Section 5.0**).

Particular emphasis will be placed on the applicability and limitations associated with the reviewed monitoring techniques. Conclusions and a brief summary of existing knowledge gaps will be presented in **Section 6.0**.

2.0 Portable Instruments

Monitoring odours/odorants in the field using portable instrumentation offers many advantages, namely; eliminating the need for sample storage and shipping (and the potential odorant transformation/loss), reduced cost per sample analysis, providing immediate results that can be used to identify odour sources or optimise abatement processes, and reducing instrumentation burden for small sites requiring only infrequent monitoring by allowing multiple sites to be monitored using a single instrument. Towards this end portable instruments have been developed and are commercially available for a wide range of parameters. A subset of these instruments (limited based on potential applicability to sewer odour and odour abatement process monitoring) have been reviewed. Generally the applicable instruments utilise one of two approaches:

- odorant monitoring using specific sensors (**Section 2.1**); and
- odour concentration (total odour) monitoring using field olfactometry (**Section 2.2**).

The benefits associated with portable instrumentation must, however, be balanced against instrument maintenance requirements, reliability and accuracy. This review will focus on key instrument properties using available literature (both peer reviewed and grey literature from manufacturers).

2.1 Specific Gas Sensors

Specific sensors are designed to respond to compounds of interest while minimising the response to all other compounds. Because of this specificity, it is necessary to ensure that the parameter being measured is indeed relevant to the application (i.e. a dominant odorant). Specific gas sensors encompass a range of sensing techniques including chemical, electrochemical, catalytic, and optical sensors.

This review will focus on specific sensors for three parameters identified as being of interest for sewer odour monitoring; hydrogen sulfide (H_2S , **Section 2.1.1**), ammonia (NH_3), and volatile organic compounds (VOCs, **Section 2.1.2**). Ammonia sensors are most commonly found as part of multisensor instruments in conjunction with other parameters of interest, which will be discussed in **Section 2.1.3**. Despite the high level of application of these sensors in industry, knowledge gaps exist with regards to their application, and these gaps will be discussed in **Section 2.1.4**. It should be noted that the majority of the available technical information for specific sensors is from manufacturers/suppliers, which may be subject to optimistic interpretations.

2.1.1 Portable H_2S Monitors

A review of commercially available portable H_2S monitors was conducted based upon manufacturer information. Primary instruments of interest are depicted in **Figure 1**, and key characteristics (based on supplier literature) are summarised in **Table 2**. Where possible, quotations were obtained for instruments (exclusive of GST). It should be noted that these prices are subject to change and highly dependent on the current US dollar exchange rate), and should only be used to assess relative costs of various instruments versus their other characteristics.

Table 2 Comparison of portable H₂S monitoring instruments.

Manufacturer	Model	Sensor Type	Range (ppm)	Resolution (ppm)	Response Time (90%)	Accuracy	Operating Conditions	Calibration Interval	Battery Life (months)	Supplier	Price ¹ (AUD)
Arizona Instrument LLC	Jerome 631-X	Gold Film	0.001 - 0.099 0.1 - 0.99 1 - 9.9 10 - 50	0.003	30 s 25 s 16 s 13 s	± 0.003 ppm ± 0.03 ppm ± 0.3 ppm ± 2 ppm	0°C - 40°C Non-condensing	Monthly + Annual Factory Calibration	12	Active Environmental Solutions	\$17695
App-Tek International Pty Ltd.	OdaLog Type L2 - Standard (H ₂ S)	EC	0 - 200 0 - 1000	0.1 1	-	± 2 ppm	-20°C - 50°C 15 - 90% RH	6 Monthly Factory Calibration	> 8	App-Tek International Pty Ltd.	-
	OdaLog Type L2 - Long Term (H ₂ S)	EC	0 - 50 0 - 200 0 - 1000 0 - 2000	0.1 1 1	-	± 2 ppm	-20°C - 50°C 15 - 90% RH	6 Monthly Factory Calibration	> 8	App-Tek International Pty Ltd.	-
	OdaLog Low Range H ₂ S Logger	EC	0 - 2	-	-	± 0.2 ppm	0°C - 40°C 15 - 90% RH	-	2	App-Tek International Pty Ltd.	-
	OdaLog Logger	EC	0 - 200	0.1	< 60 s	± 1 ppm	-10°C - 40°C 15 - 90% RH	6 Monthly Factory Calibration	6	App-Tek International Pty Ltd.	\$2500

¹prices subject to change and dependent on USD exchange rate

EC Electrochemical sensor

- no data

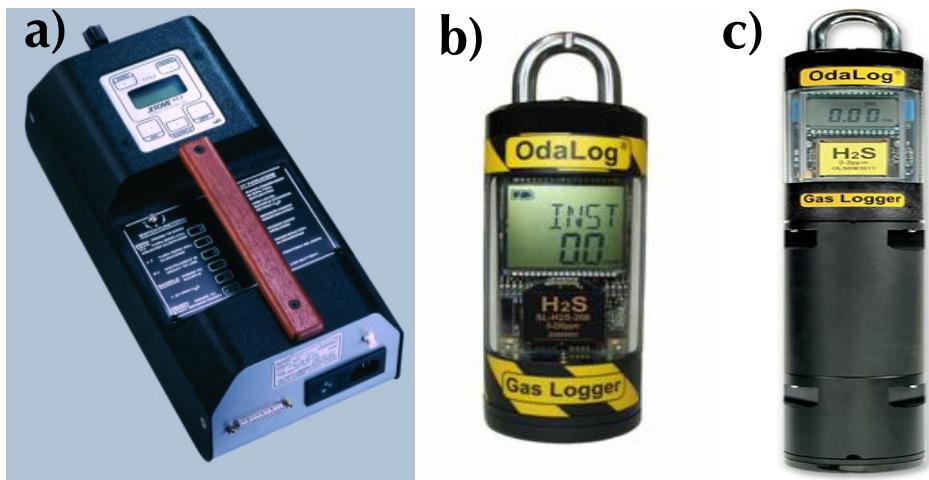


Figure 1 Commercially available portable H₂S monitors.

a) Jerome 631-X (Arizona Instrument LLC), b) OdaLog Logger (App-Tek International Pty Ltd.), c) OdaLog Low Range H₂S Logger (App-Tek International Pty Ltd.) All images courtesy of respective corporate websites.

Two primarily types of sensors (electrochemical and gold film) were utilised in the reviewed instruments. The gold film sensor is extremely sensitive to H₂S (in the ppb range), with a high level of accuracy, although this comes at a significantly higher cost per instrument (\$17965 AUD compared to \$2500 AUD for an OdaLogger).

The manufacturer literature for these instruments provided minimal information with regards to instrument cross sensitivities to other sulfur compounds; only SO₂ was assessed for the Jerome 631-X, and no information was provided for the OdaLogger. A review of grey literature obtained a report on an evaluation of the Jerome 631-X by Winegar and Schmidt (1998), who concluded that the instrument had acceptable accuracy and precision in the range of 2 ppb to 50 ppm, but noted that the gold film sensor is affected by sulfides other than H₂S, although at lower response factors (**Table 3**). The authors also concluded that provided the other sulfide compounds are in low abundance, the instrument is quantitative for H₂S, however, they did propose that the results instead be reported as total sulfides (Winegar and Schmidt 1998). No other studies of commercially available portable H₂S sensors were identified in the reviewed literature.

Table 3 Jerome 631-X response factors for reduced sulfur compounds.
 (Winegar and Schmidt, 1998)

Class	Compound	Response Factor (%)
Sulfides	<i>Hydrogen sulfide</i>	100
	Carbonyl sulfide	36
Mercaptans	Methyl mercaptan	45
	n-Propyl mercaptan	40
	n-Butyl mercaptan	33
Disulfides	t-Butyl mercaptan	35
	Carbonyl disulfide	0.01
	Dimethyl disulfide	40
Alkyl Sulfides	Diethyl disulfide	17
	Dimethyl Sulfide	7
	Diethyl Sulfide	25
Cyclic	Thiophene	0.8
	Tetrahydrothiophene	10

Winegar and Schmidt (1998) also assessed moisture impacts on the Jerome 631-X, and noted that while the instrument did not respond to water vapour at ambient levels, the presence of moderate to high water vapour concentrations reduced the instrument response. However, samples used in the study were collected in bags prior to analysis, and as noted by the authors this loss could be due to dissolution of H₂S into microlayers of condensed water on the bag walls (Winegar and Schmidt 1998). Thus the results do not necessarily reflect the impact of moisture on the instrument when used to measure directly from the sources. It should be noted that the reviewed instruments were designed to operate in humid conditions, and not in gas environments containing free moisture.

A range of portable instruments are available for H₂S monitoring, but the need exists for further assessment of these instruments, particularly with regards to potential interferences, calibration requirements, operating costs, maintenance requirements/costs, and instrument reliability. In particular, further assessment of the OdaLog series of instruments is warranted to determine the impact of interferences as they appear to be a cost effective monitoring solution for applications where H₂S is a dominant odorant.

2.1.2 Portable VOC Monitors

Commercially available portable VOC monitoring instruments are based on photoionization detectors (PIDs). PIDs use photons (UV light) to fragment VOCs into electrically charged fragments (ions), which generate a current that is proportional to the VOC concentration (RAE Systems Inc. 2005). A range of PID based VOC detectors are available, with RAE Systems being the dominant PID instrument manufacturer. Like H₂S sensors, available online VOC sensors were reviewed based upon manufacturer literature. These instruments are depicted in **Figure 8**, and key instrument characteristics are summarised in **Table 4**.



Figure 2 Commercially available portable VOC monitors.

a) MiniRAE 3000 (RAE Systems), b) MiniRAE 2000 (RAE Systems), c) MiniRAE Lite (RAE Systems), d) ppbRAE 3000 (RAE Systems), e) ppbRAE Plus (RAE Systems), f) ProCheck (Ion Science Ltd.). All images courtesy of respective corporate websites.

Table 4 Comparison of portable VOC monitoring instruments.

Manufacturer	Model	Sensor Type	Range (ppm)	Resolution (ppm)	Response Time (90%)	Accuracy	Operating Conditions	Calibration Interval	Battery Life (hours)	Supplier	Price ¹ (AUD)							
RAE Systems	MiniRAE 3000	PID	0.1 - 2000	0.1	2 s	± 3%	-20°C - 50°C 0 - 95% RH	-	16	Active Environmental Solutions	\$6824							
			0.1 - 5000	0.1	2 s													
			0.1 - 15000	0.1	2 s													
	MiniRAE 2000	PID	<i>0 - 10000²</i>		2 s	± 10% ± 20% ± 20%	-10°C - 40°C 0 - 95% RH	-	10	Active Environmental Solutions	-							
			0 - 99.9	0.1														
			100 - 1999	1														
	ppbRAE 3000	PID	2000 - 10000	1	2 s													
			<i>0 - 199²</i>			± 5% ± 3% ± 10%	-20°C - 50°C 0 - 95% RH	-	12	Active Environmental Solutions	-							
			0.01 - 2000	0.01														
Ion Science Ltd.	ppbRAE Plus	PID	0.01 - 5000	0.01	2 s		-20°C - 50°C 0 - 95% RH	-	12	Active Environmental Solutions	\$10461							
			0.001 - 10000	0.001														
			<i>0 - 199²</i>				-10°C - 40°C 0 - 95% RH	-	10									
			0 - 9.999	0.001	< 5 s	± 10%												
			10 - 99.9	0.1	< 5 s													
	ProCheck 1000	PID	100 - 199	1	< 5 s	-20°C - 60°C 0 - 99% RH	-	14	Gastech Australia	-								
	ProCheck 3000Ex	PID	0.1 - 4000	-	1 s													
	ProCheck 3000Ex	PID	0.1 - 10000	-	1 s	± 5%	-20°C - 60°C 0 - 99% RH	-	14	Gastech Australia	-							

¹prices subject to change and dependent on USD exchange rate

²overall instrument range, measurement properties variable based on measurement magnitude

PID Photoionization Detector

- no data

The portable VOC monitoring instruments reviewed in **Table 4** offer a wide analysis range and relatively high accuracy, with more recent instruments having reported accuracies on the order of 3 - 5%. It should be noted that the range of VOCs analysed by a PID is limited based on the instrument's lamp energy output (available ionization energy) and the type of lamp should be considered during selection (**Figure 3**). All of the reviewed instruments were designed for non-condensing environments and should not be used in applications where free moisture is present in the gas phase. No published assessments of the impact of moisture on instrument operation were found during the literature review.

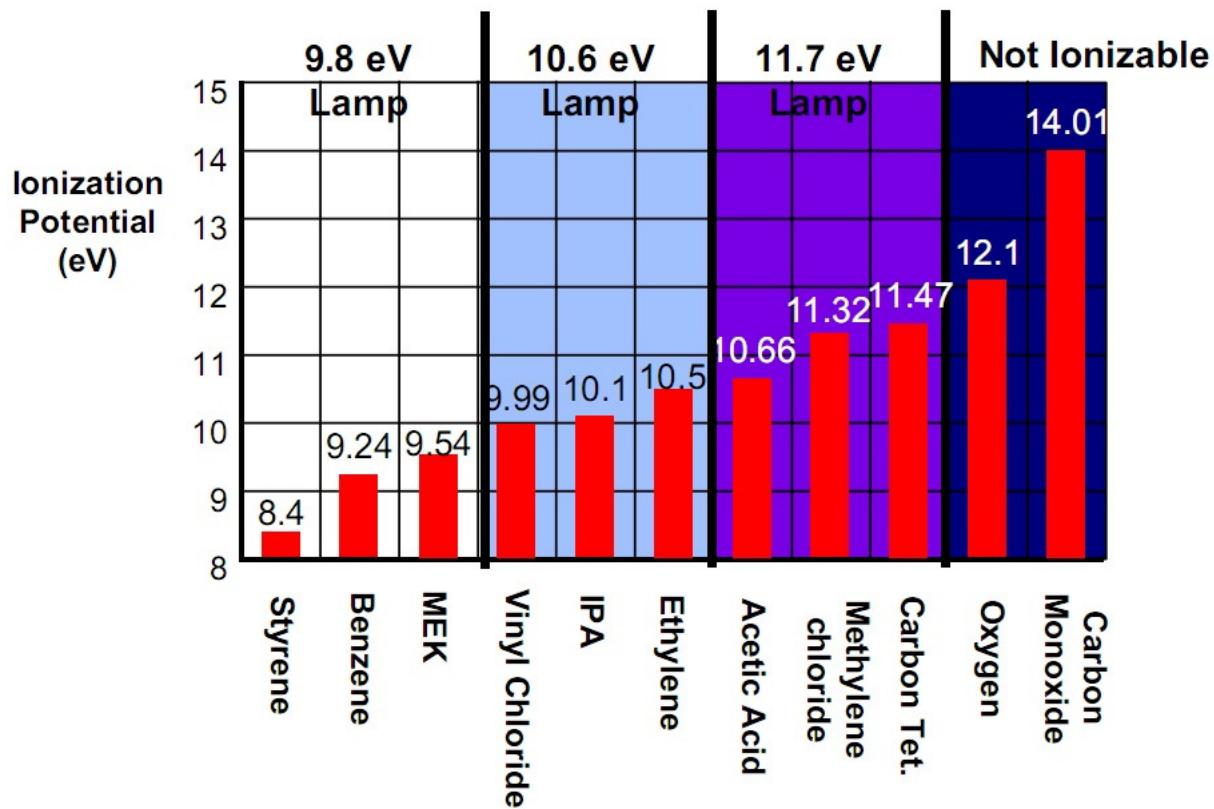


Figure 3 VOC Ionisation potential relative to lamp intensity.

Reproduced from Rae Systems Inc. (2005)

As with H₂S sensors, minimal guidance was provided in manufacturer literature with regards to instrument calibration and maintenance frequency. No independent reviews of these instruments, or assessments of lifespan, calibration and maintenance requirements were found in the reviewed literature.

2.1.3 Multigas Monitors

Multigas monitors combine multiple gas sensors to provide a single, versatile gas monitoring platform. Commercially available multigas monitors were reviewed based upon manufacturer literature and are depicted in **Figure 4**, with key instrument characteristics summarised in **Table 5**. These monitors share many of the same limitations discussed for H₂S monitors (electrochemical sensors) and for PID based VOC instruments. Based on manufacturer literature, typical sensor lifespans were on the order of 2 years for electrochemical sensors, and 3 years for PID lamps. Once again, none of the reviewed instruments were designed for use in environments with free moisture and no independent reviews of these instruments were found in the reviewed literature.



Figure 4 Commercially available portable multigas monitors.

a) OdaLog 6000 (App-Tek International Pty Ltd.), b) OdaLog 7000 (App-Tek International Pty Ltd.), c) MultiRAE Plus (RAE Systems), d) MultiRAE IR (RAE Systems), e) DirectSense® TVOC (GrayWolf Sensing Solutions), f) iBrid MX6 (Industrial Scientific), g) FirstCheck+ (Ion Science Ltd.). All images courtesy of respective corporate websites.

Table 5 Comparison of portable multigas monitoring instruments.

Manufacturer	Model	Parameter (Sensor Type)	Range (ppm)	Resolution (ppm)	Response Time (90%)	Accuracy	Operating Conditions	Battery Life (hours)	Supplier	Price ¹ (AUD)
App-Tek International Pty Ltd.	OdaLog 6000	O ₂ (EC)	0 - 25%	0.1%	-	-	-10°C - 40°C	> 16	App-Tek International Pty Ltd.	-
		H ₂ S (EC)	0 - 100	1	-	-				
		NH ₃ (EC)	0 - 100	1	-	-				
		CH ₄ (-)	0 - 5%	0.01%	-	-				
	OdaLog 7000	O ₂ (EC)	0 - 25%	0.1%	-	-	-20°C - 40°C	> 12	App-Tek International Pty Ltd.	\$3000
		H ₂ S (EC)	0 - 100	1	-	-	15 - 90% RH			
		NH ₃ (EC)	0 - 100	1	-	-				
		CH ₄ (-)	0 - 5%	0.01%	-	-				
RAE Systems	MultiRAE Plus	VOC (PID)	0 - 2000	0.1	10 s	-	-	-	Active Environmental Solutions	-
		O ₂ (EC)	0 - 30%	0.1%	15 s	-	-20°C - 45°C	-		-
		NH ₃ (EC)	0 - 50	1	150 s	-	0 - 95% RH	14		\$5590
		H ₂ S (EC)	0 - 100	1	35s	-				
	MultiRAE IR	VOC (PID)	0 - 2000	0.1	10 s	-	-	-	Active Environmental Solutions	-
		O ₂ (EC)	0 - 30%	0.1%	15 s	-	-20°C - 45°C	-		-
		CO ₂ (NDIR)	0 - 20000	10	60 s	-	0 - 95% RH	12		\$6056
		LEL	0 - 100%	1%	15 s	-				
		H ₂ S (EC) or NH ₃ (EC)	0 - 100	1	30 s	-				
		NH ₃ (EC)	0 - 50	1	150 s	-				
GrayWolf Sensing Solutions	DirectSense® TVOC (TG 503-L)	Temperature	-10°C - 70°C	0.1°C	-	± 0.3°C	-	-	TestEquip Pty Ltd	-
		RH	0 - 100%	-	-	± 2%	-	-		-
		CO ₂ (NDIR)	0 - 50000	-	< 60 s	± 3%	0°C - 90°C	-		-
		VOC (PID)	0.1 - 4000	-	-	-	0 - 90% RH	60		\$8547 (USD)
		NH ₃ (EC)	0 - 100	0.1	-	-				
		H ₂ S (EC)	0.00 - 50	0.01	-	-				
Industrial Scientific	iBrid MX6	VOC (PID)	0 - 2000	0.1	-	-	-	-	Air-Met Scientific Pty Ltd.	\$5074
		NH ₃ (EC)	0 - 100	1	-	-	-20°C - 55°C	-		For VOC, H ₂ S and NH ₃
		H ₂ S (EC)	0 - 500	0.1	-	-	15 - 95% RH	24		-
		CH ₄ (Cat)	0 - 5%	0.1%	-	-				
		VOC (PID)	0.1 - 4000	-	< 1 s	-				
Ion Science Ltd.	FirstCheck+ 1000/2000	O ₂ (EC)	0 - 28%	-	< 15 s	-	-20°C - 60°C	-	Gastech Australia	-
		CO (EC)	1 - 1000	-	< 15 s	± 5%	0 - 99% RH	11		-
		H ₂ S (EC)	0.1 - 100	-	< 20 s	-				
		LEL (Pellistor)	0 - 100%	-	< 15	-				

¹prices subject to change and dependent on USD exchange rate

²overall instrument range, measurement properties variable based on measurement magnitude

EC Electrochemical sensor
NDIR Non-dispersive Infrared

PID Photoionization Detector
Cat Catalytic

LEL Lower Explosive Level
no data

2.1.4 Limitations and Future Direction

Overall, a wide range of portable instruments are commercially available. However, despite significant uptake and use by the water industry, no independent, systematic studies comparing instruments/sensor types with regards to key operating parameters (including performance, maintenance, calibration requirements and interferences) have been reported. As a result, nearly all existing information with regards to the performance of these instruments originates from their manufacturers. Independent assessment of these instruments is needed to address this gap and support instrument selection.

While specific sensors aim to only respond to the analyte of interest, in practice sensors are rarely 100% specific to the analyte, and other compounds can evoke a sensor response. An understanding of instrument cross sensitivities is crucial to effective implementation of these sensors. While there has been some work addressing cross sensitivities for gold film H₂S sensors, no significant assessment of sensitivities for electrochemical sensors (the most commonly used type of H₂S sensor in the reviewed instruments) was found in manufacturer or published literature. The far majority of the reviewed instruments were designed for non-condensing environments and not for condensing environments such as those often found at the outlet of some biological odour abatement processes. In addition to this gap, no assessments of the impact of moisture on instrument operation in non-condensing environments were found during the literature review. These are significant knowledge gaps that need to be addressed in future work.

The use of H₂S for sewer odour abatement monitoring is relatively widespread in comparison to the use of other parameters. While H₂S is indeed a major sewer odorant and a useful monitoring parameter, it is not always the primary odorant (particularly in areas where industrial sources are discharged into sewer systems), and while the presence of H₂S is an indicator of an odour, its absence cannot be assumed to indicate the converse (Frechen 2008). Similarly, the application of NH₃ monitoring is only useful for sites where NH₃ has been identified as a key odorant.

The usefulness of VOC measurements for odour abatement process monitoring is limited. VOCs are a bulk measurement representing a wide range of compounds, of which many are non-odorous. Hence the presence of VOCs does not necessarily indicate emissions of an odorous nature. Furthermore, if non-VOC odourants such as H₂S or volatile sulfur compounds are present in the emissions, they will not be detected by the instrument. Thus the absence of VOCs does not necessarily indicate the absence of odorous emissions. VOCs do, however, include non-odorous compounds that can rapidly saturate activated carbon filters and compounds whose biodegradation interfere with the biodegradation of other odorants due to microbial competition (Cho et al. 1991; Deshusses et al. 1995; Guisasola et al. 2008; Smet et al. 1997), thus there may be some value in VOCs as a monitoring parameter, although further work is needed to assess its utility.

As a result of the inherent limitations in the available portable instrument monitoring parameters (H₂S, NH₃, VOC), care must be taken to assure that the monitored parameters are indeed appropriate for the source and monitoring objectives.

2.2 Field Olfactometry

While laboratory based dynamic olfactometry is well established and has seen significant standardisation and extensive application for monitoring high strength odour sources (**Section 4.1.2**), as noted by Gostelow et al. (2001), its accuracy in the range of typical ambient odour concentrations which can elicit odour complaints (5-10 ou/m³) is limited. As such, laboratory based dynamic olfactometry is not seen as being suitable for ambient odour monitoring (Henry 2009). In addition to accuracy limitations, the application of laboratory based dynamic olfactometry for ambient monitoring is further restricted by the long sampling times required (Nicell 2009), which can result in short term exceedences of odour standards being missed, and as such is not sufficient to establish compliance with these standards.

To address the need for ambient odour monitoring, portable field olfactometers with detection limits on the order of 2 – 500 ou/m³ have been developed (McGinley and McGinley 2004). In addition to possessing an appropriate level of sensitivity, these instruments are seen as offering the advantages of providing immediate results, eliminating the need for sample storage and transport (along with the associated potential for odorant degradation and transformation), and having a low cost per sample (McGinley and McGinley 2004; Sheffield et al. 2004).

Two dominant types of field olfactometers exist in practice, box scentometers (**Section 2.2.1**) and the Nasal Ranger® (**Section 2.2.2**), although these instruments operate on the same fundamental concepts. “Home-made” field olfactometers based on half-face respirators (mask scentometers) have also been proposed (Henry 2009; Sheffield and Ndegwa 2008). These instruments, however, have a more restrictive operating range on the order of 0.35 – 18 ou/m³ (Henry 2009) and require further validation along with standardisation of the manufacturing process and a commercial supplier before they will be suitable for more widespread application. Given these limitations, mask scentometers will not be discussed further in this report.

2.2.1 Box Scentometers

Box scentometers were first developed in the last 1950s under grants by the US Public Health Service and were manufactured by the Barneby Sutcliffe Corporation until 2004 when it was acquired by Calgon Carbon (Henry 2009; St. Croix Sensory Inc. 2005). These instruments are seen as being a simple, low cost (on the order of \$500 -\$700 USD for the instrument) method of ambient odour monitoring (Sheffield et al. 2004).

A box scentometer (**Figure 5**), consists of a rectangular box with two activated carbon beds through which dilution air is drawn to mix with odorous air from one of the six odour inlet air holes (representing dilution ratios of 2, 7, 15, 31, 170, and 350), after which the mixed air is delivered to the analyst through two glass nostril sniffing tubes (Bokowa 2008; McGinley and McGinley 2004; St. Croix Sensory Inc. 2005). Like dynamic olfactometry (discussed in **Section 4.1.2**), the measured odour concentration is based on the amount of dilution (odourless) air required to reduce the odorant concentration to its detection threshold.



Figure 5 Box scentometer, glass sniffing tubes on the left, odorous air inlet ports on the right.

Reproduced from Newby and McGinley (2004)

Over their long period of use, a number of shortcomings have been identified in box scentometers, and these shortcomings have become the source of much criticism. In particular, box scentometers have been criticised for their lack of control of inhalation rates, discomfort associated with the glass nostril sniffing tubes, and odour fatigue (which results in reduced analyst sensitivity) due to poor sniffing tube sealing (Bokowa 2008; Henry 2009; Sheffield et al. 2004; Sheffield and Ndegwa 2008). Questions have also been raised with regards to the accuracy of the dilution ratios achieved by the instrument due to observed discrepancies in flow vs. inlet hole diameter for a mask scentometer based on orifice diameters used for box scentometers (Henry 2009). These discrepancies, however, could be due to differences in flow resistance between the two instruments. Despite these limitations and criticisms, box scentometers continue to be specified for compliance ambient odour monitoring in a number of jurisdictions in the United States (Sheffield and Ndegwa 2008), although as noted by Bokowa (2008), there is a view by many odour monitoring experts that box scentometers should be replaced by more modern field olfactometers.

2.2.2 Nasal Ranger®

The Nasal Ranger® was developed by St. Croix Sensory, Inc., with the goal of bridging the accuracy gap between box scentometers and laboratory based olfactometers (Sheffield and Ndegwa 2008). Similar to the box scentometer, the Nasal Ranger® (**Figure 6**) allows dilution air to be drawn through activated carbon filters and mixed with odorous air to be delivered to the user for analysis. Like the box scentometer, the Nasal Ranger is used to measure odour concentration based on the dilution to threshold concept.



Figure 6 Nasal Ranger® field olfactometer.

Reproduced from St. Croix Sensory, Inc. (2008)

While similar in fundamental concept to the box scentometer, the Nasal Ranger® contains many upgrades to address instrument limitations and increase measurement accuracy. Significant changes from the box scentometer noted in the literature (McGinley and McGinley 2004; Sheffield and Ndegwa 2008; St. Croix Sensory Inc. 2005; St. Croix Sensory Inc. 2008) include:

- the addition of check valves on the inlet and outlet air paths to ensure appropriate flow direction;
- pressure transducers and indicator lights to guide users in achieving appropriate and consistent sniffing rates;
- a more ergonomic nasal mask to improve comfort;

- replacement of odorous air intake holes (requiring individual sealing with tape or fingers) with an orifice wheel selector having six settings (dilution ratios of 2,4,7, 15, 30, and 60);
- an optional replacement orifice wheel allowing expanded dilution ratios (60, 100, 200, 300, 400, and 500); and
- blank settings in between odour orifices that provide the user with filtered (odourless) air only, allowing continuous wearing of the instrument and reduction in the potential for olfactory fatigue by exposure to ambient odorants.

Some concerns have been raised in the literature with regards to background odour concentrations associated with the materials used to produce the instrument (Bokowa 2008; Newby and McGinley 2004). Newby and McGinley (2004) observed a “plastic-like” odour from the unit when unpacked that interfered with the measurement of odours at the lower end of the instrument range (at the 2:1 level), although this odour dissipated over time and the authors indicate that the manufacturer has made adjustments to address the issue. Bokowa (2008) also observed a background odour in the Nasal Ranger®, although upon investigation the odour was attributed to the foam used to attach the sniffing mask to the body of the instrument. Samples of the foam allowed to off-gas in Tedlar™ bags filled with nitrogen produced odours of 19 – 27 ou when analysed by dynamic olfactometry. This appears to be a different odour from that observed by Newby and McGinley (2004), and contradicts their assertions of any instrument background odours being addressed. It should, however, be noted that the measured concentration was an equilibrium value, and the actual concentration in the sniffing mask during use could be lower. Furthermore, dynamic olfactometry at such low odour concentrations is generally viewed as the having poor accuracy and this needs to be considered along with the results. The presence of background odours in olfactometers (laboratory or field) is a fundamental issue that can have significant impacts on data quality, thus this issue warrants further evaluation.

Bokowa (2008) assessed the efficacy of the instrument’s activated carbon beds, concluding that while the beds were capable of removing methylamine less than 1.5 ppm, they were not

capable of removing a number of other compounds (**Table 6**). The breakthrough of ambient odourants through the instrument's activated carbon filters would serve to reduce instrument sensitivity and promote olfactory fatigue, biasing the results downward. It should be noted that specific concentrations were tested and the work was not conducted to establish exact concentrations leading to filter breakthrough. These results serve to highlight the importance of the instrument's activated carbon filters and the need to verify their performance in testing environments.

Table 6 Nasal Ranger® activated carbon filtration limitations.

Source: Bokowa (2008)

Compound	Breakthrough Concentration
Formaldehyde	2 ppm
Trimethylamine	12 ppm
Dimethylamine	2.8 ppm
Butyric acid	0.1 ppm
Hydrogen sulfide	70 ppb

At approximately \$1500 (USD), the cost of the Nasal Ranger® is greater than that of the traditional box scentometer (Sheffield et al. 2004). However, despite the increased cost and existing concerns with regards to background odours and activated carbon efficacy, the Nasal Ranger® provides significant improvement in measurement standardisation and instrument ease of use over the box scentometer.

2.2.3 Evaluation and Application of Field Olfactometry

While field olfactometry has seen significant application for ambient odour monitoring, reported assessment of the accuracy and quality of the data obtained using these techniques has been somewhat limited, particularly with regards to comparison with laboratory based dynamic olfactometry, as well as between different field olfactometers.

Comparison with laboratory based dynamic olfactometry

A number of researchers have compared field olfactometry with laboratory based dynamic

olfactometry (Bokowa 2008; Henry 2009; Sheffield et al. 2004). All of the reported studies obtained similar results, with a significant difference being observed in odour concentrations measured using field olfactometry compared to laboratory based dynamic olfactometry. Specifically the field based measurements were significantly lower than those using laboratory based dynamic olfactometry (Bokowa 2008; Henry 2009; Sheffield et al. 2004). This consistent difference suggests a fundamental limitation in one of the two techniques being assessed. With the existing view that laboratory based dynamic olfactometry offers limited accuracy at low odour concentrations (typical of ambient conditions) and is not suitable for this form of monitoring (Gostelow et al. 2001; Henry 2009), it is most likely that these results demonstrate the accepted limitation of laboratory based dynamic olfactometry at low odour concentrations instead of identifying any significant limitation in the tested field olfactometers.

Instrument comparison (Nasal Ranger® and box scentometer)

Three studies were identified in the reviewed literature where existing field olfactometers (Nasal Ranger® and box scentometer) were compared: McGinley and McGinley (2004) using H₂S; Sheffield et al. (2004) using a range of odour sources including food processing wastewater, mixed municipal and food processing wastewater, a dairy, and a beef feedlot; and by Newby and McGinley (2004) for animal feed lots. None of the studies could demonstrate any significant difference between odour concentration measurements made using the two instruments, suggesting that they are equivalent. Sheffield et al. (2004) also assessed measurement variability and concluded that the variability in results obtained using the Nasal Ranger® was lower than for those obtained using the box scentometer.

Applications and limitations

Field olfactometry has been applied to address odour issues in a range of industries/environments including WWTPs (Cesca et al. 2007; Witherspoon and Barnes 2004), manure application sites (Agnew et al. 2006), industrial areas (Gerrity 2005), and livestock operations (Newby and McGinley 2004; Pan et al. 2007; Sheffield et al. 2004). With their flexibility and relative ease of use, field olfactometers have been proposed or applied for a range

of uses (Cesca et al. 2007; Gerrity 2005; Nicell 2009; St. Croix Sensory Inc. 2005; Witherspoon and Barnes 2004) including:

- routine monitoring to evaluate the effectiveness of odour abatement processes and odour management practices in terms of effect of reducing odour impacts;
- providing baseline data to support process expansion planning;
- identifying specific odour sources to prioritise abatement;
- odour complaint investigation;
- documentation of specific odour events/episodes;
- monitoring compliance with regulatory limits; and
- verifying odour dispersion modelling results.

There are, however, a number of limitations associated with ambient odour monitoring (i.e. sampling from a discrete location) that must be considered when applying this technique. Terrain complexity, wind direction variability, and variations in odour character (emission variability can produce ambient odours that differ from the source odours) can hamper data collection and impede odour plume tracking (Nicell 2009). Additionally, odour concentrations do not provide character information, thus it may not be possible to differentiate between odours from sources of interest and other ambient sources in the local area, and while a single measurement can demonstrate non-compliance with regulatory limits, due to the variable and transitory nature of odours, a comprehensive study over a wide range of conditions and locations is required to demonstrate compliance (Nicell 2009). The discrete dilution ratio settings on commercially available field olfactometers places a limitation on the accuracy of these measurements (Pan et al. 2007), while the transitory nature of odour emissions and wind direction can complicate the process of obtaining stable, repeat measurements (Witherspoon and Barnes 2004). Finally, as sensory technique, field olfactometry shares many of the same potential biases and limitations as laboratory based dynamic olfactometry (discussed in **Section 4.1.2**) and, as noted by Nicell (2009), user training is critical to ensure data reliability.

3.0 Online Monitoring

While portable instrumentation is quite useful for diagnostic and survey work, it is often desirable to monitor continuously or have access to data remotely, particularly for process control, performance monitoring, and compliance verification. The application of online gas phase instrumentation for odour abatement process monitoring has been rather limited in nature with regards to the parameters and types of instruments utilised. While a wide range of analytical techniques exist, practical implementation issues have resulted in only a small subset of these techniques being commercially available.

Online odour/odorant monitoring leverages gas sensors developed for other industries, and as a result specific gas sensors targeting key odorants (discussed in **Section 3.1**) and arrays of non-specific sensors (**Section 3.2**) are commercially available as online instrumentation (Stuetz and Nicolas, 2001; Capelli et al. 2008a; Gabriel and Deshusses, 2003; Haas et al. 2008; Sohn et al. 2008a). More complex analytical techniques are not currently suitable for widespread online implementation, in particular the online application of gas chromatography based analysis has been limited by high technical expertise requirements, high capital costs (for example an automatic thermal desorption gas chromatograph with a mass spectrometer detector can cost in the range of \$150,000 to \$250,000 AUD), and lengthy analytical time (Snopok and Kriglenko, 2002), while sensorial techniques cannot be applied continuously in an automated fashion due to the requirement for human observers.

3.1 Specific Gas Sensors

As discussed in **Section 2.1**, specific gas sensors comprise a broad variety of chemical, electrochemical, catalytic, and optical detectors with high sensitivity and selectivity for target analytes. Multiple specific sensors are often combined into a single instrument to allow simultaneous monitoring of several gases of interest. Specific sensors have the advantage of low response times (on the order of 10 to 120 seconds), low detection limits (down to ppb levels), relatively low cost (typically in the range of \$1,000 to \$20,000 AUD depending on sensor and analyte type), easy on-site implementation, and provide a direct reading of the concentration of the target analyte. Their easy operation and relative high accuracy (errors <10%) have facilitated widespread use in industrial and environmental applications.

Despite the high level of application of these sensors, significant gaps exist in the assessment of commercially available sensors (which will be discussed in **Section 3.1.4**). Furthermore, most of the technical information for these sensors is only available from manufacturers/suppliers, which may be subject to optimistic interpretations. This information has been summarised for sensors capable of monitoring three parameters of interest for odour abatement processes in the wastewater industry, namely H₂S (**Section 3.1.1**), NH₃ (**Section 3.1.2**), and VOCs (**Section 3.1.3**). Many multisensor instruments combining these parameters with other parameters (e.g. O₂ and CO₂) are available commercially, but these instruments are generally of limited (or situational) use for the industry and will not be discussed further.

3.1.1 H₂S

A review of commercially available online H₂S monitors was conducted based upon manufacturer information. Primary instruments of interest are depicted in **Figure 7**, and key characteristics (based on supplier literature) are summarised in **Table 7**. Where possible, quotations were obtained for instruments (exclusive of GST). It should be noted that these prices are subject to change and highly dependent on the current US dollar exchange rate, and should only be used to assess relative costs of various instruments versus their other characteristics.

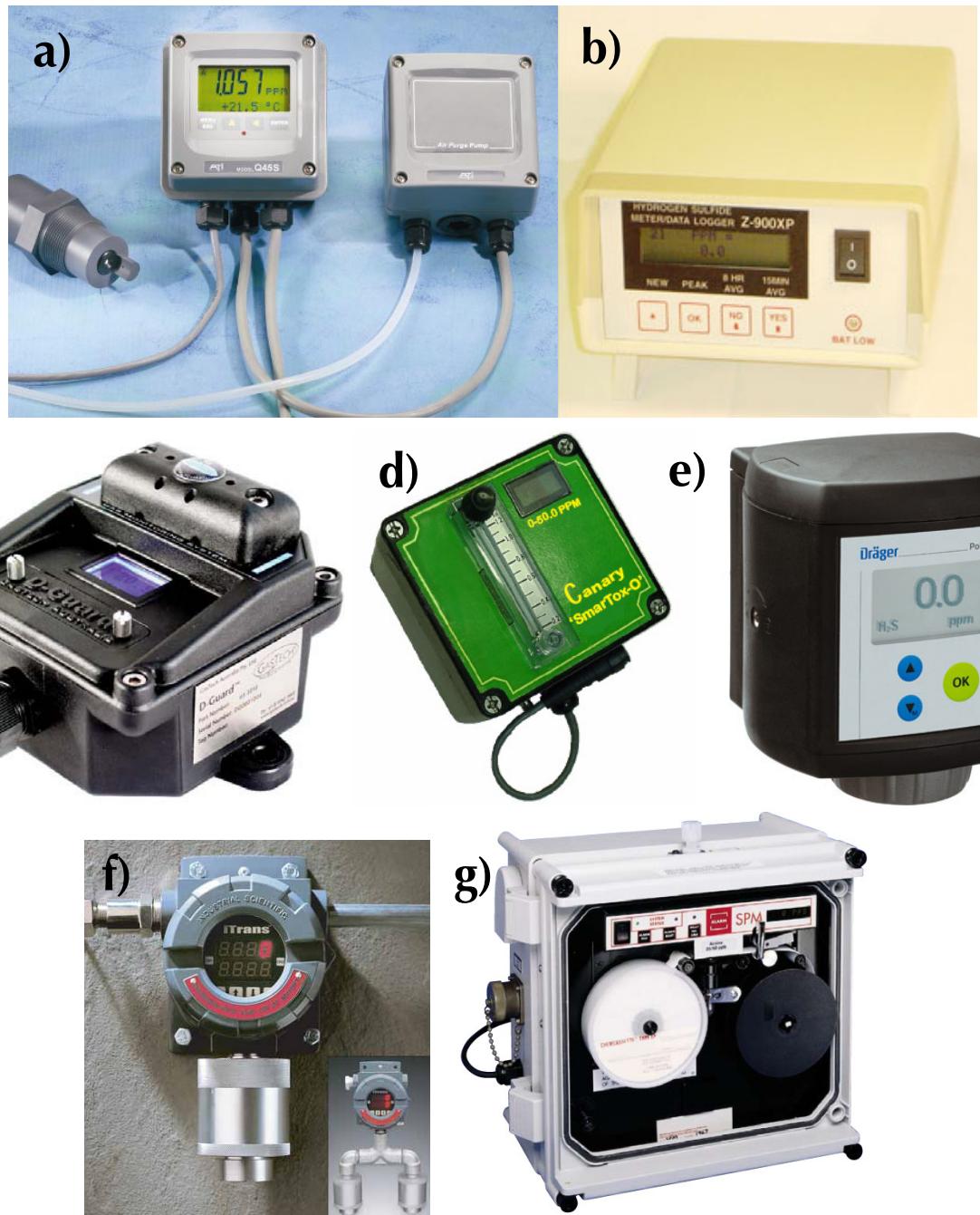


Figure 7 Commercially available online H₂S monitors.

a) Q45S (Analytical Technology, Inc.), b) Z-900XP (Environmental Sensor Co.), c) D-Guard (GasTech Australia Pty Ltd.), d) SmarTox-O (The Carnary Company Pty Ltd.), e) Dräger Polytron 3000/7000 (Dräger Safety), f) iTrans (Industrial Scientific Corporation), and g) Honeywell SPM (Honeywell Analytics). All images courtesy of respective corporate websites.

Table 7 Comparison of online H₂S monitoring instruments.

Manufacturer	Model	Sensor Type	Range (ppm)	Resolution (ppm)	Response Time (90%)	Accuracy	Operating Conditions	Calibration Interval (months)	Sensor Life (years)	Supplier	Price (AUD) ¹
Analytical Technology, Inc.	Q45S	Wet gas sensor	0 - 200	0.1	120 s	± 10%	-20°C - 50°C Free moisture	-	< 1	Hydramet Australia	\$4723
Environmental Sensors Co.	Z-900XP	EC	0 - 500	0.1	< 30 s	-	-40°C - 50°C 15 - 90% RH	-	> 2	Environmental Sensors Co.	\$995 (USD)
GasTech Pty Ltd	D-Guard	EC	0 - 200	1	< 40 s	± 5%	-20°C - 50°C 0 - 95% RH	-	-	GasTech Australia	\$4985
The Carnary Company Pty Ltd	SmarTox O	EC	0 - 5 0 - 200	0.01 -	-	-	- Free moisture	-	-	The Canary Company Pty Ltd	\$6495
Dräger Safety	Polytron 7000	EC	Adjustable 0 - 100 10 - 1000	-	< 40 s < 60 s	± 3%	-40°C - 65°C 5 - 95% RH	6	> 3	Dräger Safety Pacific Pty Ltd	\$3320 \$3740
Industrial Scientific	iTrans Fixed Point Monitor	EC	0 - 500	1	-	-	-20°C - 50°C; 15 - 90% RH	-	-	Air-Met Scientific	\$6081 (H ₂ S + NH ₃)
Honeywell Analytics	Honeywell SPM	OP	1.1 - 30	-	10 s	-	-20°C - 40°C	-	-	Honeywell Analytics Asia Pacific	-

¹prices subject to change and dependent on USD exchange rate

EC Electrochemical sensor

OP Optical analysis of Chemcassette™

- no data

In general very few specifics were provided in manufacturer's literature with regards to the sensors being utilised in the instruments other than the broad classification (e.g. electrochemical). This lack of information limits the assessment of the relative merits of different instruments. In particular, little information is provided with regards to potential interferences. Generally adsorption based instruments like electrochemical sensors are susceptible to interferences from reduced sulfur compounds and humidity (Gostelow and Parsons 2001). Of the seven instruments reviewed, only two manufacturers acknowledge potential interferences in their product literature, although the focus was primarily on combustion gases and the impact of other sulfur containing compounds were not addressed. No in-depth assessment of interference effects for commercially available online H₂S sensors has been found in existing literature.

Electrochemical sensors were dominant type utilised in the instruments, with the exception of the Honeywell SPM, which uses Chemcassette™ detection technology based on chemically impregnated paper tape that reacts with H₂S and is monitored by an optical scanning system to detect the resulting colour change. It is expected that this type of instrument would be highly specific to H₂S and a good choice for applications where electrochemical sensors are experiencing interference from non-H₂S compounds, although this should be verified experimentally.

In addition to interferences, the impact of moisture on instruments is an important consideration for monitoring applications. The majority of the reviewed instruments were designed to operate in humid conditions, while only two were designed to operate in gas environments containing free moisture (for example in scrubbers). Very little detail has been provided by the manufacturers with regards to how free moisture is dealt with, and no significant literature assessing the effectiveness of these systems or specific impacts of moisture on sensor response quality were identified during the literature review.

Overall, a wide range of instruments are available for online H₂S monitoring, although based on the limited level of information available, most of the instruments are fundamentally similar. A need exists for further assessment of these instruments (under common testing conditions), particularly with regards to potential interferences, calibration requirements, operating costs, maintenance requirements/costs, and instrument reliability.

3.1.2 NH₃

A review of commercially available online NH₃ monitors was conducted based upon manufacturer information. The majority of these instruments are based on similar platforms as the H₂S instruments (depicted in **Figure 7**), with the H₂S sensor replaced by an NH₃ sensor. Indeed many of these NH₃ sensors are also available in combination with other sensors (such as H₂S) as online multigas monitors. Key instrument characteristics (based on supplier literature) are summarised in **Table 8**. Where possible, quotations were obtained for instruments (exclusive of GST). Once again it should be noted that these prices are subject to change and highly dependent on the current US dollar exchange rate, and should only be used to assess relative costs of various instruments versus their other characteristics.

Similar to online H₂S instruments, limitations existed with regards to the level of detail provided in supplier literature, particularly with regards to potential interferences. It should be noted that none of the reviewed NH₃ monitors were designed for use in environments containing free moisture. As with the H₂S monitors, a need exists for further assessment of these instruments with regards to potential interferences, calibration requirements, operating costs, maintenance requirements/costs, and instrument reliability.

Table 8 Comparison of online NH₃ monitoring instruments.

Manufacturer	Model	Sensor Type	Range (ppm)	Resolution (ppm)	Response Time (90%)	Accuracy	Operating Conditions	Calibration Interval (months)	Sensor Life (years)	Supplier	Price (AUD) ¹
Environmental Sensors Co.	Z-800XP	EC	0 - 100	0.1	< 60 s	-	-20°C - 40°C 15 - 90% RH	-	> 2	Environmental Sensors Co.	\$1195 (USD)
GasTech Pty Ltd	D-Guard	EC	0 - 100	1	< 40 s	± 5%	-20°C - 50°C 0 - 95% RH	-	-	GasTech Australia	\$995 (Sensor)
The Carnary Company Pty Ltd	SmarTox I	EC	0 - 50 0 - 200	-	-	-	-20°C - 50°C 15 - 90% RH	-	~3	The Canary Company Pty Ltd	\$8350 (H ₂ S + NH ₃)
Dräger Safety	Dräger Polytron 7000	EC	Adjustable 0 - 100 30 - 1000	-	< 40 s < 30 s	± 5%	-40°C - 65°C 15 - 95% RH	6	> 2	Dräger Safety Pacific Pty Ltd	\$3320 \$3740
Industrial Scientific	iTrans Fixed Point Monitor	EC	0 - 200	1	-	-	-20°C - 50°C; 15 - 90% RH	-	-	Air-Met Scientific	\$6081 (H ₂ S + NH ₃)
Honeywell Analytics	Honeywell SPM	OP	2.6 - 75	-	10 s	-	-20°C - 40°C	-	-	Honeywell Analytics Asia Pacific	-

¹prices subject to change and dependent on USD exchange rate

EC Electrochemical sensor

OP Optical analysis of Chemcassette™

- no data

3.1.3 VOCs

Online process monitoring for VOCs has traditionally been the realm of flame ionisation detector (FID) instruments. Due to their size, cost and maintenance/fuel requirements, these instruments were primarily applied for large sources and were not suitable (particularly from an economic perspective) for widespread application on large numbers of sources. Advances in photoionisation detectors (PIDs) have lead to VOC monitoring devices which are significantly smaller, simpler, and less expensive than their FID counterparts. PIDs have primarily been applied for portable monitoring instruments (**Section 2.1.2**) but this technology has started to make the transition to online instrumentation.

Like other sensors, available online VOC sensors were reviewed based upon manufacturer literature. These instruments are depicted in **Figure 8**, and key instrument characteristics are summarised in **Table 9**.

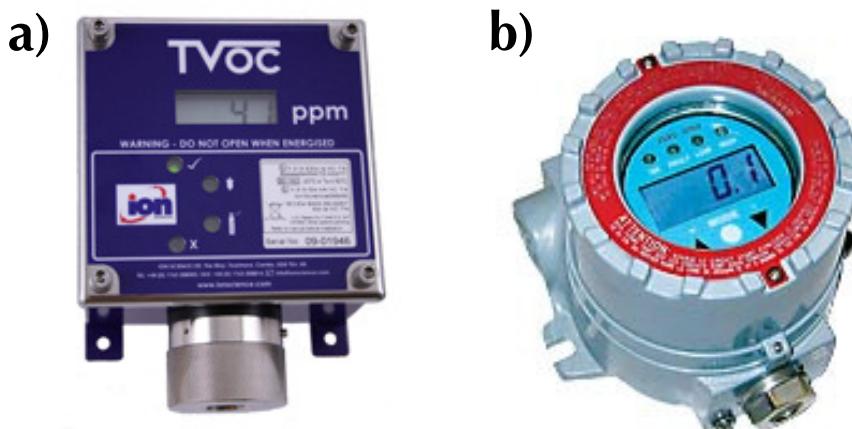


Figure 8 Commercially available online VOC monitors (PID).

a) TVOC (Ion Science Ltd.), b) RAEGuard PID (RAE Systems).
All images courtesy of respective corporate websites.

Table 9 Comparison of online VOC monitoring instruments.

Manufacturer	Model	Sensor Type	Range (ppm)	Resolution (ppm)	Response Time (90%)	Accuracy	Operating Conditions
Ion Science Ltd.	TVOC	PID	0 - 10	-	< 5 s	-	-20°C - 50°C 0 - 95% RH
			0 - 100			± 1 ppm	
			0 - 1000			± 2 ppm	
RAE Systems	RAEGuard PID	PID	0.01 - 20	-	40 s	-	-20°C - 55°C 0 - 95% RH
			0.1 - 100				
1 - 1000							

PID Photoionization Detector
- no data

As with other sensors, a lack of information with regards to sensor life and calibration intervals was observed. It should be noted that these instruments are not designed to be suitable for application in environments containing free moisture. No independent reviews of these instruments, or assessments of lifespan, calibration and maintenance requirements were found in the reviewed literature.

3.1.4 Limitations and Future Direction

The majority of the reviewed specific sensor literature focused on the development of new sensor types or modification of existing sensor types. There has been very little comparative analysis of commercially available sensors, and no systematic studies comparing sensor types with regards to performance, maintenance, and interferences (in terms of both compounds and moisture). This lack of independent assessment results in nearly all existing information originating from instrument manufacturers. The need thus exists for studies to address this gap, particularly with regards to the uncertainty that remains with regards to sensor specificity and interferences.

Commercially available sensors cover a very limited range of compounds, of which only a small subset are of interest for odour abatement processes (H_2S , NH_3 , VOCs), with H_2S being the most commonly applied parameter for wastewater/sewer odour abatement process monitoring. As discussed previously for portable instruments (**Section 2.1.4**), consideration must be given to the appropriateness and limitations of these specific monitoring parameters, particularly in situations

where H₂S or NH₃ are not the primary odorants (for example where industrial sources are discharged into sewer systems). Once again, the usefulness of online VOC monitoring is likely to be limited due to it being a bulk measurement representing a range of odorous and non-odorous compounds, although as discussed in **Section 2.1.4** VOC monitoring may have some use in tracking interfering compounds for absorption based processes, however, further work is needed to assess its utility.

Since specific sensors are restricted with regards to the measured parameters, the need exists to support their application with comprehensive initial monitoring and assessment of odorous emissions to identify the most appropriate specific sensors. Improved understanding of sewer odorants could also lead to the identification of other appropriate monitoring parameters for which specific sensors could be applied and/or developed.

3.2 Non-specific Gas Sensor Arrays

Non-specific gas sensor arrays are non-specific monitoring devices which attempt to mimic human sensory systems, in particular the senses of smell (electronic nose) and taste (electronic tongue). From a technical standpoint, the application of non-specific gas sensor arrays differs from conventional monitoring techniques, which focus on maximising the sensor specificity to the analyte of interest. Non-specific gas sensor arrays attempt to mimic the human process of odour recognition through the use of a bank of sensors which are partially specific by design (i.e. they are designed to respond to a range of chemical compounds). Due to their lack of specificity towards specific odorants, non-specific gas sensor arrays are capable of responding to the presence of most of the volatile compounds in the odour sample, which generates a unique odour fingerprint (Sohn et al. 2008; Stuetz and Fenner 2001). The sensors produce a complex set of digital signals that are then processed to extract the key features required for odour discrimination and quantification (Capelli et al. 2008a; Hudon et al. 2000; Sironi et al. 2007a).

Figure 9 shows a simplified schematic of the analogies between the operation of human olfaction and the different processes occurring in a non-specific gas sensor array (Arshak et al. 2004; Dewettinck et al. 2001).

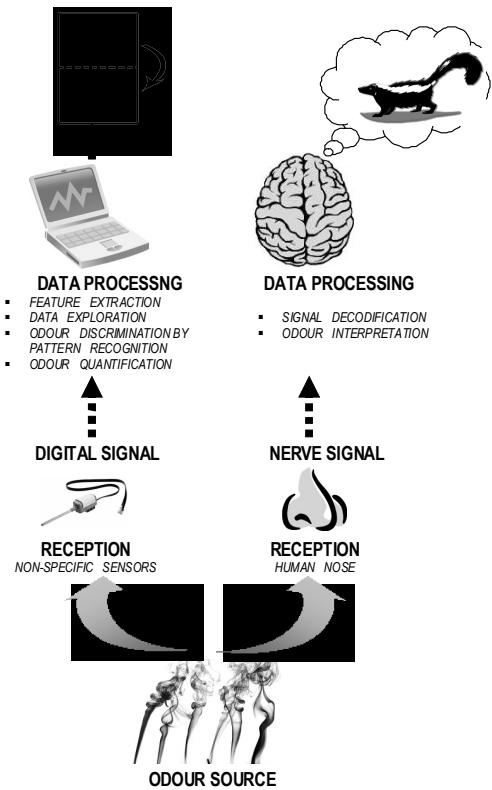


Figure 9 Comparison of a non-specific gas sensor array and human olfaction during exposure to an odour sample.

3.2.1 Operation and Data Analysis

Non-specific gas sensors are usually employed in arrays of up to 30 sensors. Metal oxide, conducting polymer, and oscillating quartz crystal sensors constitute the most common detectors in environmental applications (Arshak et al. 2004; Bourgeois and Stuetz 2002; Nakamoto and Sumitomo 2003; Ozturk et al. 2009), although new sensor materials (such as composite polymers and nanocomposites) are constantly being developed (Ameer and Adelaju 2005).

Metal oxide sensors are based on the decrease of the electric resistance of the sensors in the presence of volatile compounds (Dewettinck et al. 2001; Goschnick et al. 2005). These sensors exhibit high sensitivity, fast response, low recovery times and low production costs (Dewettinck

et al. 2001; Goschnick et al. 2005), although they are viewed as being most useful for the detection of combustion gases (Gardner and Bartrlett 1999).

The chemo-resistive sensing layer of **conducting polymer** gas sensors change their electrical conductivity and/or resistance in the presence of volatile compounds (Sohn et al. 2009b). Conducting polymer sensors provide excellent reproducibility (4% and 2% relative standard deviation for liquid and gas samples, respectively), stability, and versatility, along with allowing for customisation to a particular application through the modification of functional groups attached to the polymer chains (Stuetz et al. 1999a). These sensors are, however, more dependent on humidity and temperature (Nake et al. 2005).

Oscillating quartz crystal sensors are based on the VOC-induced change in frequency of oscillation of quartz crystals coated with commercial gas chromatography stationary phases (Haas et al. 2008; Stuetz and Fenner 2001). Despite exhibiting fast response times (<10s), oscillating quartz crystal sensors are highly sensitive to temperature and humidity fluctuations and the manufacturing process remains complex and non-reproducible (Arshak et al. 2004), limiting their use in environmental analysis.

Regardless of the sensors employed, the operation of sensors is characterised by a measurement phase (0.5-5 min) followed by a sensor recovery phase (0.5-12 min) that is necessary to desorb the volatile compounds adsorbed into the sensors and to bring their response back to baseline levels (Bourgeois and Stuetz 2002; Fuchs et al. 2008; Sironi et al. 2007a; Stuetz et al. 1999a). Before key features from the digital signal generated by the sensor array can be extracted, the signal must be pre-processed to compensate for noise and drift variations (Arshak et al. 2004). Most sensor arrays utilise steady states signals to extract the features of the odour response, however recent studies have shown that the use of both transient and steady state signals outperforms the results obtained using steady state signal values exclusively (Sohn et al. 2009a; Trincavelli et al. 2009). Feature extraction is followed by a dimensionality reduction stage where statistical techniques (typically principal component analysis and Fisher linear discriminant

analysis) are employed to reduce the multidimensional data to 1 or 2 dimensions, greatly facilitating interpretation.

The final data analysis step consists of applying pattern recognition techniques to the dimensionally reduced data to classify and quantify odours (Gutierrez Osuna, 2002 (Onkal-Engin et al. 2005). Statistical based pattern recognition techniques (in particular principal component analysis) have been utilised in the majority of the reviewed studies (Bourgeois and Stuetz 2002; Capelli et al. 2008a; Dewettinck et al. 2001; Haas et al. 2008; Nake et al. 2005; Sironi et al. 2007a; Sohn et al. 2008) to recognise patterns in sensor array data by reducing the number of dimensions while at the same time maximising the variance of the data. The application of artificial neural networks (ANNs) for data analysis is widely used in many research fields for pattern recognition purposes (Gardner and Bartrlett 1999), and while ANNs have seen extensive use in the food and beverage industries to interpret sensory array data, their application in environmental monitoring is more recent (Onkal-Engin et al. 2005). The primary difference between statistical methods and ANNs is the requirement for training. Statistical methods are primarily untrained approaches, thus the data is examined for patterns without any outside influences. ANNs require training, which introduces an outside influence into the interpretation of the results, in addition to the cost and time associated with collecting the data used for training.

While no definitive data analysis methodology has been selected for non-specific gas sensor arrays, both statistical and ANN methods have been employed successfully to analyse non-specific sensor array data, and good agreement was found when Onkal-Engin et al. (2005) analysed datasets using both statistical techniques and an ANN. Recent advances in pattern recognition techniques (including partial least square-discriminant analysis, artificial neural networks, Kohonen self-organising maps, principal component analysis, and vector machines classifiers) have allowed for enhanced identification, with correlations in the range of 80 to 95% to odour concentrations measured using dynamic olfactometry (Capelli et al. 2008a; Onkal-Engin et al. 2005; Sironi et al. 2007a; Sironi et al. 2007c; Sohn et al. 2008; Sohn et al. 2009b;

Stuetz et al. 1999a; Trincavelli et al. 2009).

3.2.2 Monitoring Applications

Application of non-specific gas sensor arrays have increased rapidly in the food and beverage industries, as well as for environmental monitoring to qualitatively and quantitatively characterise odours (Gardner and Bartrlett 1999; Hodgins and Simmonds 1995; Stuetz and Fenner 2001). In the wastewater industry, recent work has focused on qualitative and quantitative odour assessment, although there has been some work on the detection of undesirable components in influent wastewater such as diesel fuel. **Table 10** illustrates some of the most recent environmental odour monitoring applications of non-specific gas sensor arrays.

Table 10 Recent environmental applications of non-specific gas sensor arrays.

Instrument	Sensor	Company	Application	Results	Reference
AromaScan A32S	CP	AromaScan plc	Identification of odour sources causing annoyance	Sensor was capable of discriminating between 4 odour categories from a pig farm and an abattoir with a reasonable efficiency ($\approx 80\%$)	Sohn et al. (2009b)
AromaScan 32	CP	AromaScan plc	Monitoring odours in a biofilter treating piggery odorous emissions	Good odour classification, poor odour quantification (best correlation 79%)	Sohn et al. (2009a)
EOS 3 & EOS 9	MO	Sacmi Group	Monitoring of odour from a composting plant	Positive correlation between sensor records and odour annoyance. Correlation between sensor response and odour concentration $\approx 80\%$, good qualitative characterisation	Sironi et al. (2007c)
EOS ⁸³⁵ 25	MO	Sacmi s.c.a.r.l	Monitoring odours from a composting plant	Data processing and sensor array training crucial. Odour classification: 96% accuracy, odour quantification: 90% correlation	Sironi et al. (2007a)
EOS 28, EOS 25, EOS 35	MO	Sacmi Group	Monitoring odours from WWTP	Good qualitative odour characterisation with 3 olfactory classes. Correlation between sensor array response and odour concentration $> 90\%$ in the range of $20\text{--}80 \text{ Ou}_E \text{ m}^{-3}$	Capelli et al. (2008a)
FOX 3000	MO	Alpha M.O.S	Monitoring WWTP effluent	Good sample differentiation, repeatability 7-15%, reproducibility 8-17%	Dewettinck et al. (2001)
Homemade	MO	-	Monitoring odours from a poultry shed	Odour quantification: 96% correlation Sensor array data correlates shed operation	Sohn et al. (2008)
NOSE	CP	Neotronics Scientific	Monitoring odours from WWTP	No universal correlation between sensor response and odour concentration for all WWTPs Good correlation between sensor response and odour concentration for individual WWTPs	Stuetz et al. (1999a)
OdourVector	OQC	GMBH	Monitoring of an activated carbon systems	Good identification of activated carbon breakthrough points, poor correlation between sensor response and odour concentration. Pre-concentration unit increased sensitivity	Haas et al. (2008)
Pen-2 Cyranose	MO CP	WMA Airsense Cyrano Science	Identification of odour in a WWTP	MO performed better in odour discrimination CP were more dependent on T and humidity	Nake et al. (2005)
ProSAT	CP	Marconi Applied Technology	Monitoring for the presence of diesel in WWTP influent	Good detection of organic compounds Headspace analysis	Bourgeois and Stuetz (2002)

3.2.3 Limitations and Future Development

Non-specific gas sensor arrays are a cost effective means of continuously monitoring complex environmental odours, which is their primary competitive advantage over specific gas sensors and gas chromatography for odour characterisation (Hudon et al. 2000). However, their non-invasive nature and operational similarities to human olfaction resulted in overoptimistic performance expectations. Thus, when early researches faced severe limitations derived from the still primitive state of development, a progressive loss of interest in non-specific sensor array technologies resulted (Stetter and Penrose 2002).

One of the primary limitations of non-specific sensors is response variability associated with environmental factors, particularly temperature and relative humidity (Bourgeois et al. 2003a; Nake et al. 2005). Two approaches have been applied to deal with these effects: establishing a controlled environment for the sensor to operate in, and software compensation (Bourgeois et al. 2003b). The use of controlled sensing environments has become relatively common, with the primary approaches consisting of bubbling inert nitrogen gas through the liquid sample to transfer the odorants to the gas phase, delivering them to a temperature controlled non-specific sensor array in the headspace (Bourgeois et al. 2003a; Bourgeois and Stuetz 2002). These modifications increase the cost and technical complexity of the monitoring system. Furthermore, they result in the system being partially invasive since a liquid sample must be removed from the bulk process and sent to the analysis chamber. This introduces several of the limitations associated with invasive monitoring techniques, particularly sample representativeness, sample collection system fouling, and increased sensor response time.

An approach to compensate for the effects of these parameters in the sampling results (called parametric compensation) has been investigated by Bourgeois et al. (2003b), who utilised a moving window technique to mitigate the effects of temperature and relative humidity changes, sensor drift, and changes in background matrices. While this method was quite successful in identifying deviations from normal influent conditions, it is not suitable for the determination of

specific component concentrations. The development of correlations between temperature, relative humidity and flow with sensor response has been problematic, although some success has been achieved by utilising these parameters as inputs to ANNs, which have resulted in significant enhancement of sensor performance for odour classification and quantification (Bourgeois et al. 2003b; Li 2005; Onkal-Engin et al. 2005; Sohn et al. 2009a; Sohn et al. 2008).

Long term sensor response stability in particular remains an area of ongoing investigation. Exposure to the high odorant concentrations found in wastewater over extended periods of time can contribute to sensor aging or poisoning, reducing instrument sensitivity (Gardner and Bartrlett 1999). Furthermore, sewage odours are a reflection of sewage composition (Stuetz et al. 1999b) and experience corresponding time dependent variations (Stuetz et al. 1999c). In utilising non-specific sensors to predict wastewater biochemical oxygen demand (BOD), poor correlation was observed over the long-term (due to temporal variations), although strong correlations could be obtained for short term periods of 4 weeks or less (Stuetz et al. 1999b; Stuetz et al. 1999c). This temporal dependence could impose the requirement for frequent recalibration or training which would limit their suitability and acceptance at wastewater treatment plants.

Overall, the use of non-specific gas sensor arrays for non-invasive wastewater process monitoring is a rapidly emerging application. While the sensor arrays themselves are commercially available and possess the advantages of being a relatively low cost means of odour monitoring, a number of research and technical challenges remain before these applications become commercially viable and accepted monitoring techniques. These challenges are primarily related to data analysis, in particular reducing the expertise requirement, development of a systematic method for selecting appropriate data analysis techniques, and advancement of data analysis techniques to enhance compensation for sensor drift, aging, temperature/relative humidity effects, and temporal variations in the wastewater matrix. While recent developments in non-specific gas sensor technology such as high-performance pre-concentration units, precise temperature control in sensor chamber and the use

of dry odourless reference air have increased sensor accuracy, sensitivity, and robustness (Haas et al. 2008; Nakamoto and Sumitomo 2003). However, much greater sensitivities are needed to reach the human annoyance threshold range, and more successful case-study applications are needed in order to regain the credibility lost due to overoptimistic performance expectations.

4.0 Laboratory Based Assessment – Gaseous Samples

The assessment of odorants in the laboratory can be conducted using a wide range of techniques and methodologies, depending on the overall analytical objectives (end use of the data). Sensorial analysis (discussed in **Section 4.1**) is an extremely useful tool for the regulation of odorant impacts and in the assessment of treatment efficiency since the analysis is based directly upon the human perception of odours. These methods however do not provide for the quantification of the chemical compounds present in malodorous emissions, which is particularly important with regards to the management of wastewater odours, odour abatement system design, and for understanding underlying reactions and sources responsible for odorant emissions. Analytical techniques such as gas chromatography (**Section 4.2**) are utilised to provide qualitative and quantitative chemical information, along with significantly enhanced repeatability and accuracy (Gostelow et al. 2001). These techniques however do not provide impact information (qualitative aspects of the odorants), which is required to identify the subset of compounds that are the dominant odorants. As a result, there has been a move towards the combination of both the analytical and sensorial methods (gas chromatography-olfactometry) to leverage the benefits inherent in each method. These combined techniques will be discussed in **Section 4.3**. A survey of the reported applications of laboratory based techniques for odour abatement process monitoring is presented in **Section 4.4**.

4.1 Sensorial Analysis

Sensory techniques allow for the qualitative and quantitative evaluation of the sensorial component of odours using the human nose as a detector, and as a result measure the total effect of the target odour on human perception (Gostelow and Parsons 2000). Unlike analytical analyses, sensorial techniques have lower accuracy and repeatability due to their subjective nature, and their results must be carefully interpreted. These techniques can be applied to determine odour concentrations quantitatively through dynamic olfactometry, or to describe them subjectively in terms of parameters such as hedonic tone, quality and intensity (Gostelow et al. 2001; Sneath 2001; Suffet and Rosenfeld 2007).

4.1.1 Qualitative Sensorial Odour Analysis (Odour Profile Method)

Subjective aspects of odorant emissions such as the relative pleasantness or unpleasantness of an odorous emission (odour hedonic tone), the type of odour descriptor from a standard odour wheel that best represents the odour smell (odour quality), or the perceived strength of odour sensation (odour intensity) are assessed using sensorial analysis techniques (Burlingame et al. 2004; Sneath 2001; Suffet et al. 2004a). These three dimensions of an odour, although not explicitly employed in odour regulation policies, are crucial to establish odour-impact criteria (Jiang et al. 2006). In fact, most of the dose-effect relationships between odour exposure and annoyance used in European legislation are based on the empirical determination of odour concentration-intensity relationships (Jiang et al. 2006; Schulz and van Harreveld 1996).

4.1.1.1 Odour Profile Method

While qualitative sensorial analysis has had a role in the development of odour standards, the application of these techniques for wastewater odour assessment has been limited. Only relatively recently has there been a concerted effort to apply qualitative sensorial analysis techniques in a rigorous manner to enhance our understanding of odorant emissions, most notably in the form of the Odour Profile Method (OPM).

The OPM utilises a panel that has been trained to characterise the individual components of odours using odour descriptors and intensity ratings (Burlingame 1999). Individual odour descriptors can be linked to typical odorants, although confirmation through combined sensory and chemical analytical techniques (such as GC-O) is required to complete the identification (Suffet et al. 2004b).

Due to the subjective nature of these methods and the observed variability in dilution olfactometry results (van Harreveld et al. 2009), comparison and interpretation of data collected by different laboratories (or even between different analysts) can be difficult. Towards resolution of this issue, odour wheels have recently been introduced to standardise the basis on which to classify, communicate and identify odour qualities (Burlingame et al. 2004; Suffet et al. 2004a; Suffet et al. 2009; Suffet and Rosenfeld 2007) . A wastewater odour wheel (Suffet et al. 2004a) is provided as **Figure 10**.

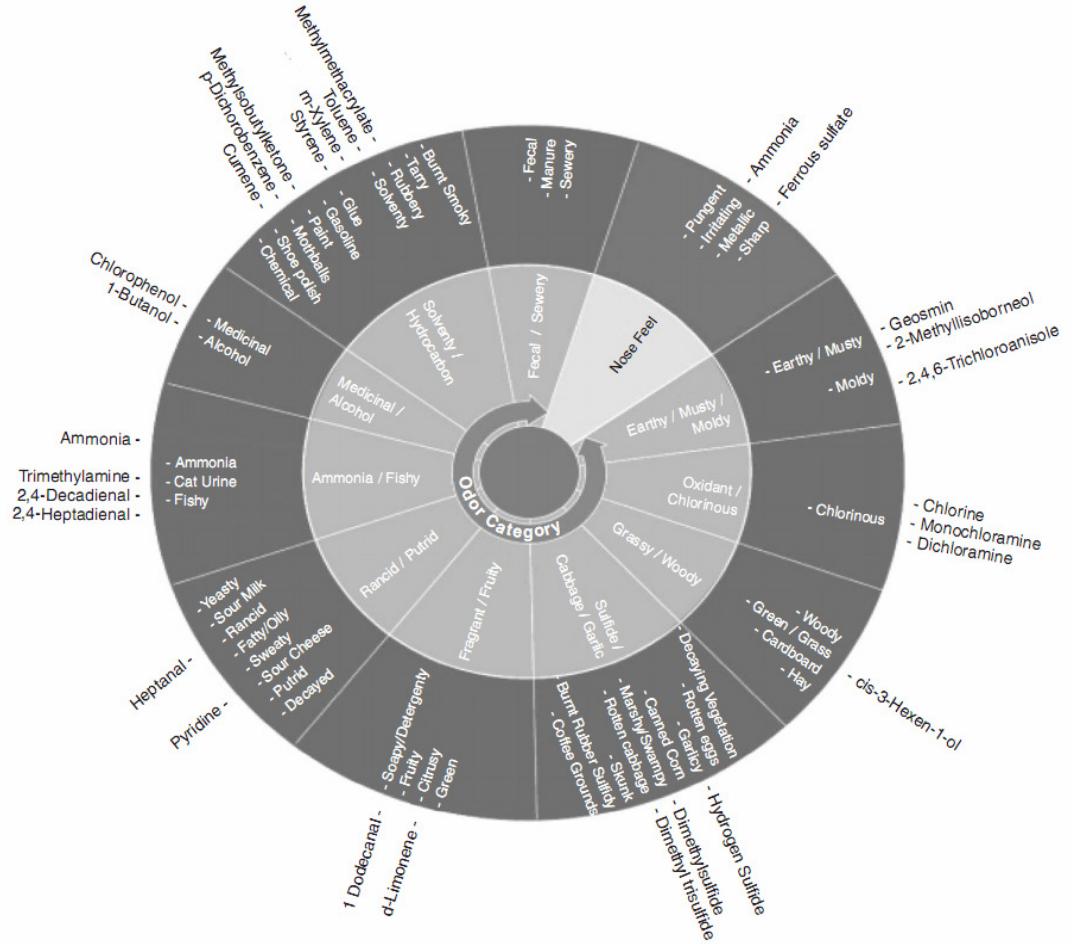


Figure 10 Wastewater Odour Wheel, reproduced from Suffet et al. (2004).

While this technique has been applied with much success to address odour issues in the drinking water industry, reported application for wastewater odour assessment has been limited (Burlingame 1999; Burlingame 2009). Through the application of OPM over a three year period at a wastewater treatment plant, Burlingame et al (1999) demonstrated the potential for this technique to identify specific odour sources at the facility based upon their odour profile. More recent work has focused on fenceline monitoring using this technique to assess annoyance associated with odorous emissions to prioritise abatement (Burlingame 2009). Due to the limited number of reported applications, a need exists for further case studies demonstrating the utility of this technique in identifying the responsible odour sources to support the abatement of nuisance odours. Furthermore, additional work to characterise odour profiles for specific

wastewater treatment processes (and operating conditions) and sewer conditions using the established wastewater odour wheel to provide consistent descriptors would assist the industry in the identification of key odour sources and causes.

4.1.1.2 Qualitative Field Analysis of Odorants

While laboratory based techniques provide useful information, there is a push towards the application of these techniques in the field for the purposes of identifying and assessing environmental odour sources and impacts. In addition to field application of the OPM, innovative sensorial methodologies based on odour field measurement such as “odour profiling”, “field of odours”, and “reverse modelling” have significantly improved both odour mapping and odour emission estimation (Bilsen and De Fre 2008; Burlingame 1999; De Bruyn et al. 2008; Leger 2008).

In France, the French Ministry for the Environment has promoted the “field of odours” method in the last decade through the development of odour monitoring networks based on trained panels of neighbourhood volunteers (Leger 2008). These panels evaluate air quality by sniffing the air twice a day (all at the same time) during 3-12 month campaigns, identifying the major odour sources contributing to odour pollution (associating an “olfactory imprint” to each source) and quantifying the impact of any potential odour abatement process on air quality (Leger 2008). More scientifically-grounded studies are being conducted at both the European and national level (Belgium) in order to standardise odour field measurements using “reverse modelling”. In a recent study, Bilsen and De Fré (2008) achieved satisfactory estimations of odour emissions using sniffing teams of at least 2 qualified panellists (according to EN 13725) under stable atmospheric conditions, moderate wind velocities (2-8 m/s), and using at least 10-15 sniffing measurements. By carefully recording the extent of the odour plume using teams of 4-6 panellists, odour emissions were estimated by “reverse modelling” using bi-Gaussian atmospheric dispersion models and local meteorological conditions.

Overall, sensorial techniques such as the OPM are still regarded as emerging techniques for odour assessment. However, given their track record to date in assisting other industries in addressing odour issues and their inherent advantages in terms of speed and cost compared to more intensive analytical procedures, it is expected that the application of these qualitative techniques will contribute significantly to the advancement of odour abatement for sewerage collection networks and wastewater treatment processes.

4.1.2 Quantitative Sensorial Odour Analysis (Dynamic Olfactometry)

The fact that odour concentration can be easily related to odour intensity and therefore odour impact (using either Weber-Fechner or Steven's law to describe the relationship between the physical magnitude of stimuli and the perceived stimuli intensity), combined with improvements in dynamic olfactometry accuracy and precision, have triggered an international movement towards environmental odour policies based on dynamic olfactometry measurements (Schulz and van Harreveld 1996; van Harreveld et al. 1999; van Harreveld et al. 2009). Today, most international odour policies include a required compliance frequency (based on a time percentage) with maximum allowable odour concentrations. As a result, odour concentration measurements by dynamic olfactometry has indisputably become the most commonly employed sensorial technique (Dincer and Muezzinoglu 2007; Gostelow and Parsons 2000; Romain et al. 2008).

In dynamic olfactometry, the odour concentration of a sample is quantified as the number of dilutions with odourless air required to reduce the odorant concentration to its detection threshold (i.e. the concentration at which there is a 50% probability of detection) (Gostelow et al. 2001; Sneath 2001). In practice, the analysis is carried out by presenting the diluted sample to a panel of selected and screened human assessors (4-10 panellists, **Figure 11**) using a dilution device called an olfactometer (Capelli et al. 2008b; Gostelow et al. 2003; Hobbs et al. 1995; Sneath 2001).



Figure 11 Dynamic olfactometry analysis of an odour sample using a 6 person panel.
Courtesy of Silsoe Odours Ltd.

Olfactometers (**Figure 12**) are in essence serial diluters based on rotameters or mass flow controllers equipped with flushing systems to minimise cross-contamination. Both stationary and portable olfactometers must be built from low permeability, odourless materials exhibiting minimal interactions with the volatile compounds present in the odour sample (such as stainless steel, glass, Teflon® or Tedlar™) (Gostelow et al. 2001; Sneath 2001). Dynamic threshold olfactometric measurements can be performed either in an odourless stationary laboratory hosting the olfactometer, or in the field using portable olfactometers such as Scentometer or the Nasal Ranger (Gostelow et al. 2001; McGinley and McGinley 2004; Schulz and van Harreveld 1996).

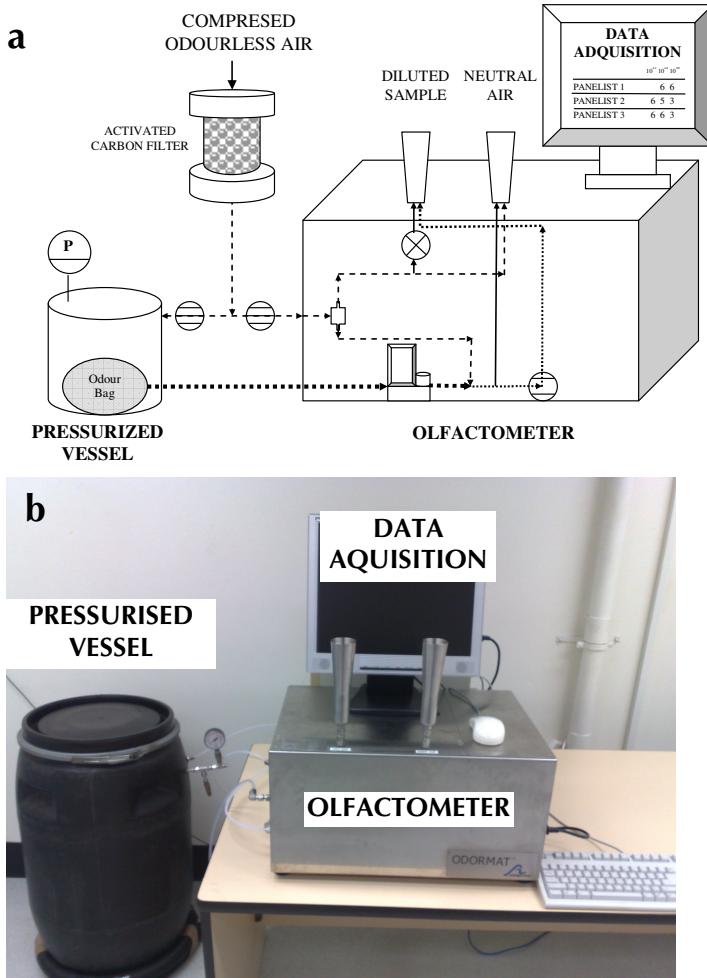


Figure 12 Dynamic olfactometer: schematic illustration (a), photograph (b).

The threshold value of the panel, calculated as the geometric mean of the individual threshold values of the panellists, is considered by definition as 1 odour unit (formerly called threshold odour number or dilution to threshold ratio, and ou_E/m^3 in the recently accepted European Standard: EN 17325, 2003). Dynamic olfactometry can be performed in 3 modes: a yes/no mode where either odourless air or the diluted odour is presented in a single sniffing port and the panellist assess only the presence or absence of odour; a forced choice mode where the panel members assess which of the 2 or 3 sniffing ports contains the diluted odour sample with a certain probability: certainty, inkling, or guess; and a forced choice probability mode, which uses a more systematic and statistical approach to implement the forced choice method (Gostelow et al. 2001; Sneath 2001).

4.1.2.1 Standardisation of Dynamic Olfactometry Methodologies

Although olfactometry dates back to the 1890s, significant advances leading to improved accuracy, repeatability, and reproducibility only occurred one century later (Schulz and van Harreveld 1996). The first rigorous inter-laboratory tests carried out in the 1980s revealed unacceptable variations (up to 3 orders of magnitude) in odour concentration determination. The urgent need to correct these deficiencies due to the progressive establishment in Northern Europe of strict quantitative odour policies based on odour concentration, resulted in an intensive research in the field leading to the first rigorous dynamic olfactometry standards: NVN2820 in the Netherlands and VDI 3881 part 2 in Germany (Schulz and van Harreveld 1996).

Based on the success of this initiative, the European committee for Normalisation and its equivalent in Australia and New Zealand published similar technical standards for dynamic olfactometry (EN 13725:2003 and AS/NZ 4323 part 3: 2001, respectively). Strict compliance with these standards' recommendations regarding the technical characteristics of the olfactometer, selection criteria of the panel members, and dynamic olfactometry test procedures is intended to guarantee a reasonable level of accuracy and repeatability in the obtained results (Mannebeck and Mannebeck 2001; van Harreveld et al. 2009). Despite the availability of these standards, in proficiency tests organised in 2007 and 2008, 2/3 of the laboratories claiming to work in accordance to the EN 13725 standard failed to demonstrate compliance with the required performance criteria (van Harreveld et al. 2009). In the United States, the prevalence of "no nuisance" odour policies (not based on impact odour concentrations) has not triggered any requirement to comply with a particular ASTM standard (Schulz and van Harreveld 1996).

4.1.2.2 Limitations and Future Development

The accuracy, repeatability and reproducibility of dynamic olfactometry are primarily a function of three factors: (i) variability in human olfactory perception, (ii) instrumental performance and operation methodology, and (iii) the method for threshold value calculation.

Due to the large variations in olfactory sensitivities among the general population, the majority of the current standards and guidelines for dynamic olfactometry recommend the selection of average-sensitivity panellists (hyper and hypo-sensitive noses are discarded) in order to produce more reproducible results (Bliss et al. 1996; van Harreveld et al. 2009). In this context, between 50 and 70% of potential panellists are rejected due to their unsuitable olfactory sensitivity based on a reference gas (n-butanol) (Sneath 2001; van Harreveld et al. 1999). It should be noted that no significant differences in olfactory response have been found with regards to panellist gender (Bliss et al. 1996). Panellist selection is further complicated by the decrease in human olfactory sensitivity and accuracy with age (which is also dependent on the type of odour sensed), and by olfactory fatigue (adaptation) during continuous exposure to odours as well as increases in sensitivity that are commonly observed under repeated but not continuous exposures (Gostelow et al. 2001). As a result, monitoring of panellist sensitivity is highly recommended in most international dynamic olfactometry standards.

Studies have shown that olfactometer operation may introduce sources of error in dynamic olfactometry. The use of single sniffing stations composed of two sniffing cups prevents olfactory fatigue in panellists as result of the resting time between assessments (2 minutes). Cross contamination as a result of odorant adsorption on tubing, rotameters or mass flow controllers is suggested to be common bias in dynamic olfactometry. Olfactometers based on needles valves (rather than rotameters or mass flow controllers) flushed with high-speed/high pressure odourless air have also been suggested to minimise cross-contamination (which allows the random presentation of diluted samples) while exhibiting reasonable dilution accuracy (Jiang et al. 2006). Finally, constant flow rates at the sniffing cup are a prerequisite for accurate odour threshold determination (Dravnieks and Jarke 1980). Flow rates of 20 L/min (sufficient flow rate to support normal human breathing and sniffing rates) are normally used in commercial olfactometers (van Harreveld et al. 1999).

The employed test procedure has also been reported to bias the panellists. For instance, a

decreasing order of presentation can cause olfactory fatigue or adaptation and is not recommended (Gostelow et al. 2001). Better repeatability can be achieved by using forced choice with a certainty approach (guess/inkling/certain) that allows reducing the size of the panel to 4-6 persons (Schulz and van Harreveld 1996). Other observations have suggested that the schedule of sample presentation can bias the panellist's response (Jiang et al. 2006).

The method for threshold value calculation has also been suggested as influencing the accuracy of dynamic olfactometry. In Europe and Australia, the individual threshold value is often calculated as the geometric mean of the first dilution where the diluted odour sample can be detected and the previous dilution factor where the panellist could not detect the stimulus.

Despite significant breakthroughs in the last 20 years in the field of sensory analysis, dynamic olfactometry still exhibits higher variability than its analytical counterparts (replicate measurements of a sample under the EN 13725 standard can differ by a factor of 3), with a significant analysis cost (\$300 - \$400 AUD per sample). Recent advances in the design and operation of olfactometers are gradually increasing their accuracy and precision, while decreasing detection limits (Gostelow et al. 2001). Even with recent advances, current detection limits are on the order of 20-50 ou/m³, hence the applicability of dynamic olfactometry to assess ambient air samples around the threshold for nuisance (5 - 10 ou/m³) is limited (Gostelow et al. 2001). Field olfactometers are seen as being more convenient for the determination of ambient air concentrations near this threshold as a result of their lower operating range of 2 - 500 ou/m³ (McGinley and McGinley 2004). On-going work at the European level by the CEN TC264/WG27 working group will result in a field inspection standard for the determination of odour exposure in ambient air (Bilsen and De Fré, 2008).

Significant concern also exists in the preservation of sample prior to analysis due to the high reactivity of some odorants or potential interferences due to water condensation in hot and wet samples (Hobbs et al. 1995; Sluis and Vossen 2008). Most of the current dynamic olfactometry standards recommend sample storage in TedlarTM and / or Nalophan NATM bags for periods not

exceeding 24-30 h (Gostelow et al. 2001). However, knowledge gaps exist with regards to permeation (loss) of specific odorants through these materials in addition to odorant transformation during collection and storage. Additional work is required to assess the impact of these factors on dynamic olfactometry in addition to developing guidelines for sample collection and storage.

While dynamic olfactometry has been widely applied for compliance assessment in existing odour regulations and for evaluation of odour abatement performance, the binary nature of the measurement (detection or non-detection) fundamentally limits the ability of this technique to enhance existing understanding of the specific types of odorants, their production mechanisms, or sources of odour abatement failure. The current poor understanding of non-H₂S odorant emissions from sewers is hindering the development of odour abatement technology. Further uptake of more informative analytical techniques (such as GC-O or OPM) is needed to advance odour management for wastewater sources.

4.2 Chromatography Methods

A wide range of instrumental techniques including gas chromatography, colorimetric reaction-based assays, catalytic, infrared and electrochemical sensors, differential optical absorption spectroscopy, and fluorescence spectrometry are used to identify and quantify chemicals present in gaseous emissions from sewers and WWTPs (Bourgeois and Stuetz 2002; Dewulf and Van Langenhove 2002; Guisasola et al. 2008; Hobson and Yang 2002; Rehmann et al. 2008). Despite the large number of analytical techniques, gas chromatography (**Figure 13**) is the dominant method and the focus of this review.



Figure 13 Gas chromatograph with mass spectrometer detector.

Gas chromatography (GC) is viewed as the most precise and powerful analytical tool for the quantification and identification of volatile organic compounds and volatile sulfur compounds (VOCs and VSCs, respectively) (Dewulf and Van Langenhove 2002). In gas chromatography, a

gaseous mobile phase (usually He or N₂) is used to carry the mixture of VOCs and VSCs through the interior of a column coated with a stationary phase that has a differential affinity to the volatile compounds, to facilitate their separation (Hobbs 2001). The combination of enhanced peak resolution provided by capillary columns and the low detection limits achieved by mass spectrometer detectors (MSD), flame ionization detectors (FID), photoionization detectors (PID) and electron capture detectors (ECD) makes gas chromatography an ideal technique for the measurement of complex mixtures of chemicals at trace levels concentrations (Eiceman et al. 1998; Wang and Austin 2006). A typical GC-MS chromatogram for an air sample collected from the inlet of a WWTP is provided as **Figure 14**.

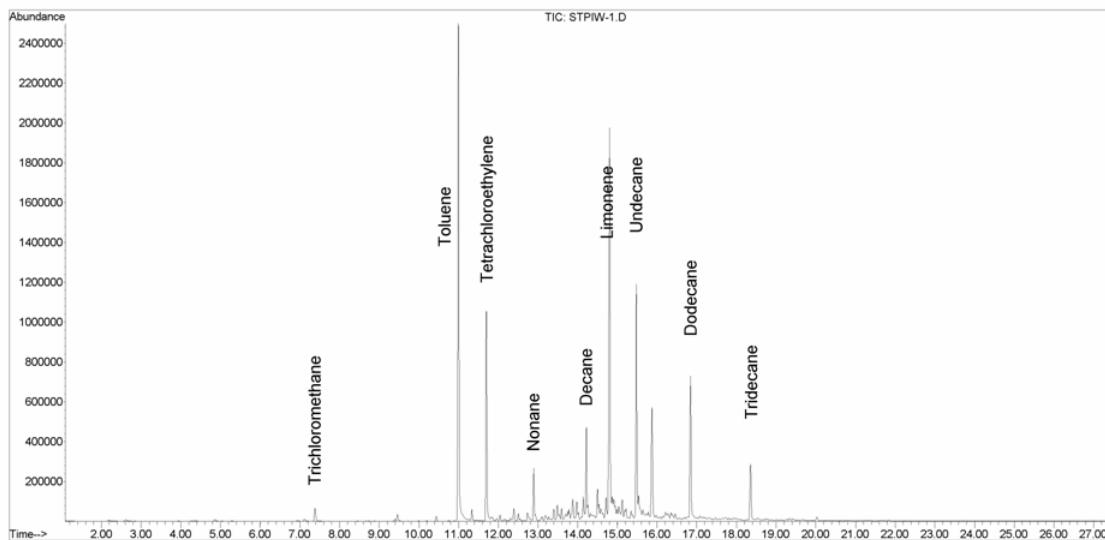


Figure 14 Typical GC-MS chromatographic analysis of inlet gas at WWTP, carried out at UNSW (Australia).

4.2.1 Operation and Application

Conventional capillary chromatography typically employs narrow (0.18-0.53 mm internal diameter) 10-100 m long silicone-type wall coated open tubular (WCOT) or alumina-based porous layer open tubular (PLOT) columns, which allow for an improved separation of hundred of compounds in a single run of 10 to 60 min at carrier gas velocities of 1-2 mL/min (Wang and Austin 2006). Recent developments in gas chromatography have resulted in shorter analysis

times as a result of the use of shorter and narrower columns (2-10 m and 0.03-0.25 mm) and fast temperature programs (70 °C). Conventional run times in the range of 10 to 60 min can be reduced to few minutes (fast GC), seconds (very fast GC), or even milliseconds (ultrafast GCs).

PID, MSD, FID and ECD are among the most popular detectors, with typical detection limits in the order of 10-100 pg for FID and MSD (in full scan mode) and 1 pg for ECD and MSD (in single ion mode). While FID and ECD remain highly selective for VOCs and halogenated compounds, respectively, some specific applications such as the determination of VSCs require the use of more specific detectors such as sulfur chemiluminescence detectors (SCD) or flame photometric detectors (FPD), which are also in the picogram range of detection (Eiceman et al. 2000; Fox 1999; Hobbs 2001). MSD is likely the most versatile and powerful detector for GC analysis, allowing simultaneous identification and quantification of both VOCs and VSCs. In this type of detector, qualitative identification is achieved by direct comparison of the mass spectra of the eluted compounds from the column with mass spectra libraries. Mass spectra comparison (with a quality match higher than 90%) can only be considered a putative identification, and independent confirmation of the identity of the compounds is still required (Leff and Fierer 2008).

Typical GC detection limits are in the range of few tens of ng per cubic meter with repeatabilities of approx 10% in the ppbv range and up to 20-30% in the pptv range (Dewulf and Van Langenhove 1999). **Table 11** summarises some of the most recent applications of GC analyses of VOCs and VSCs for wastewater and biosolid emissions and the typical detection limits achieved.

Table 11 Examples of the analysis of volatile chemical compounds by Gas Chromatography.

Process	Analyte	Detector	Column	Analytical Quality	Detection Limit	Reference
WWTP	VOCs	FID/MSD	C ₂ -C ₄ Chrompack-50 m × 0.32 mm × 5 µm C ₄ -C ₁₀ J&W Scientific DB-1-60 m × 0.32 mm × 1 µm	Accuracy: 0.1 - 23% deviation	0.1 – 1 ppbv	Wu et al. (2006)
Rendering plant	VOCs	FID/MSD	J&W Scientific 100% dimethyl polysiloxane column 60 m × 0.53 mm × 1.5 µm.	-	0.2 – 5 µg/m ³	Defoer et al. (2002)
SWTP	VOCs	MSD	Agilent DB 624 - 30 m × 0.32 mm × 1.8 µm	-	-	Srivastava et al. (2004)
SWTP	VOCs	MSD	Supelco- Supelcowax 30 m × 0.25 mm × 0.25 µm	Reproducibility: 5 - 26% rsd*	0.04-0.83 µg/m ³	Bruno et al. (2007)
WWTP/ Biogas plant	VSCs	MSD	Chrompack-CP-SIL 5 CD 50 m × 0.32 mm × 5 µm	Reproducibility: 2 - 12% rsd*	1 – 470 pptv	Nielsen and Jonsson (2002)
WWTP	VSCs	PFPD**	J&W Scientific GS-GasPro 30 m × 0.32 mm	-	-	Li and Shooter (2004)
WWTP	VOCs VSCs	MSD	J&W Scientific DB-VRX 30 m × 0.25 mm × 1.4 µm	Reproducibility: 0 - 8% difference	1-5 µg/L	Cheng et al. (2007)
WWTP	VSCs	MSD	Agilent DB-5MS-30 m × 0.25 mm × 0.5 µm	-	-	Turkmen et al. (2004)
WWTP	VSCs	MSD	Teknokroma TRACSL Meta X5 60 m × 0.32 mm × 1 µm	Reproduciblity: < 3% rsd*	0.01-0.04 µg/m ³	Ras et al. (2008)
WWTP	VSCs	MSD	Agilent, HP-1 60 m × 0.32 mm × 1 µm	Relative precision: < 6% difference	0.03-0.06 µg/m ³	Sheng et al. (2008)
WWTP	VSCs	SCD/FPD	Fused silica 50 m × 0.25 mm	-	0.2-0.35 mg/m ³	Muezzinoglu et al. (2003)
WWTP	VOCs	MSD/FID	-	-	-	Zarra et al. (2009)
WWTP	VOCs	MSD	J&W Scientific DB-5-60 m × 0.25 mm × 0.25 µm	-	-	Escalas et al. (2003)

*rsd = relative standard deviation

**PFPD = Pulse Flame Photometric Detector

With the widespread application of GC analysis, there has been some standardisation of GC protocols for VOC and VSC analysis by regulatory agencies such as the U.S National Institute of Occupational Safety and Health and the U.S Environmental Protection Agency (e.g. methods TO-1, TO-2, TO-14, TO-15, TO-17). It should be noted that these methodologies have been benchmarked for a range of gaseous emissions from industrial and waste management processes, and specifically optimised for the analysis of odorous emissions from wastewater sources.

4.2.2 Sample Pre-concentration

Despite the high sensitivity of modern GC detectors, the concentration of most volatile compounds is low so that pre-concentration of the chemicals is often necessary prior to analysis. The selected pre-concentration technique is a function of the type of matrix analysed (air or wastewater), as well as the employed sampling methodology.

If the odour management strategy requires analysis of liquid phase (wastewater) samples, direct liquid-liquid extraction or dynamic headspace analyses (purge and trap sampling) are generally employed. While liquid-liquid extraction is relatively easy to implement, the presence of the solvent limits the range of compounds analysed and increases the detection limits due to the limitations inherent to the injection of large solvents volumes into capillary GC (Dewulf and Van Langenhove 1999). Headspace sampling involves purging of the volatiles present in the liquid sample with an inert gas to generate a gas phase sample which is then collected and analysed using one of the following gas phase pre-concentration techniques.

Gas phase samples can be pre-concentrated using a number of techniques, in particular cryogenic sampling, sorbent tubes, and solid-phase micro extraction (Gostelow et al. 2003).

Cryogenic sampling pre-concentrates all volatile chemicals present in the air sample by direct condensation at very low temperatures (< -150°C). Despite minimising the generation of artefacts and allowing the retention of practically all compounds, water retention severely challenges the performance of this technique (Dewulf and Van Langenhove 1999).

Sorbent tube sampling involves the absorption of target volatile compounds in a sorbent tube (**Figure 15**) at a controlled sample flow rate, followed by either thermal desorption or sorbent

desorption (Defoer et al. 2002). Ideally sorbent materials should have an infinite breakthrough volume for all VOCs and VSCs present in the air sample, allow for a complete desorption of the compounds, exhibit no water retention capacity, and have a low reactivity with the adsorbed compounds to prevent the generation of artefacts that interfere with the analysis (Dewulf and Van Langenhove 1999).



Figure 15 Sorbent tubes.

Unlike cryogenic pre-concentration (which allows the analysis of all VOCs and VSCs present in the sample), the type of volatile chemicals retained on sorbent tubes is primarily dependent on the nature of the sorbent and imposes a limit on the range of compounds which can be analysed (Van Langenhove et al. 1985). In addition to limitations in the range of compounds captured, a further limitation is imposed by the use of thermal desorption, which can result in the transformation of thermally unstable volatile compounds, particularly VSCs (Clausen et al. 2008; Delahunty et al. 2006).

Despite their widespread use in both environmental and occupational health applications, no single sorbent material is applicable to the entire range of odorous compounds, which makes the use of multi-bed sorbent tubes a very popular alternative. **Table 12** shows the range of application of some of the most common commercially available solid sorbent materials.

Table 12 Commercially available sorbent materials (Markes International Limited, Perkin Elmer, Sigma-Aldrich; SKC).

Sorbent	Strength	Surface Area (mg/g)	Volatility range	Remark
Carbotrap/Carbopack C Carbograph 2TD	Very weak	≈ 12	n-C ₈ to n-C ₂₀	Ideal for very hydrophobic VOCs, minimal artefacts
Tenax TA or GR	Weak	≈ 35	n-C ₇ to n-C ₃₀ Bpt* 100-450 °C	Very hydrophobic, efficient desorption Graphitised form best for PAHs and PCBs
Carbopack B Carbograph 1 TD	Medium/ Weak	≈ 100	n-C ₅ to n-C ₁₄	Ketones, alcohols, aldehydes and components within the above volatility range
Chromosorb 102	Medium	≈ 350	Bpt* 50-200 °C	High artefacts Alcohols, oxygenated compounds, haloforms less volatile than methylene chloride
Chromosorb 106	Medium	≈ 750	n-C ₅ to n-C ₁₂ Bpt* 50-200 °C	High artefacts Hydrocarbons and volatile oxygenated compounds
Porapak N	Medium	≈ 300	n-C ₅ to n-C ₈ Bpt* 50-150 °C	High artefacts Volatile nitriles, volatile alcohols
Porapak Q	Medium	≈ 550	n-C ₅ to n-C ₁₂ Bpt* 50-200 °C	High artefacts VOCs within this volatility range
Spherocarb/Unicarb	Strong	≈ 1200	n-C ₃ to n-C ₈ Bpt* -30-100 °C	Low artefacts Very volatile compounds, Volatile polar compounds
Carbonsieve SIII	Very strong	≈ 800	C ₂ hydrocarbons and small Bpt* -60 °C – 80 °C	Low artefacts, easily contaminated by higher Bpt components, ultravolatile compounds
Carboxen 1000	Very strong	> 1200	Permanent gases and light hydrocarbons (C ₂ , C ₃) Bpt* -60 °C – 80 °C	Low artefacts, easily contaminated by higher Bpt components, ultravolatile compounds
Molecular Sieve	Very strong		Bpt* -60 °C – 80 °C	High artefacts Hydrophylic

*- Bpt = Boiling point are used when vapour pressures are not readily available.

Solid-phase micro-extraction (SPME) is a pre-concentration technique based on the absorption of the VOCs and VSCs from a container for a fixed period of time using

microfibers coated with polydimethylsiloxane and carboxen-polydimethylsiloxane, respectively (Ábalos et al. 2002). SPME is a simple, fast, and solvent-free methodology that is valid for both VOCs and VSCs, although the accurate quantification of these compounds seems to be limited by matrix effects and water interferences (Larroque et al. 2006; Nielsen and Jonsson 2002). This technique is, however, not without its limitations. In particular, only averaged air concentrations can be obtained using the procedure, and there is a high level of uncertainty in the estimation of the uptake rates of substances of interest (Bruno et al. 2007; Monn and Hangartner 1996).

Due to the limitations associated with sorbent tube pre-concentration and SPME (particularly with regards to the analysis of VSCs), cryogenic sampling is the preferred pre-concentration technique. Although pre-concentration is commonly used for samples where analyte concentrations are within the instrument detection limits, the option exists for direct analysis from bag/canister samples (**Figure 16**). This methodology allows the analysis of all chemical compounds present in the sample and replicate analyses of the same sample, without the potential for artefacts or biases introduced by pre-concentration techniques.



Figure 16 Gas sampling bag (left) and canister (right).

4.2.3 Limitations and Future Direction

The development of both high performance capillary columns and effective pre-concentration techniques, coupled with the high sensitivity and specificity of available detectors has resulted in enhanced description of odorous emissions both from a qualitative and quantitative viewpoint. Odorant analysis has been further advanced through the development of multidimensional gas chromatography (MDGC) which decreases the analytical problems derived from peak co-elution (overlapping peaks). Two-dimensional (2D) chromatography is based on the separation of overlapping peaks in a second polar column in series with a first non-polar column, with co-eluting peaks sent to the second column as sharp pulses controlled by a thermal modulator. In this context, up to 550 individual peaks have been separated in a single 2D chromatography run (Lewis 2000).

Despite recent advances in gas chromatography, several limitations remain. The broad concentration and species range of compounds present in the odorous emissions results in complications due to the inherent difficulties involved in the preparation of multi-component gaseous standards (Dewulf and Van Langenhove 2002). Water interferences exist in multi-bed sorbent tubes used to concentrate volatiles with a broad range of boiling points (Wang and Austin 2006). Concerns also exist with regards to the potential decomposition of thermally unstable volatile compounds (especially sulfur compounds), associated with the high operating temperatures in both thermal desorption units and injectors (Clausen et al. 2008; Delahunty et al. 2006). Finally, the high cost of the instrumentation and the need for a highly qualified operator is a limiting factor in the widespread application of gas chromatography techniques.

4.3 Combined Gas Chromatography and Olfactometry

Gas chromatography-olfactometry (GC-O) is based on the sensory evaluation of the elute following GC separation and aims at characterising odour active volatile compounds from odorous samples (Pollien et al. 1999; Ranau and Steinhart 2005). While the most sensitive physical detectors (MSD, ECD, and FID) exhibit limits of detection ranging from 1 to 10 pg, human noses can easily detect down to 0.050 pg of odour active compounds (Marin et al. 1991). GC-O brings together the high resolution power of capillary gas chromatography (**Section 4.2**) with the high selectivity and sensitivity of human olfaction (**Section 4.1**).

This technique is primarily implemented in parallel to an MSD (Hochereau and Bruchet 2004), and is known as GC-MS-O. In this particular configuration, the elute from the capillary column is split into a portion reaching the MSD and a portion delivered to a dedicated olfactory detection port (ODP) made of glass or PTFE (polytetrafluoroethylene) and fitted to the shape of a nose (Plutowska and Wardencki 2008). By superimposing the conventional MSD chromatogram with the aromagram recorded by the human assessor (also called an O-chromatogram), the odour character can be identified and quantified (Kleeberg et al. 2005; Parcsi and Stuetz 2007; Wright et al. 2005). A typical GC-O system equipped with an additional chemical detector for odorant quantification and identification is illustrated in **Figure 17**.

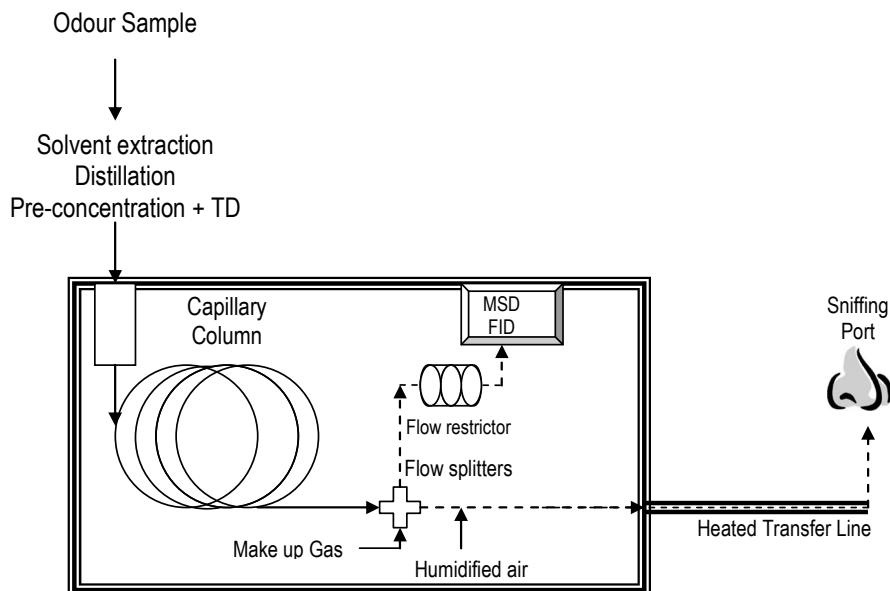
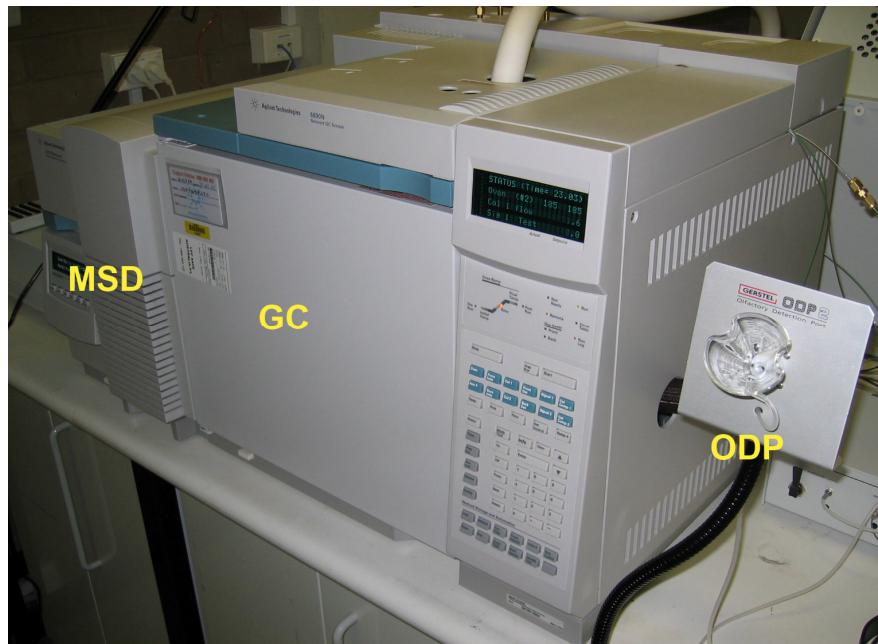


Figure 17 GC-O system equipped with a physical detector and an ODP, photographic view (top), schematic (bottom).

4.3.1 Application

Since its conception in 1952, GC-O has been primarily applied for food, beverage, and perfume research (Delahunty et al. 2006; Fuller et al. 1964), with limited application to

environmental analysis. Currently no published data on GC-MS-O characterisation of emissions from sewers and WWTPs exist, and the characterisation of odorous emissions from intensive livestock operations and the monitoring of indoor air and drinking water quality represent the most relevant applications of GC-MS-O in the environmental field (Cai et al. 2006; Clausen et al. 2008; Hochereau and Bruchet 2004; Kleeberg et al. 2005; Koziel et al. 2005; Parcsi and Stuetz 2007; Wright et al. 2005).

While the initial applications of GC-O have been limited to the qualitative screening of odour active compounds, several robust methodologies are now available for the quantification of odorant intensity and concentration, including dilution to threshold techniques, detection frequency techniques, and direct intensity techniques (Pollien et al. 1999; van Ruth and O'Connor 2001). The first rationalisation of GC-O resulted in the development of the dilution to threshold techniques in the mid-1980s, which were based upon sniffing increasingly diluted odour samples until no odour was detected. Aroma Extract Dilution Analysis (AEDA) and CharmAnalysis are the most commonly utilised dilution techniques (van Ruth and O'Connor 2001). AEDA quantifies the odour potency of each odorant as the maximum dilution of the odour sample that an odour is perceived in, and is reported as a Factor Dilution (FD). CharmAnalysis methods require the determination of the duration of the eluting odorant in order to yield a chromatographic peak (Plutowska and Wardencki 2008). Due to the long duration of these analyses, the number of assessors is practically limited to 3, limiting the precision of the results.

For direct intensity techniques, odorant intensity is recorded on-line during peak elution or scored on a previously defined intensity scale after peak elution. The obtained aromagrams represent the odorant intensity as a function of the retention time in a similar manner as conventional GC-MS or GC-FID chromatograms represents odorant mass. The main drawback inherent to direct intensity techniques is the need for an experienced and trained panel of assessors in order to obtain fast and repeatable aromagrams (Delahunty et al. 2006). Extensive reviews of the fundamentals underlying the above described GC-O methods have been published by van Ruth (2001), Delahunty et al. (2006) and Plutowska and Wardenski (2008).

4.3.2 Limitations and Future Direction

The performance of GC-O is strongly dependent on quality of sample injected into the gas chromatograph, which is in turn dependent on the method of volatile compound extraction (e.g. solvent extraction, distillation, or headspace sampling) and sample storage conditions (Plutowska and Wardencki 2008). The chromatographic conditions used for the separation of the odorants are also crucial (Begnaud et al. 2006; Eyres et al. 2007), in particular the injection temperature (thermally labile compounds decompose at high injection temperatures) and the selection of the optimum chromatographic columns for high peak resolution (both detection frequency and intensity scoring are influenced by the shape of the elution) (Drawert and Christoph 1984; van Ruth and O'Connor 2001). Many of the limitations associated with olfactory analysis (due to the use of human detectors) are also applicable to GC-O analysis, including sensitivity/alertness reduction by fatigue, missed odorant inhalation due to the assessor breathing cycle, nose saturation in sensitive assessors, and bias derived from the ability of the assessors to remember odour profiles and predict odour composition (Delahunty et al. 2006; Hochereau and Bruchet 2004; van Ruth and O'Connor 2001).

GC-O has the potential to fill the gap between chemical and sensorial analysis of environmental emissions, although the reconstruction of odour character from the combinations of individual odours is not straightforward. The inability to predict synergistic, antagonistic, or additive interactions among odorants limits the usability of results obtained from GC-O analysis (Ryan et al. 2008). Despite these limitations, GC-O analysis is extremely valuable in the design of odour abatement processes by identifying specific odorants of interest (although it is of limited practical use for continuous process monitoring).

4.4 Odour Abatement Process Monitoring Using Laboratory-based Assessment Techniques

A review of the laboratory based measurement techniques utilised for performance monitoring of pilot/full scale and laboratory (bench) scale odour abatement processes was undertaken based upon existing literature. This review covered 115 odour abatement processes, 59% of which were pilot and full scale processes treating real odorant emissions, while the remaining 41% were laboratory scale processes treating synthetic odorant mixtures (primarily H₂S, NH₃, and VSCs). Specific details of individual reviewed studies are provided in **Appendix A (Tables A-1 and A-2)** for laboratory scale and pilot/full scale processes, respectively), while monitoring trends will be discussed in the following sections.

While most of the large scale studies involved the participation (and therefore economic support) of private companies or associations, the majority of laboratory scale monitoring was carried out at universities or public research centres. It should be noted that these studies were conducted from a research perspective for very specific monitoring objectives, and the results of this survey would not necessarily be representative for routine process monitoring at full scale installations.

4.4.1 Laboratory Scale Processes

At the laboratory scale, GC analysis was the dominant technique applied for performance monitoring (**Figure 18**), being employed in 54% of the studies. The use of GC analysis correlated well with the relevance of VOCs/VSCs, which were utilised as model odorants in 48% of the studies. Specific sensors constitute the other major group of techniques employed (used in 54% of the studies), due to H₂S and NH₃ (parameters commonly measured using specific electrochemical sensors) being the model odorants utilised in the majority of the studies.

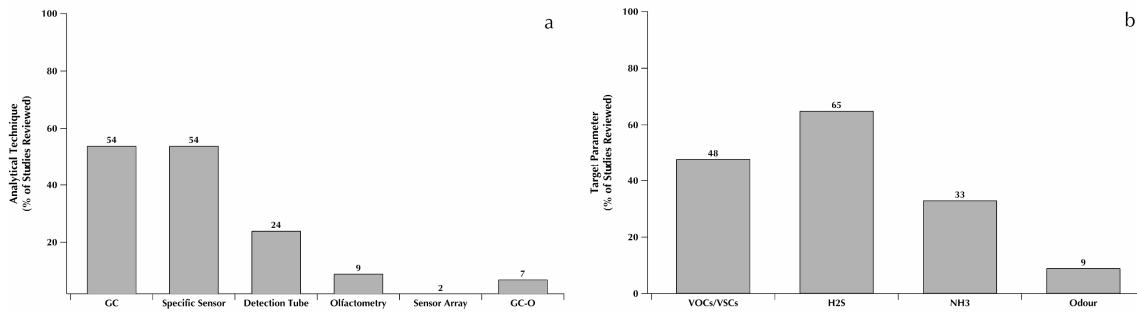


Figure 18 Overview of odour measurement techniques (left) and monitoring parameters (right) for laboratory scale odour abatement processes.

Surprisingly, olfactometric analysis (a direct analysis of odour abatement performance) was rarely used for laboratory scale process performance monitoring (in 9% of the studies). This lack of use is likely due to the high cost of sensorial analysis. While most modern laboratories at Universities and Research Centres host a GC-FID or GC-MS, the technical requirements to run a specialised dynamic olfactometry laboratory and the labour costs of panellists significantly reduce the routine use of odour concentration measurements. Likewise, non-specific gas sensor arrays and GC-O were scarcely employed for performance evaluation.

A summary of the specific analytical techniques employed for the three dominant monitoring parameters (VOCs/VSCs, H₂S, and NH₃) is provided as **Figure 19**.

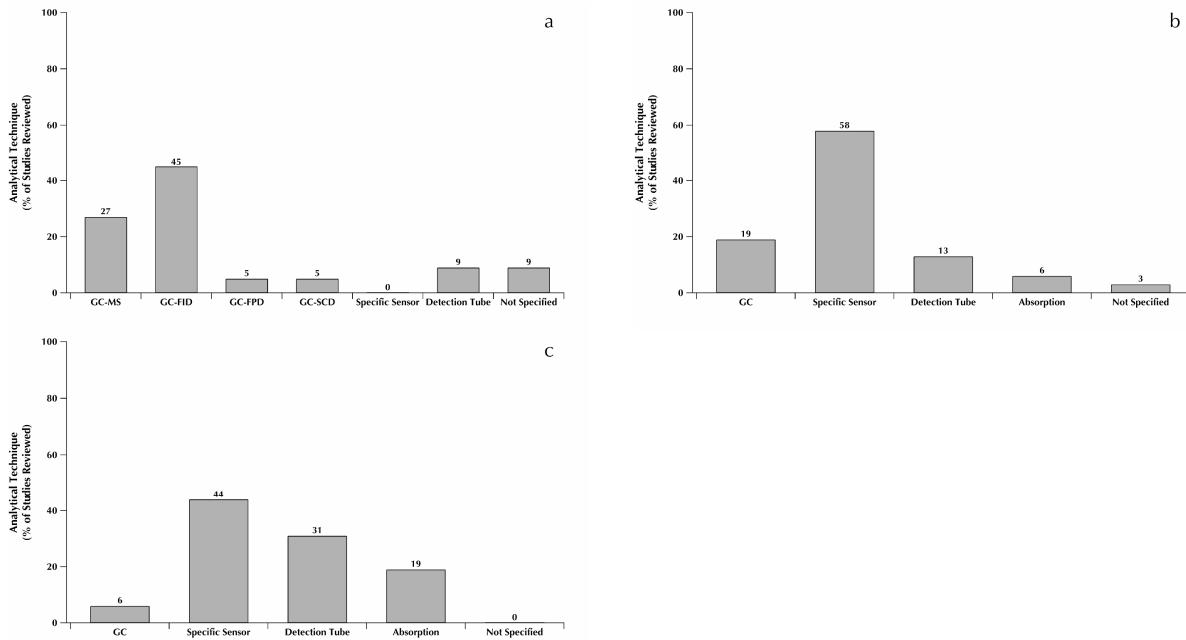


Figure 19 Distribution of monitoring techniques for VOCs/VSCs (a), H₂S (b), and NH₃ (c) for laboratory-scale odour abatement processes.

GC-FID was the most common technique employed for VOC/VSC monitoring (45%), likely due to the lower associated capital cost compared to GC-MS, GC-FPD, and GC-SCD systems. GC-MS was the second most commonly applied technique for VOC/VSC monitoring due to its ability of identify odorants. H₂S monitoring was dominated by specific detectors (58%), while GC was less frequently employed (19%), likely a reflection of the ease of application and cost effectiveness of specific detectors. A similar trend was observed for NH₃ monitoring, with specific sensors being the dominant analytical technique (44%), closely followed by detection tubes (31%) and absorption based techniques (19%).

4.4.2 Pilot and Full Scale Processes

Monitoring techniques employed at a pilot and full scale facilities treating real odorant emissions from a range of industries were reviewed. As seen in **Figure 20a**, wastewater treatment plants (WWTP) and solid waste treatment plants (SWTP) accounted for 70% of the data available in literature, with the remaining reported investigations focusing on livestock farms (18%) and the food industry (12%).

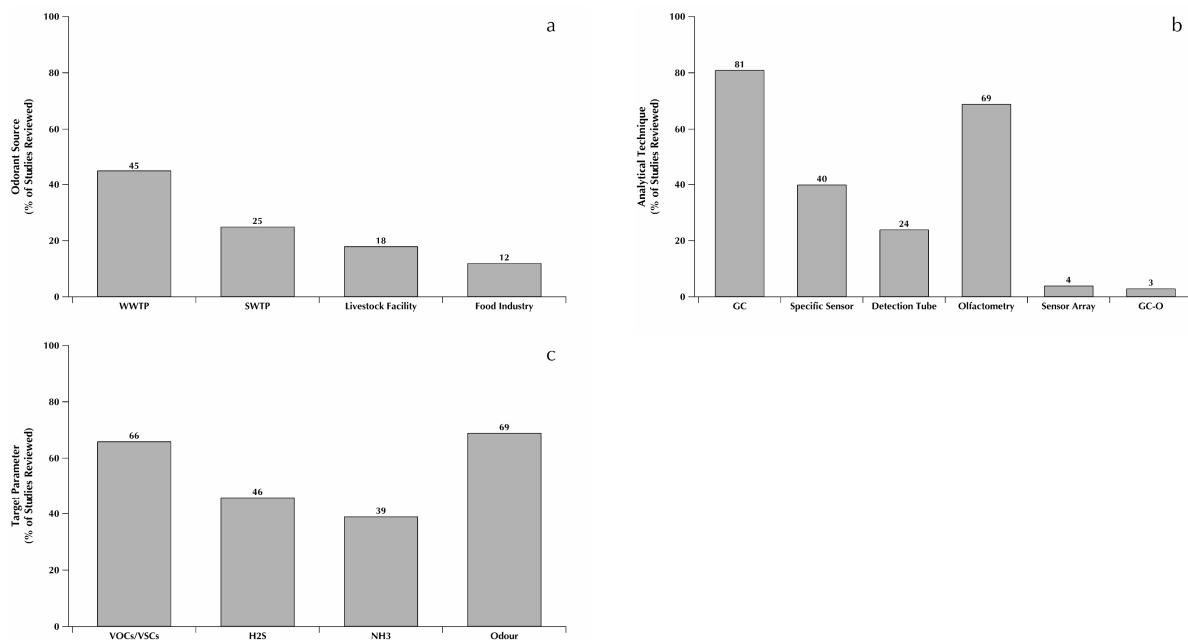


Figure 20 Odour abatement monitoring for full and pilot scale processes; source types (a), analytical techniques employed (b) and target parameters (c).

Gas chromatography and dynamic olfactometry were the most frequently applied analytical technique for odour abatement process monitoring, employed in 81% and 69% of the performance evaluations, respectively (**Figure 20b**). This was expected since these two measurement techniques provide the most valuable data in terms odour policy compliance (when coupled with odour dispersion models), along with specific odorant removal efficiencies. Applications of specific sensors and detection tubes were also well represented in the reviewed literature, being employed in 40% and 24% of the studies, respectively. The use of non-specific gas sensor arrays and GC-O was incidental and always complementary to one of the two major process monitoring techniques. As expected from the wide use of GC and dynamic olfactometry, VOCs/VSCs (66%) and odour concentrations (69%) were the

major parameters measured (**Figure 20c**).

GC-based analysis of VOCs and VSCs was relatively evenly distributed amongst the individual techniques, with no single technique dominating (**Figure 21a**). Application of photoionization detectors and detection tubes were in the minority (12% combined), likely due to their poor specificity and limited range of odorants analysed, respectively.

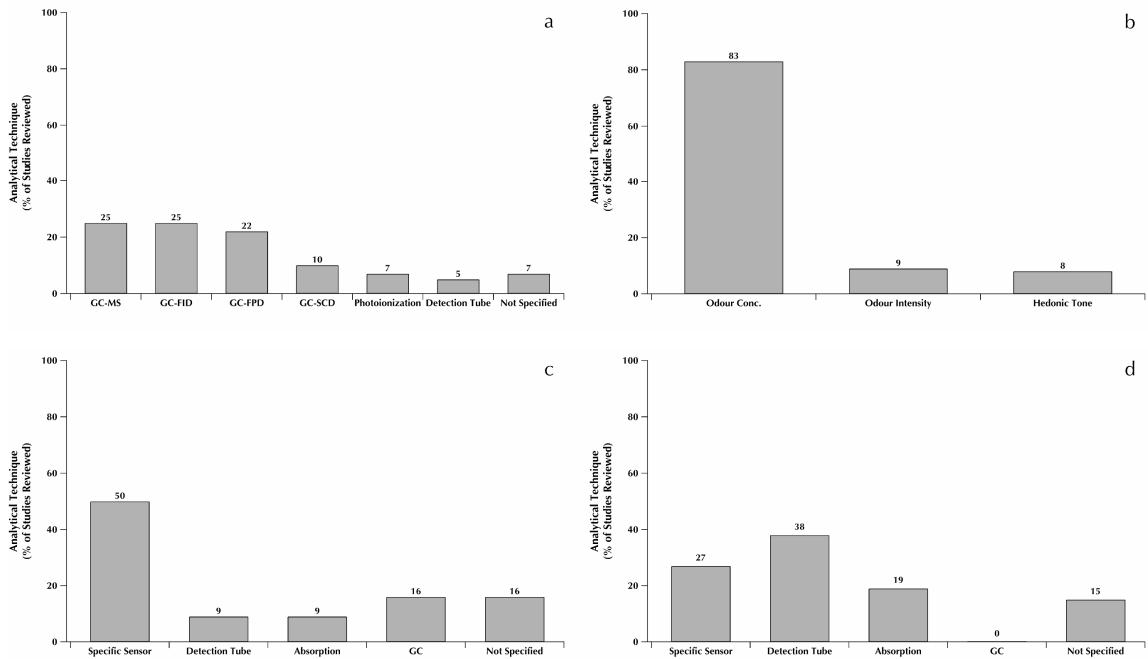


Figure 21 Distribution of the analytical techniques employed to monitor VOCs/VSCs (a), odour (b), H₂S (c), and NH₃ (d) in field and pilot-scale odour abatement processes.

With most environmental odour regulations being based on odour concentrations, odour concentration was (as expected) the most commonly applied sensorial technique, used for 83% of the reviewed applications of sensorial analysis (**Figure 21b**). Odour concentration measurements were often (52%) carried out in accordance with existing protocols (34% and 18% in accordance with the European standard EN 13725 and the American ASTM standard E679, respectively). However, in many of the reviewed studies (39%), no reference to an analytical standard being utilised for the work was provided, and as a result the conclusions drawn from the odour concentration data in these studies must be interpreted with care. The determination of odour intensity and hedonic tone were in the minority (17% of sensorial

analysis applications, combined), and were always associated with odour concentration analysis.

H₂S analysis was relatively common, being utilised in 46% of the reviewed studies (**Figure 20c**). It should once again be noted that these results are based on work conducted from a research perspective (and not necessarily a routine monitoring perspective), and it is expected that H₂S analysis would have a significantly higher utilisation in practice at full scale installations for routine monitoring. Specific sensors were the dominant H₂S analysis technique (similar to the reviewed laboratory scale studies), being employed in half (50%) of the reported H₂S analysis applications (**Figure 21c**). Overall, the use of detection tubes, GC approaches and absorption based methodologies for the determination of H₂S were in the minority, a reflection of the cost effectiveness and ease of use of existing specific H₂S sensors.

NH₃ monitoring was employed in 39% of the reviewed studies (**Figure 20c**). Unlike for H₂S monitoring, there was a more even distribution of the employed analytical techniques (**Figure 21d**), with detection tubes playing a major role (38% of reported NH₃ analyses).

Overall, despite their complexity and higher cost, GC and dynamic olfactometry analysis were the dominant monitoring techniques applied for full scale odour abatement processes. This is likely due to the relevance of the data provided with regards to demonstrating compliance with environmental odour legislation and characterising removal performance from a chemical viewpoint. This trend in monitoring is in contrast to that for laboratory scale monitoring, where budget restrictions and the fundamental nature of the research results in the use of more odorant specific measurement techniques such as electrochemical sensors and GC-FID methodologies.

5.0 Laboratory Based Assessment – Liquid Samples

Up to this point, this review has focused on direct analysis of odours. That is, the analysis of odorants which are already in the gas phase. While direct assessment of odorants already in the gas phase is extremely useful from a compliance monitoring perspective (and is the dominant measurement technique), limitations exist with regards to the application of this monitoring in sewer systems. In particular, sampling from manholes can be difficult and erratic due to the inability to continuously determine whether the air at the respective manhole is leaving or entering the sewer system (Frechen 2008).

The primary rationale driving liquid phase analysis is the understanding that the emission rates of odorants to the gas phase are governed by physical parameters (such as turbulence, temperature and size of the gas-liquid interface) and the odorant concentration in the liquid phase (Frechen and Köster 1998; Frechen 2008). In situations such as in sewer systems and WWTPs where the physical aspects are generally fixed, the concentrations of odorants in the liquid phase are the dominant factor controlling odorant emission rates (Frechen and Köster 1998; Frechen 2008). Thus liquid phase analysis offers potential advantages with regards to the identification of specific liquid streams/sources responsible for odorant emissions and allows directly evaluation of liquid phase odour abatement effectiveness (Frechen 2004).

Several methodologies have been proposed over the last 20 years, primarily based on sparging a liquid sample with a gas to transfer odorants to the gas phase , from which a sample is collected and analysed using the techniques discussed in **Section 4.0**. Initial work in the early 1990s by Koe and Tan (1990) focused on an odorant emission rate based technique called Odour Generation Potential (OGP). While this technique can provide a peak emission rate (essentially a stripping rate), the rates themselves are entirely dependent on physical parameters (for example bubble patterns and sparging intensity) and would have poor transferability to real systems. Frechen (2008) discussed a second early liquid phase odorant analysis technique developed in 1989 by Köppke that was based upon heating a liquid sample to 60 °C to volatilise the odorants. Not only would heating the sample alter the character of the odour in the headspace above the liquid, but could result in chemical

transformation of individual odorants. Both of these techniques have since fallen out of favour and liquid phase analysis is dominated by net emission based techniques.

The Odour Potential technique developed by Hobson (1995) represented a movement towards a net emission measurement to allow for broader applicability of the results. In this method, a volume of air is sparged through a liquid phase sample in a loop until equilibrium is reached, after which a sample of the air is collected for analysis to determine the odour concentration. This method indeed provides a good representation of the net odorants present in the sample, although recycling the air sample until equilibrium is reached limits the ability of this method to represent the character of the odorant emissions since the method would artificially enrich the sample with less volatile odorants.

Net emission based techniques have seen continued development in recent years, primarily as a sparging method referred to as Odour Emission Capacity (Frechen and Köster 1998; Frechen 2004; Frechen 2008) which will be discussed in **Section 5.1**, and as a volatilisation based method (Odour Emission Ability), discussed in **Section 5.2**.

5.1 Odour Emission Capacity

Odour Emission Capacity (OEC) relates the emittable mass of odorants in a liquid sample to its volume, and has been defined by Frechen and Köster (1998) as "...the total mass of odorants, expressed in ou/m³_{liquid}, which can be stripped from 1 cubic meter of liquid under given, standardised conditions". The use of standardised physical conditions eliminates the influence of physical parameters such as interface area, providing a measurement that is purely dependent on the odorant content of the sample.

OEC measurements are conducted using a test reactor (**Figure 22**) containing a 30 L liquid sample with specified geometry and aerator characteristics (Frechen and Köster 1998). Immediately after filling/sealing, the sample is aerated and off-gas samples are collected at regular intervals for odour analysis via dynamic olfactometry (Frechen and Köster 1998). Typical test duration is on the order of 40 minutes to 1 hour, based on an endpoint of 100 ou/m³ (selected to reflect odorant concentrations inherent in the apparatus and technical limitations in odour abatement technologies), although since the dynamic olfactometry measurements are conducted offline the actual test duration is subjective and typically based on operator experience (Frechen and Köster 1998). The sample's OEC is determined by integrating the area between the measured odour concentrations and the lower limit (100 ou/m³) over the amount of air in linear scale (**Figure 22**) and then standardising the result to 1 m³ of liquid (Frechen and Köster 1998).

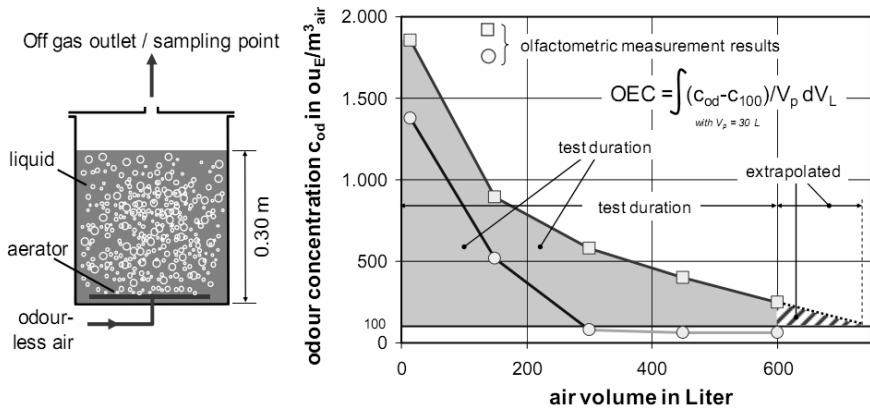


Figure 22 OEC test reactor (left), calculation of OEC from test data (right). Reproduced from Frechen (2008).

Odour based monitoring is a departure from the more prevalent H₂S based monitoring that has been the primary technique applied in sewer systems due to its relative simplicity. However, while the presence of H₂S is an indicator of an odour, its absence does not indicate the converse, thus the application of an odour based monitoring technique offers significant advantages in scenarios where H₂S is not a dominant odorant, for example in areas where industrial sources are discharged into sewer systems (Frechen 2008). It should be noted that since this technique generates a gas phase sample, the potential exists to further enhance this method through the application of other instrumental analysis techniques such as GC and GC-O analysis.

The OEC technique has been used extensively over the last 10 years for a range of industries from WWTPs and sewer systems to food processing, paper, and chemical industries (Frechen and Köster 1998; Frechen 2008). OEC measurements from WWTPs and sewer systems can vary strongly based upon the sample type and source (**Figure 23**), and based on a bank of over 100 measurements, Frechen (2008) identified an average OEC for domestic wastewater of 90,000 ou/m³, with a moderate odour load being in the range of 20,000 ou/m³, and concluded based upon typical conditions near sewers that the OEC should not exceed 50,000 ou/m³. An OEC below 5,000 ou/m³ has been identified for domestic wastewater as not having significant odour problems.

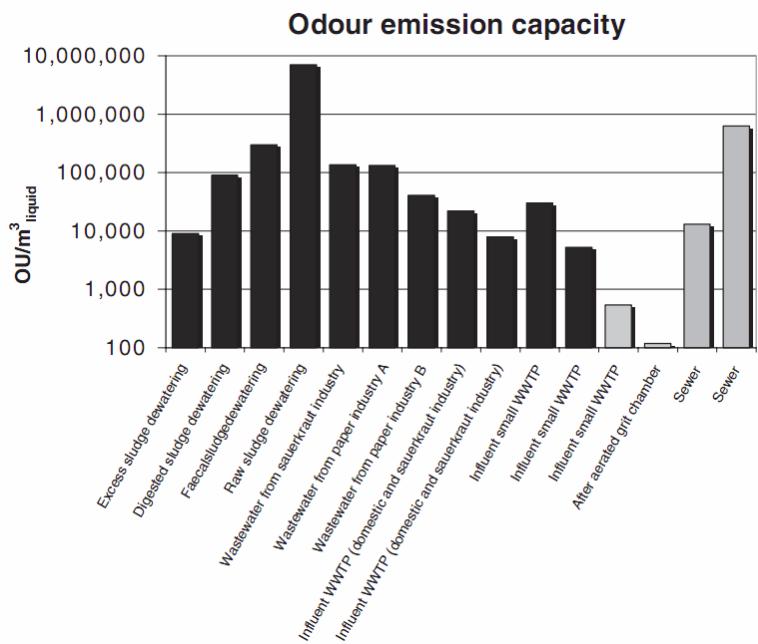


Figure 23 Wastewater OEC measurements, reproduced from (Frechen, 2004).

OEC measurements have been applied for a wide range of odour abatement applications to identify high odour liquid streams to prioritise treatment, evaluate liquid phase treatment effectiveness, and optimise treatment doses (Frechen 2008). It has also been used in Germany to set legally enforceable discharge standards for users discharging to sewer systems (Frechen 2008)

More recently, there has been interest in the application of automated OEC measurement devices (using a non-specific gas sensor array and liquid phase sulfide measurements in place of traditional dynamic olfactometry) for online control of liquid phase odour control dosing (Frechen 2008). However, a need remains for long-term studies to address the impacts of existing limitations in non-specific gas sensor arrays (**Section 3.2.3**) such as long term stability, sensor aging, and sensitivity to environmental parameters such as changes in humidity and temperature.

5.2 Odour Emission Ability

The OEC technique, while quite useful and generating interesting data, is somewhat complex with regards to the testing vessel and sampling regime. The Odour Emission Ability (OEA) technique was developed at the University of New South Wales to provide similar type of high quality odorant data but using a much simplified approach.

Instead of a sparging based method to strip the odorants form the liquid sample (such as for OEC), a small (100-200 µL) sample is injected into a 12 L odour bag filled with high purity nitrogen. The liquid sample is allowed to evaporate at ambient temperature, allowing all of the contained odorants to enter the gas sample which is well mixed prior to analysis. This gas sample can then be analyzed via the techniques discussed in **Section 4.0** (e.g. GC, GC-O, or dynamic olfactometry). It should be noted that the specific sample and odour bag volumes are selected based upon the appropriate concentration ranges for the analytical method being employed.

Liquid samples are collected in 5 mL sealed sample vials, compared to 30 L samples used for OEC testing. This smaller sample size allows for significantly easier (and less expensive) transportation from the sampling site to the laboratory for analysis. Furthermore, the OEA methodology reduces the number of analyses required per measurement, which correspondingly reduces analysis costs and laboratory time demands, allowing for more replicates and quality assurance/quality control samples to be run.

The OEA method has seen some initial application in assessing the effectiveness of liquid phase odorant treatment for food processing wastewater. This technique, however, remains an emerging technique and additional validation trials are required to further its development and acceptance.

6.0 Conclusion - Gaps and Future Work

A review of existing and emerging odour assessment techniques was conducted. Through this review, strengths, limitations and existing knowledge gaps for a range of odour/odorant monitoring techniques have been identified and assessed. A summary is provided as **Table 13.**

With each technique having different strengths and limitations, and considering the variability in chemical character of odorous emissions, no single analytical technique can be applied universally for the measurement of odours from sewers and abatement processes. The sensory and analytical techniques currently used to characterise odours must be regarded as complementary rather than mutually exclusive since the information provided by each technique will cover different monitoring needs for odour abatement processes.

Based upon the literature, GC and dynamic olfactometry represented the most widely used odorant monitoring techniques for pilot and full scale applications, suggesting a disconnect between monitoring conducted for research purposes and more practically oriented monitoring conducted by the wastewater industry, where specific sensor H₂S monitoring is by far the dominant monitoring technique employed for odour abatement processes. While specific sensor H₂S monitoring is cost effective and performs well in many applications, in situations where H₂S is not the dominant odorant (or the presence of significant interfering substances) this form of monitoring is of limited benefit. The need thus exists to provide more information rich monitoring techniques (particularly those allowing the identification of key odorants and interferents of concern) to the industry in a cost effective manner to enhance odour abatement process selection, design and performance assessment.

Table 13 Summary of odour/odorant assessment techniques.

Technique	Strengths	Limitations	Knowledge Gaps
Specific Gas Sensors	<ul style="list-style-type: none">• Ease of operation• Portability• Low cost per analysis• Rapid results• Industry acceptance	<ul style="list-style-type: none">• Specific compounds monitored, of limited value if key odorants in system change• Limited range of monitoring parameters of interest (few odorants)	<ul style="list-style-type: none">• Sensor cross sensitivity and interferences• Impact of moisture poorly understood• Dependence on manufacturer data, no independent reviews of instruments (calibration requirements, operating costs, maintenance, reliability)
Field Olfactometers	<ul style="list-style-type: none">• Portability• Rapid results (odour concentration)• Low cost per analysis	<ul style="list-style-type: none">• Subjectivity• High training requirement• Does not provide odour character information and cannot discriminate between sources	<ul style="list-style-type: none">• Activated carbon filter effectiveness
Online Sensors (Specific Gas)	<ul style="list-style-type: none">• Ease of operation• Suitable for online monitoring and process control• Low cost per analysis• Rapid results• Industry acceptance	<ul style="list-style-type: none">• Specific compounds monitored, of limited value if key odorants in system change• Limited range of monitoring parameters of interest (few odorants)	<ul style="list-style-type: none">• Sensor cross sensitivity and interferences• Impact of moisture poorly understood• Dependence on manufacturer data, no independent reviews of instruments (calibration requirements, operating costs, maintenance, reliability)
Non-specific Gas sensor arrays	<ul style="list-style-type: none">• Cost effective• Continuous odour monitoring	<ul style="list-style-type: none">• Sensitive to environmental factors• Instrument not sufficiently sensitive to reach the human odour annoyance threshold• High expertise requirements	<ul style="list-style-type: none">• Standardisation of data analysis• Techniques to compensate for environment parameters, sensor ageing, sensor drift, and wastewater matrix changes
Qualitative Sensorial Odour Analysis (OPM)	<ul style="list-style-type: none">• Odour character information provided	<ul style="list-style-type: none">• Limited history of application in wastewater industry	<ul style="list-style-type: none">• Database of observations and linkage of key odorants/descriptors to common sources for the wastewater industry

Table 13 Summary of odour assessment techniques (continued).

Technique	Strengths	Limitations	Knowledge Gaps
Quantitative Sensorial Odour Analysis (Dynamic Olfactometry)	<ul style="list-style-type: none">Allows verification of compliance with standards/regulationsStandardised analysis technique	<ul style="list-style-type: none">Low accuracy/reproducibilityBinary result, does not provide character information or identification of odorantsNot applicable for ambient sampling	<ul style="list-style-type: none">Limited information on odorant transformation/loss during sample collection and storageGuidelines for sample collection and storage
Gas Chromatography	<ul style="list-style-type: none">Identifies odorants and interferencesQuantitative analysisFlexible technique	<ul style="list-style-type: none">Does not provide confirmation of odorantsHigh expertise requirements and equipment cost	<ul style="list-style-type: none">Degradation and transformation of odorants during analysisSorbent performance (range of odorants captured and capture efficiency)Limited information on odorant transformation/loss during sample collection and storageGuidelines for sample collection and storage
Combined Gas Chromatography and Olfactory Analysis	<ul style="list-style-type: none">Allows identification and confirmation of odorantsIdentifies interferencesQuantitative analysisFlexible technique	<ul style="list-style-type: none">High expertise requirements and equipment costLack of standardised methods	<ul style="list-style-type: none">Degradation and transformation of odorants during analysisSorbent performance (range of odorants captured and capture efficiency)Limited information on odorant transformation/loss during sample collection and storageGuidelines for sample collection and storageStandardised analysis methodology

Regardless of the monitoring techniques employed, the sampling component of the analysis chain remains a source of weakness due to the continued existence of significant knowledge gaps. In particular, there exists a lack of standardised sampling methodologies, as well as knowledge gaps with regards to the fate and transformation of odorants in sample containers (in particular during sample transport and storage), as well as odorant transformation during analysis. Further research and development is required to address these issues.

Existing liquid phase odour analysis techniques were reviewed, in particular the Odour Emission Capacity (OEC) and Odour Emission Ability (OEA) techniques. The application of these techniques could enhance and simplify the assessment of liquid phase odour abatement treatment performance and provide an efficient means of identifying potential odorants of concern in liquid phase streams. While the OEC technique has been well established, the OEA technique potentially offers significant advantages including reduced analysis cost and time, and providing more relevant information through odorant identification and quantification. However, the OEA technique remains an emerging technique and additional validation trials are required to further its development and acceptance.

Overall, there has been substantial development in recent years with regards to analytical techniques for odorant analysis. It is anticipated that these techniques will be further enhanced as the result of continued technological development, and their adoption to allow the identification of key odorants will play a significant role in future improvements in the selection, design and management of odour abatement processes.

SP3 will focus on addressing several of the knowledge gaps (**Table 13**) associated with quantitative sensorial odour analysis (dynamic olfactometry) and GC-based analysis (including combined GC and olfactory analysis). Experimental work conducted in SP3 will lead to several deliverables that will contribute to addressing these knowledge gaps, in particular:

- characterisation of odour/odorant transformation/loss during sample collection and

storage;

- evaluation of the degradation and transformation of odorants during analysis;
- assessment of sorbent performance (range of odorants captured and capture efficiency);
- development of a standardised analysis methodology for GC based analysis; and
- preparation of guidelines for sample collection and storage for both dynamic olfactometry and GC-based analysis.

Addressing the knowledge gaps related to specific sensors and online sensors (sensor cross sensitivity and interferences, the impact of moisture, and lack of independent instrument reviews) is beyond the existing scope of SP3. Given that these parameters can have a strong impact on the accuracy/quality of monitoring data and that these instruments are widely used in the wastewater industry for H₂S monitoring, the industry would benefit from these knowledge gaps were addressed.

7.0 References

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Appendix A

Odour Abatement Monitoring Summary Tables

Table A-1 Laboratory Scale Odour Abatement Process Measurement Technique Survey

Abatement Process	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
9 mm Cuvette Sewage-based Activated Carbon	-	H ₂ S: Photo-ionization detector	-	-	-	Ros et al. (2007)
0.136 Sludge-Based Char Column	-	H ₂ S: GC-TCD	-	-	-	Ros et al. (2006)
0.08 L Activated Carbon Bed	COS: Specific sensor	H ₂ S: Specific sensor NH ₃ : Specific sensor	-	-	-	Sattler and Rosenberk (2006)
0.06 Activated Carbon Biofilter	-	H ₂ S: Specific sensor	-	-	-	Jiang et al. (2008)
4.5 L Activated Carbon and Compost Biofilter	VOCs: GC-MS	H ₂ S: Specific sensor	-	-	-	Webster et al. (1996)
0.1 L Activated Carbon Biotrickling Filter	GC-FID	-	-	-	-	Kirchner et al. (1989)
37.5 m ³ Compost Biofilter	GC-MS Electrochemical sensor	H ₂ S: Specific sensor NH ₃ : Detection tubes	-	-	-	Hort et al. (2009)
12 L Proprietary Packing Media Biofilter	-	H ₂ S: Specific sensor NH ₃ : Absorption	-	-	-	Gaudin et al. (2008)
26.L Pine Wood Chip Biofilter	VOCs: GC-FID	NH ₃ : Specific sensor	-	-	-	Cabrol et al. (2008)
1 L Biofilter	VOCs: GC-FID	-	-	-	-	Tsang et al. (2008)
6.3 L Coconut Fibre Biofilter	-	NH ₃ : Specific sensor	-	-	-	Baquerizo et al. (2007)
3.4 L LavaRock biofilter	-	H ₂ S: Specific sensor	-	-	-	Limpaseni and Rattanamuk (2007)

Table A-1 Laboratory Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
1.7 L Lava Rock Biofilter	VOCs: GC-FID	H ₂ S: Specific sensor	-	-	-	Ramirez-Saenz and Garcia-Peña (2007)
230 L Wood Bark Biofilter	GC-FID	-	-	-	-	Andres et al. (2006)
7.2 L Compost Biofilter	-	NH ₃ : Specific sensor	-	-	-	Pagans et al. (2005)
0.1 L Ca-alginate beads Biofilter	-	H ₂ S Detection tubes & Specific sensor NH ₃ Detection tubes & Specific sensor	-	-	-	Chung et al. (2000)
0.7 L Compost/Hog Fuel Biofilter	CH ₃ SH Detection tubes	H ₂ S: Detection tubes	-	-	-	Wani et al. (1998)
19 L yard waste compost Biofilter	-	H ₂ S: GC-FPD	-	-	-	Yang & Allen (1994)
Alginate Packed Bed Biofilter	CH ₃ SH: GC	H ₂ S: GC	-	-	-	Pinjing et al. (2001)
1 L Polyurethane Foam Biotrickling Filter	-	H ₂ S Specific sensor NH ₃ : Specific sensor	-	-	-	Ramirez et al. (2009)
42 L Mesh Wire Packing Biotrickling Filter	HPLC-UV	H ₂ S: Specific sensor	-	-	-	Couvert et al. (2008)
1.1 L Glass Raschig Ring Biotrickling Filter	-	H ₂ S: GC-FPD	-	-	-	Bailón-Allegue (2007)
1 L Polyurethane Foam Biotrickling Filter	-	NH ₃ : Specific sensor	-	-	-	Ramirez et al. (2007)

Table A-1 Laboratory Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	VOCs/VSCs	H2S/NH3	Dynamic Olfactometry	GC-O	Sensor Array	Reference
HD-QPAC® Biotrickling Filter	-	H ₂ S: Specific sensor	-	-	-	Fortuny et al. (2007)
6.4 L Activated Carbon Biotrickling Filter	-	H ₂ S: Specific sensor	-	-	-	Duan et al. (2005)
4-L Raschig Rings Biotrickling filter	-	H ₂ S: Absorption	-	-	-	Jha and Bliss (2001)
10 L PP Pall Ring Biotrickling Filter	-	H ₂ S: Specific sensor	-	-	-	Wu et al. (2001)
0.6 L Packed Chemical Scrubber	GC-MS	-	Odour Conc.: VDI-Guideline 3881	-	-	Freudenthal et al. (2005)
LO/PRO a 3 -stage Chemical Scrubber	-	H ₂ S: Not specified	-	-	-	Strzelecki (2001)
0.8 L Chemical Scrubber	VOCs & VSCs: GC-FID & GC-FPD	NH ₃ : GC-FPD	Odour Conc.: method not specified	GC-MPD-O	-	Pope et al. (1981)
0.06 L Packed Scrubber	CH ₃ SH: Sensor	H ₂ S: Specific sensor	-	-	-	Sanchez et al. (2006)
10 L Ceramic Packed Bed Reactor	-	NH ₃ : Absorption	-	-	-	Melse and Mol (2003)
33.4 L TiO ₂ Photoreactor	-	H ₂ S: Specific sensor	-	-	-	Li et al. (2006)
0.2 L TiO ₂ Photocatalytic Reactor	VOCs: GC-FID C ₂ S: Sensor	-	-	-	-	Upadhyay (2006)

Table A-1 Laboratory Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
1 L TiO ₂ -AC Glass Reactor	CH ₃ SH: Detection tubes	H ₂ S: Detection tubes NH ₃ : Detection tubes	-	-	-	Nozawa et al. (2001)
0.405 L TiO ₂ /UV Photoreactor	-	H ₂ S: Absorption	-	-	-	Canela et al. (1998)
230 L Pall Ring / Structure Packing Scrubber	CH ₃ SH: GC-Electrochemical detector	H ₂ S: GC-Electrochemical Detector	-	-	-	Charron et al. (2004)
0.24 L Dielectric Barrier Reactor	-	H ₂ S: Specific sensor NH ₃ : Absorption	-	-	-	Chang et al. (1996)
0.8 L Annular Photoreactor	GC-FID Online GC-MS/MS	-	-	Flavor Profile Analysis	-	Canela et al. (1999)
UV-Photocatalytic Reactor	VOCs: GC-MS	H ₂ S: GC-MS	Odour Conc.: method not specified	MD-GC-MS-O	-	Koziel et al. (2008)
36 L wire-plate pulse corona reactor	VOCs: GC	NH ₃ : Detection tubes	-	-	-	Ruan et al. (2005)
2800 V 20 m ³ /h Ionization Purifier	VOCs: GC-MS & FID	-	-	-	-	Steinberg et al. (2005)
PVDF Hollow Fiber Reactor	-	H ₂ S: Specific sensor	-	-	-	Tan et al. (2005)
0.84 m ² PP Hollow Fiber Membrane Reactor	-	H ₂ S: Detection tubes NH ₃ : Detection tubes	Odour Conc.: EN 13725	-	Quartz Microbalance Sensors	Willers et al. (2003)
0.4 L Polydimethyl Siloxane Membrane Reactor	Dimethyl sulfide: GC-FID	-	-	-	-	De Bo et al. (2002)
12 L Activated Sludge Reactor	-	H ₂ S: Specific sensor	-	-	-	Hardy et al. (2001)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
72 L Activated Carbon Biofilter	Pig Farm	VSCs: GC-FID Methanethiol: GC-FPD	H ₂ S: GC-FPD	Odour Concentration: method not specified	-	-	Ho et al. (2008)
Biofilter	SWTP	-	-	Odour Concentration: EN13725	-	Metal Oxide Sensors	Sironi et al. (2007b)
Biofilters	SWTP	Protron Transfer Reaction-MS	-	Odour Concentration: method not specified	-	-	Biasoli et al. (2004)
Biofilter	Rendering Plant	VOCs: GC-MS, GC-FID	-	Odour Concentration: EN 13725	-	-	Defoer et al. (2002)
Biofilters	WWTP	VOCs: GC- FID VSCs GC-FPD	H ₂ S: Specific sensor	Odour Concentration: ASTM E-679	-	-	Easter et al. (2008)
5 - 1.1 m ³ Biofilters	Pig farm	-	-	Odour Concentration: EN 13725	-	-	Hartung et al. (2001)
1500 m ³ Biofilter	SWTP	Not specified	-	Odour Concentration: method not specified	-	-	Phillips (2009)
24 m ³ Biofilter	Anaerobic WWTP	Not specified	H ₂ S: Not specified	Odour Concentration: method not specified	-	-	Phillips (2009)
3 m ³ 3-Stage Biofilter	SWTP	VOCs: GC-MS VSCs: GC-MS	H ₂ S: Detection tubes NH ₃ : Detection tubes	-	-	-	Chung et al. (2003)
12 m ³ Ceramic Biofilter	SWTP (Compost)	VSCs: GC-FPD	H ₂ S: GC-FPD NH ₃ : Detection tubes	Odour Concentration: method not specified	-	-	Park et al. (2001)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
23 m ³ Porous Ceramic Carriers Biofilter	WWTP	VSCs: GC-FPD	-	-	-	-	Shinabe et al. (1995)
1 m ³ Polystyrene/Peat moss Biofilters	Animal Farm	-	H ₂ S: Specific sensor NH ₃ : Detection tubes	Odour Concentration: method not specified Hedonic tone	-	-	Armeen (2006)
35-120 m ³ Scoria-Soil Biofilters	WWTP	-	-	Odour Concentration: EN13725	-	-	Sharma (2001)
150 m ³ Proprietary Media Biofilter	WWTP	-	H ₂ S: Specific sensor	Odour Concentration: EN 13725	-	-	Frechen et al. (2007)
Biofilter & Compost Heaps	SWTP	-	-	Odour Concentration: EN13725	-	Metal Oxide Sensors	Sironi et al. (2007c)
27 L Compost Biofilter	Pig Farm	-	NH ₃ : Absorption	-	-	-	Poulsen and Moldrup (2007)
200 L Compost Biofilter	SWTP (Compost)	-	NH ₃ : Not specified	-	-	-	Park et al. (2002)
180 L Compost Biofilter	SWTP	TVOCs: Photoionization VOCs: GC-MS	-	-	-	-	Liu et al. (2009)
42 m ³ Compost Biofilter	SWTP	-	H ₂ S: Absorption	-	-	-	Rands et al. (1981)
272 m ³ Compost Biofilter 19 m ³ Chemical Scrubber	WWTP	VOCs: GC-FPD VSCs: GC-FPD	H ₂ S: Specific sensor	-	-	-	Gao et al. (2001)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
0.2 m ³ Compost/Activated Carbon/Sludge Biofilter	SWTP	VOCs: GC-FID VSCs: GC-FPD VNCs: GC-PID	-	Odour Concentration: method not specified	-	-	Chung (2007)
0.5 m ³ Compost/Perlite/Oyster Shell Biofilter	WWTP 1 400 000 m ³ /d	VOCs: GC-FPD & GC-FID VSCs GC -SCD	H ₂ S: Specific sensor	Odour Concentration: method not specified Odour Intensity	-	-	Converse et al. (2003)
340 m ³ Mulch/Bark Biofilter	Poultry- Rendering Facility	VOCs: GC-MS VSCs: GC-MS	-	-	-	-	Kastner and Das (2005)
18 m ³ Straw Biofilter	WWTP	Specific sensor	H ₂ S: Specific sensor NH ₃ : Specific sensor	-	-	-	Xie et al. (2009)
258 m ³ Root Wood Biofilter	Anaerobic WWTP	VSCs: GC-FPD	H ₂ S: Detection tubes NH ₃ : Detection tubes	-	-	-	Shanchayan et al. (2006)
2000 m ³ Root Wood Biofilter	SWTP	GC-MS	NH ₃ : Detection tubes	Odour Concentration: VDI guideline 3881 & EN 13725	-	-	Schlegelmilch et al. (2005)
0.28 m ³ Bark/ Soil/Bark Biofilter	WWTP	-	-	Odour Concentration: NVN2820	-	-	Luo (2001)
0.21 m ³ Pine Bark Biofilter	Rendering Plant	-	-	Odour Concentration: 1990 Dutch Pre-Standard for Sensory Odour Measurement using an Olfactometer	-	-	Luo and Lindsley (2006)
2.8 m ³ Shredded Wood/Bark/Compost Biofilter	WWTP	VOCs :GC-FID VSCs GC-FPD	NH ₃ : Detection tubes	Odour Concentration: ASTM E-679-544	-	-	Amirhor et al. (1997)
166 m ³ Wood Chip Biofilter	WWTP	-	H ₂ S: GC-FPD and Specific sensor	-	-	-	Zhuang et al. (2001)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
55 m ³ Wood Chips Biofilter	Pig Farm	-	NH ₃ : Detection tubes	Odour Concentration: EN13725 Hedonic Tone: VDI 3882	-	-	Riis (2007)
264 m ³ Woodchips Biofilter	WWTP	GC-FID	H ₂ S: Specific sensor	-	-	-	Chitwood et al. (1999)
125 L Wood Chips Biofilter	Pig Farm	GC-FID	H ₂ S: Specific sensor NH ₃ : Specific sensor	Odour Concentration: ASTM standard E679-04	Direct Intensity Method	-	Chen et al. (2009)
0.2 m ³ Wood Chips Biofilter	Pig Farm	VSCs: GC-FPD	NH ₃ : Specific sensor	Odour Concentration: EN-13725 Odour Intensity: VDI 3882	-	-	Sheridan et al. (2002)
164 m ³ & 74 m ³ Wood Chips Biofilter	SWTP	VOCs: GC-FID	NH ₃ : Specific sensor	-	-	-	Colon et al. (2009)
25 m ³ Wood Chips Biofilters	WWTP	-	H ₂ S: Specific detector	[Odour Concentration: ASTM E679-91 Odour Intensity: ASTM E544-75/88	-	-	Cooper (2001)
800-150 m ² Wood Chips/Compost Biofilter	SWTP 120000 tn/year	-	-	-	-	-	Schulz and McAll (2007)
18- 110 L Wood Chips/Compost Biofilters	Pig Farm	-	NH ₃ : Absorption H ₂ S: Specific sensor	Odour Concentration: method not specified	-	-	Nicolai and Janni (2001)
15 m ³ Wood Chips/Compost Biofilter	Pig Farm	-	H ₂ S: Specific sensor NH ₃ : Detection tubes	Odour Concentration: method not specified	-	-	Debruyn (2000)
212 m ³ Wood-Based Biofilter (BIOMIX™)	Rendering Plant & WWTP	VOCs: FTIR VSCs: GC-FID	NH ₃ : Not specified	Odour Concentration: method not specified	-	-	Shareefdeen (2002)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
0.34 m ³ Biotrickling Filter	WWTP	-	H ₂ S: Not specified	Odour Concentration: method not specified	-	-	Morton and Caballero (1998)
3 m ³ Biotrickling Filter	Pig Farm	-	NH ₃ : Absorption	Odour Concentration: Dutch olfactometric standard method NVN2820/1A	-	-	Melse and Mol (2003)
4 m ³ Inorganic Media Biotrickling filter	WWTP 60 000 p.e	VSCs: GC-Electrochemical detector	H ₂ S: Absorption NH ₃ : Absorption	-	-	-	Patria et al. (2001)
10.5 m ³ Foam Polymer Biotrickling Filter	WWTP	TC-GC-MS	H ₂ S: Specific sensor	Odour Intensity	-	-	Zhukov et al. (2007)
7.3 m ³ Polyurethane Foam Biotrickling Filter	WWTP	VSCs: GC-FPD & GC-SCD	H ₂ S: Specific sensor NH ₃ : Specific sensor	Odour Concentration: method not specified	-	-	Gabriel and Deshusses (2003)
3.8 m ³ PVC Packing Biotrickling Filter	WWTP	VOC: GC-FPD VSCs: GC-SCD	H ₂ S: Specific sensor	Odour Concentration: ASTM E-679-91 & ASTM E-544-99	-	-	Cox et al. (2002)
8.4 m ³ Synthetic Media Biotrickling Filter	Lift-Station	Total Mercaptans: not specified DMDS: not specified	H ₂ S: Not specified NH ₃ : Not specified	-	-	-	Zappi et al. (2004)
5550 m ³ Rock Biotrickling Filter	WWTP 190.00 m ³ d ⁻¹	VOCs: GC-MS VSCs: GC-FPD	H ₂ S: GC-FPD	Odour Concentration: method not specified	-	-	Ponte and Boyd (1995)
400 m ³ Wood Chips/Peat Moss Biotrickling filter	Pig Farm	-	-	Odour Intensity: Suprathreshold Method Hedonic Tone	-	-	Buelna et al. (2008)
400 m ³ Wood Chips/Peat Moss Biotrickling filter	Food Processing Plant	-	-	Odour Concentration: method not specified	-	-	Zolghadr and Rix (2001)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
380 m ³ Bioscrubber	Coffee Bean Roasting	VOCs: GC-MS	-	Odour Concentration: EN 13725	GC-MS-O	-	Ranau (2005)
52 000 m ³ Treatment System - 4 Bioscrubber + 4 AC Filters	WWTP	VOCs: Portable PID CH ₃ SH: Detection tubes DMS: Detection tubes	H ₂ S: Detection tubes	Odour Concentration: AS4323.3	-	-	Finke et al. (2008)
Bioscrubber: 0.2 m ³ Absorption Tower + 1 m ³ Bioreactor	Rendering Plant	VOCs: GC-MS	H ₂ S: Absorption NH ₃ : Absorption	Odour Concentration: Portable olfactometer TECNODOOUR (ASTM E544, VDI 3882 and AFNOR X43-103)	-	-	Turgeon et al. (2008)
12 m ³ Bioscrubber + 11 m ³ Bioreactor- 1.4 m ³ Polishing Filter	WWTP 350 000 p.e.	VSCs: not specified	H ₂ S: Not specified	Odour Concentration: method not specified	-	-	Hansen and Rindel (2001)
2 Stage- Chemical Scrubbers	WWTP	DMS: Detection tubes	NH ₃ : Detection tubes	-	-	-	Muirhead et al. (1993)
290 m ³ 3-Stage Chemical Scrubber	WWTP	GC- Detector not specified	H ₂ S: Not specified	-	-	-	Speth and Card (2004)
Chemical Scrubber	Rendering Plant	VOCs: GC-MS & GC-FID & HPLC VSCs: GC-SCD	-	Odour Concentration: method not specified	-	-	Bokowa and Thorndyke (2003)
Acid Scrubber + Biofilter + Caustic Scrubber	SWTP 15000 tn/year	VOCs: GC-PID	NH ₃ : Specific sensor	-	-	Metal Oxide Sensors	Senante et al. (2008)
Scrubber + Biofilter	Food Processing Plant	VOCs: GC-MS	-	Odour Concentration: EN 13725	-	-	Van Elst and Van Langenhove (2001)

Table A-2 Pilot and Full Scale Odour Abatement Process Measurement Technique Survey (Continued)

Abatement Process	Source	VOCs/VSCs	H ₂ S/NH ₃	Dynamic Olfactometry	GC-O	Sensor Array	Reference
Scrubber	WWTP	VOCs: GC-FID VSCs: GC-FPD	H ₂ S: Not specified NH ₃ : Not specified	-	-	-	Basu et al. (1998)
22 m ³ Scrubber	WWTP	VOCs: GC-MS VSCs GC-MS	-	-	-	-	Myslinski et al. (2000)
Scrubber + Biofilter	SWTP	VOCs: GC-MS	-	Odour Concentration: EN 13725	-	-	Phillips et al. (2003)
12 Wet Scrubber + 2 Biofilter	Metal, Chemical, Petrochemical & Food Industry	-	-	Odour Concentration: EN 13725	-	-	Quadros et al. (2008)
6250 m ³ Air Stripping in Sludge Holding Tank	WWTP 1700000 p.e.	-	-	Odour Concentration: EN13725 Hedonic Tone: VDI 3882:1994	-	-	Winter et al. (2004)
Activated Sludge Diffusion System	WWTP	-	-	Odour Concentration: ASTM E-679	-	-	Ostojic et al. (1992)
Neutralisers and Masking Agents	SWTP	VOCs: GC-FID + HPLC-UV VSCs: GC- Electrochemical detector	H ₂ S: GC- Electrochemical sensor NH ₃ : Specific sensor	Odour Concentration: EN 13725 Hedonic Tone: method not specified	-	-	Decottignies et al. (2007)