D-NOSES

Distributed Network for Odour Sensing,
Empowerment and Sustainability

Review on odour pollution, odour measurement, abatement techniques

D2.1

September 2019

Deliverable

DELIVERABLE REFERENCE NUMBER AND TITLE

D2.1
Review on odour pollution, odour measurement, abatement techniques

Revision: v3.2

AUTHORS

Laura Capelli
Carmen Bax

(POLIMI)

Carlos Diaz
Cyntia Izquierdo

(AMIGO)

Rosa Arias
Nora Salas Seoane

(Ibercivis)

DISSEMINATION LEVEL

✓   **P**   **Public**

    P   Confidential, only for members of the consortium and the Commission Services

Revision History

REVISION	DATE	AUTHOR	ORG...	DESCRIPTION
v1.0	23.08.2019	Laura Capelli	POLIMI	Index and chapters structure
v1.1	05.09.2019	Laura Capelli	POLIMI	Addition of section 2.5
v2.0	06.09.2019	Laura Capelli	POLIMI	First draft with addition of text in section 2
v2.1	10.09.2019	Laura Capelli	POLIMI	Second draft with addition of text in sections 2 and 3
v2.2	12.09.2019	Laura Capelli	POLIMI	Third draft with addition of text in sections 1, 2 and 3
v2.3	19.09.2019	Laura Capelli	POLIMI	Minor edits/ corrections to v2.2
v3.0	26.09.2019	Carmen Bax/ Laura Capelli	POLIMI	Draft with the addition of text regarding relevant applications of

				odour measurement methods + other minor corrections
v3.1	27.09.2019	Laura Capelli	POLIMI	Revision of new text added in v3.0 by Carmen Bax
V3.2	29.09.2019	Rosa Arias	Ibercivis	General revision of the deliverable

STATEMENT OF ORIGINALITY

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Summary

In the frame of the D-NOSES project, in order to reach the goal of creating common scientific guidelines for policy making, it is extremely important to define the scientific framework of odour pollution, by answering fundamental questions about the nature of odour pollution, the ways to measure it, and the methods available to reduce odour impacts. This document provides an up-to-date review of the methods that can be used in order to measure odours (Chapter 2), and the techniques that can be adopted for odour emissions abatement (Chapter 3).

The document is structured in 3 chapters:

Chapter 1. ODOURS & ODOUR POLLUTION: it presents the framework of the D-NOSES project, by introducing the fundamental concepts of odour and odour pollution. Since the definition of odour is strictly connected to perception, a short introduction regarding the human sense of smell (olfaction) is provided. Also the main characteristics for describing an odour are illustrated, which are in turn important to understand the mechanisms for odour annoyance.

Chapter 2. ODOUR MEASUREMENT METHODS: It illustrates the methods that are currently available to assess the presence and quantify odours, with the aim of answering the question "how can odour be measured?". Indeed, this chapter focuses on odour measurement methods, without describing other approaches based on mathematics or literature evaluations. Regarding the structure of this chapter, each method has been described briefly and in simple language by answering the following questions: i) What is it? ii) What can it be used for?, and iii) What can it not be used for?. Each entry has been complemented with some examples of relevant applications as well as a list of links to selected reference articles for further detailed information. Finally, a comparison of the different methods is provided in terms of their applicability and limitations.

Chapter 3. ODOUR ABATEMENT TECHNIQUES: It presents an overview of the methods that can be adopted in order to reduce odour emissions and their impact on the territory. There are several methods available to control odours - all with a variety of advantages, disadvantages and degrees of cost-effectiveness, and there is not a univocal rule to choose the best odour control strategy. This chapter provides an overview of the existing odour abatement techniques, thereby distinguishing between end-of-pipe treatment techniques, which can be applied to reduce the odour concentration emitted by conveyed (or point) sources, and other odour

control methods, which can be applied to odour sources in order to reduce their impact on the surroundings, and are usually also applicable to diffuse emissions. The descriptions of the different techniques have been taken mainly from the European Integrated Pollution Prevention & Control (IPPC) reference document on the Best Available Techniques for waste water and waste gas treatment in the chemical sector, which refers to the abatement of VOCs and other pollutants, and re-adapted to the specific case of odour emissions. At the end of the chapter, a comparison of the different methods is also provided.

Index

1

ODOURS & ODOUR POLLUTION

This section presents the framework of the D-NOSES project, by introducing the fundamental concepts of odour and odour pollution.

1.1 What is an odour?

ODOUR

Odour is a property of a mixture of substances capable of stimulating the olfaction sense sufficiently to trigger a sensation of odour. Odour perception starts in the nasal cavity and ends up with the transmission of a stimulus to the brain, where it may cause pleasant or unpleasant sensations, or even originate physical reactions, due to the involvement of the trigeminal nerve and of the higher levels of the brain.

THE HUMAN SENSE OF SMELL

The sense of smell is a primal sense for humans and animals. From an evolutionary standpoint it is one of the most ancient of senses. Smell (or Olfaction) allows vertebrates and other organisms with olfactory receptors to identify food, mates, predators, and provides both sensual pleasure (the odour of flowers and perfume) as well as warnings of danger (e.g. spoiled food, chemical dangers). For both humans and animals, it is one of the important means by which our environment communicates with us. Despite this importance, olfaction is one of the less known senses: in 2004 R. Axel and L. Buck won the Nobel Prize for their discoveries of "odorant receptors and the organization of the olfactory system".

Odour perception in humans begins with sniffing, which moves air containing odorant molecules past curved bony structures called turbinates. Turbinates create turbulent airflow patterns that carry the mixture of volatile compounds to the thin mucus coating of the nose olfactory epithelium, which is an area of approximately 5 cm^2 in the upper nasal cavity, where the nerve cells that sense odorants are located.

As VOCs pass over the mucus membrane lining the nose, they are trapped by the mucus and diffuse through to the epithelium. The sensory cells in the epithelium are covered in multiple cilia-hair-like structures with receptors located on the cells outer membranes. Olfactory cells are specialized neurons that are replicated approximately every 30 days. The transformation of a molecule into an odour begins when this odorant molecule binds to a receptor protein. This initiates a cascade of enzymatic reactions that result in depolarization of the cell membrane. There are more than 107 protein receptors in all, and about 103 different types. Each receptor type is sensitive to several odorants and each odorant is sensed by multiple olfactory neurons. The sensory cells in the epithelium respond by transmitting signals along neural "wires" called axons. Axons traverse a small hole in a bony structure in the base of the skull, known as the cribriform plate, to reach the olfactory bulb, where they terminate in a cluster of neural networks called glomeruli. The ca. 2000 glomeruli represent the first tier of central odour information processing. All sensory neurons containing a specific odorant receptor are thought to converge on two or three glomeruli in the olfactory bulb. The pattern of response across multiple glomeruli thus gives a first codification of olfactory quality.

The glomeruli are connected in groups that converge into mitral cells. From the mitral cells the message is sent directly to the higher levels of the central nervous system in the corticomedial amygdala portion of the brain (via the olfactory nerve) where the signaling process is decoded and olfactory interpretation and response occurs.

ODOUR CHARACTERIZATION

The following odour components can be defined:
- Odour threshold (concentration): it is the minimum concentration of an odorous substance in order to provoke a given stimulus in humans. They are usually expressed at 50% or 100%, depending on the % of people that perceive the odour. It is important to highlight that odour thresholds are not additive, giving that the odour of odorant mixtures cannot be defined by simply summing the effects of single odorants.
- Intensity: it is a measure of the strength of the odour stimulus, and it can be related to odour concentration by specific mathematical expressions (e.g., Steven's law or Weber Fechner's law), following a logarithmic or exponential relation.
- Diffusivity: An odour can only be perceived when an odorous molecule reaches the olfactory epythelium; for this reason, volatility (expressed as vapour pressure) is a fundamental parameter for the estimation of the capability of a chemical substance to cause an odour. The Odour index is defined as the ratio between the vapour pressure of an odorous compound and its odour threshold.
- Quality: it can be determined by using specific odour classes or descriptors. An example taken from the German guideline VDI 3882-2 (1994) is illustrated in Figure 1.
- Hedonic tone: The hedonic tone is a measure of the pleasantness/ unpleasantness of an odour, which can be expressed in a scale ranging from -4 (extremely unpleasant) to + 4 (extremely pleasant), being 0 an odour that is not perceived neither as pleasant nor unpleasant.
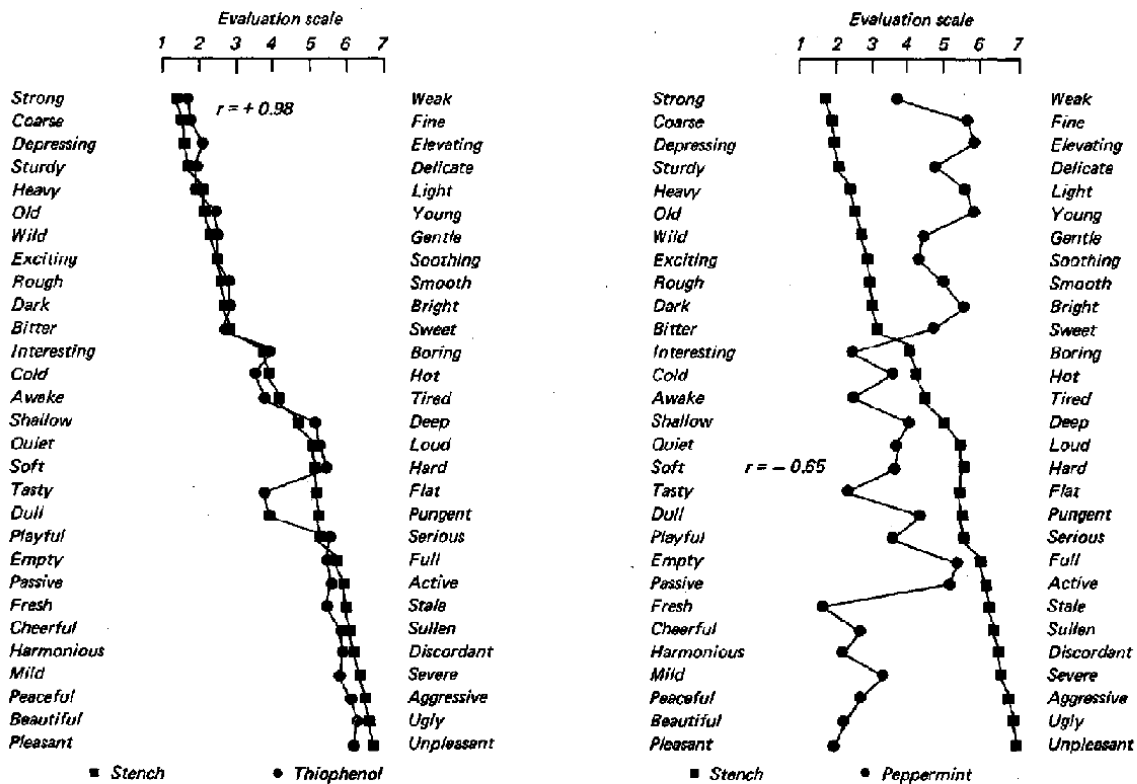
Fig. 1. Evaluation profiles for the odorous stimuli thiophenol and peppermint and their respective associations with the term "stench". The respective profile similarities are highly significant ($r = +0.98$) and significantly negative ($r = -0.65$).

Figure 1: Evaluation profiles for the odorous stimuli thiophenol and peppermint, as reported by the German VDI 3882-2 (1994) "Olfactometry: Determination of Hedonic Odour Tone"

1.2 Odour pollution

Odours are nowadays, among atmospheric pollutants, the major cause of population's complaints to local authorities.

Several conventional pollutants are generally not perceived by population, even if they might be harmful for human health, especially if normal exposure limit concentrations are exceeded.

On the contrary, some odours are perceived far below normal exposure limit concentrations, due to the presence of odorous compounds having extremely low odour detection threshold concentration.

Odour complaints often reflect a fear that odours may involve a health risk, even though this is generally not the case. Indeed, the odour threshold (OT) values for many compounds are much lower than their exposure limits (expressed as time-weighted-average threshold limit value (TWA-TLV)), giving that the dangerous compounds can be smelled at much lower concentrations than those causing adverse effects on health. For instance, the OT for H_2S is lower than 1 ppb, whereas its TWA-TLV is 1 ppm.

Although odorous compounds are not necessarily toxic or hazardous for human health, it is known that odour exposure may cause adverse effects on citizens, and negatively influence their psychophysical well-being and behaviour.

Prolonged exposure to odour can generate undesirable reaction in people, such as unease, discomfort, irritation, anger, depression, nausea, headaches.

Thus, repeated exposure to odour can lead to a high level of annoyance, with the receptor becoming sensitive to the odour, independently of the pleasantness of odour perceived.

For these reasons, odours are nowadays subject to control and regulation in many countries. As a consequence, the need to regulate odour impacts entails the requirement of specific methods for odour measurement and odour impact assessment.

A lot of chemical substances coming from a variety of different activities may originate an odour problem. Environmental odour emissions are generally composed by complex mixtures of hundreds of different compounds.

Annoyance is the complex of human reactions that occurs as a result of an immediate exposure to an ambient stressor (odour) that, once perceived, causes negative cognitive appraisal.

Nuisance occurs when people are affected by an odour they can perceive in their living environment (home, work, recreation) and:

- The perception of the smell is negative;
- The appraisal is repeated;
- It is difficult to avoid the odour;
- The smell is connected (often incorrectly) to a negative effect on health.

If fluctuating concentrations of odour emissions in the field exceed the odour threshold, thus resulting in odour perception, this does not necessarily induce an adverse effect in terms of odour nuisance.

When an individual exposed to odour perceives this as unwanted, it is argued that the following factors are the main determinants (FIDOL factors):

- Frequency of the odour exposure;
- Intensity of the odour;
- Duration of exposure to the odour;
- Offensiveness of the odour;
- Location: Tolerance and expectation of the exposed subject.

Studies of communities exposed to unwanted odour show that exposure can lead to evidence of stress induced symptoms, such as sleep disorders, headaches, respiratory problems, nausea and anxiety.

To better understand the nature of individuals' response to odours, two processes that occur in all sensory system shall be considered:

- **Adaptation**: is a reduction in responsiveness during or following repeated exposure;
- **Sensitization**: is an increase in responsiveness during or after exposure. Individuals who are not particularly sensitive to odours may become sensitized through acute events or as a result of repeated exposure.

2
ODOUR MEASUREMENT METHODS

This section illustrates the methods that are currently available for measuring odours, both at emission and at receptor level. Besides describing the different methods, focus is given on their applicability and limitations.

2.1 Introduction

Odour characterization and measurement have become very important environmental issues, due to the general public's growing awareness of the environment and the impact of air quality on health and well-being, giving that nowadays odours are subject to control and regulation in many countries. Regulating odour impacts entails the necessity of specific methods for odour measurement and odour impact assessment.

However, measuring odours is not a banal issue, since it entails the necessity of objectifying a sensation. For this reason, specific methods shall be adopted for this purpose. In recent decades, several techniques have been studied and developed for the characterization of environmental odours.

This chapter provides an overview of the methods that are currently available for measuring odours, both at emission and at receptor level, thereby focusing on their applicability and limitations.

2.2 Overview of odour measurement methods

Odour measurement methods belong to the wider category of odour impact assessment methods, which also includes mathematical methods, such as dispersion models, which are not discussed here.

Odour measurement methods shall be divided into four categories, depending if:

- they are <u>sensorial</u>, i.e. they use the human nose as the receptor, or <u>instrumental</u>

- they can be applied in order to measure odours at the <u>emission level</u>, i.e. at the odour source, or at the <u>receptor level</u>, i.e. directly where the citizens live and the complaints come from.

Figure 2 schematizes the existing methods for odour impact assessment according to the above described classification.

The following sections of this document focus on the methods for odour measurement, in order to provide an answer to the question "How can odours be measured?".
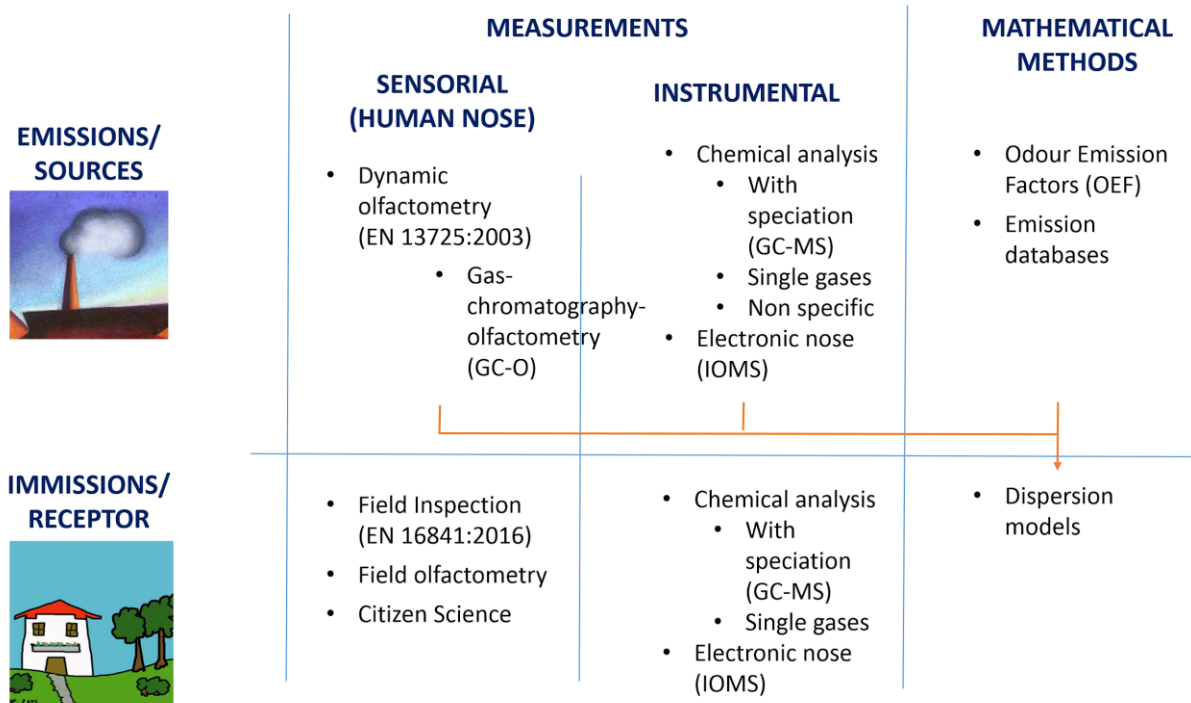
Figure 2: Overview of odour impact assessment methods, both in terms of measurement type, and from the emission or the immission (receptors' perspective) point of view.

2.3 Emission level

DYNAMIC OLFACTOMETRY

What is it? (Method description)

Dynamic olfactometry is a standardised way of measuring odour concentrations using the human sense of smell. It therefore belongs to the so called "sensorial techniques", since the measurement of the odour concentration is related to the sensation caused by the sample directly on a panel of opportunely selected people with a standard sense of smell.

Samples of odorous air are collected at the source of the odour in suitable bags, then they are analysed by diluting them with fresh, odourless or 'neutral' air in decreasing amounts.

The analysis is carried out by presenting the sample to the panel at increasing concentrations by means of a particular dilution device called **olfactometer**, until the panel members can detect an odour that is different from the reference neutral air. The outcome of this measurement is the odour concentration of the sample, which is expressed in European odour units per cubic meter (ou_E/m^3). This represents the number of times the sample has been diluted with neutral (odourless) air to reach its odour detection threshold concentration. Thus, if the sample needs to be diluted 100 times with clean air so that the panel cannot perceive the odour anymore, this means that the sample has a concentration of 100 ou_E/m^3.

Background

The most significant step towards standardisation of olfactometry in Europe was the introduction, in 2003, of the **European standard EN 13725** "Air Quality - Determination of odour concentration by dynamic olfactometry", which deals with several aspects of the measurement, such as sampling procedures and materials, sample presentation to and selection of assessors, data recording, calculation and reporting and performance quality requirements.

What can it be used for? (Applicability)

The scope of the EN 13725:2003 states that "This European Standard specifies a method for the objective determination of the odour concentration of a gaseous sample using dynamic olfactometry with human assessors and the emission rate of odours emanating from point sources, area sources with outward flow and area sources without outward flow. The primary application is to provide a common basis for evaluation of odour emissions in the member states of the European Union."

Thus, dynamic olfactometry can be used to measure the concentration of odours emitted at the source.

In some cases, odour regulations fix concentration limits at emissions (for instance in the Region of Puglia, Italy). In such cases, dynamic olfactometry can be used to ascertain if regulations are being breached.

The EN 13725:2003 only refers to dynamic olfactometry intended for the measurement of odour concentration **at emissions**. However, there are other derivations of dynamic olfactometry, described in German guidelines VDI 3882 Part 1 and VDI 3882 Part 2, which describe how to apply olfactometric measurements for the determination of odour intensity and odour pleasantness/ unpleasantness (hedonic tone). Odour intensity is expressed in a scale from 0 (not perceptible) to 6 (extremely strong), whereas hedonic tone is measured in a scale from -4 (extremely unpleasant) to +4 (extremely pleasant), with 0 corresponding to an odour that is neither pleasant nor unpleasant (Figure 3). Differently from the odour concentration as measured by the European standard EN 13725:2003, which can be considered an objective parameter to measure odours, both the intensity and the hedonic tone of the odours are subjective parameters that may differ from person to person, although they can both be measured in an standardized scale as described in the German standard VDI 3882 Part 1 & 2.
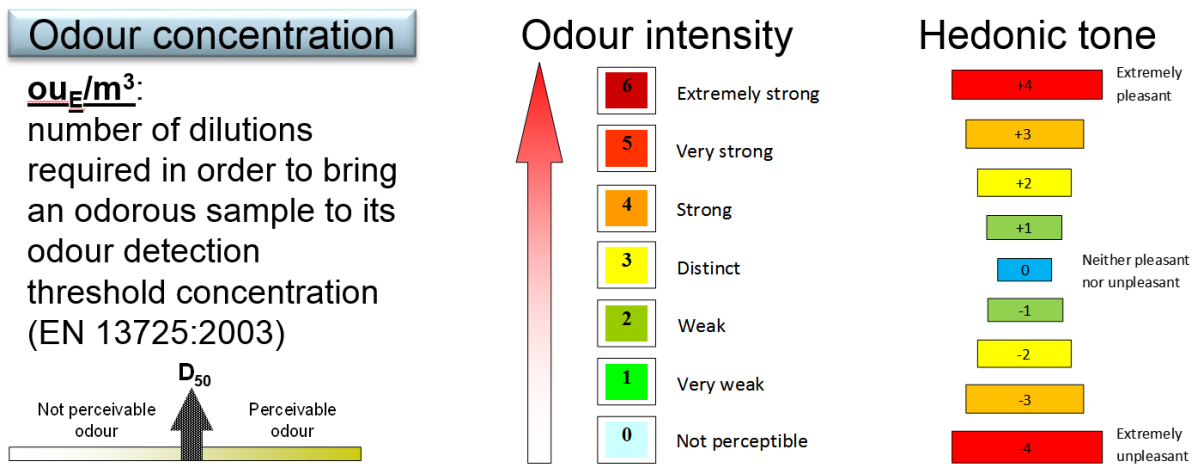
Figure 3: Schematization of olfactometric techniques for the determination of odour concentration, intensity, and hedonic tone

One important advantage of dynamic olfactometry is that it provides information that can be used as input data for dispersion modelling in order to evaluate citizens' exposure to odours. Indeed, the odour concentration, coupled with the information related to the emitted airflow, allows for the evaluation of the so called "**odour emission rate**", which is basically the odour flux emitted to the atmosphere, and is the parameter that effectively accounts for the amount of odour that is emitted into the atmosphere by a given source. This datum can be used as input data for specific mathematical models, which combine this information together with meteorological and geographical data, and thus calculate how the emitted odour is transported through the atmosphere to the affected citizens in the form of an average impact map.

This is currently the preferred way in most countries to evaluate odour impacts caused by different odour emitting activities on the surrounding communities.

What can it NOT be used for? (Limitations)

Dynamic olfactometry is a discontinuous measurement method, since samples are collected at the source in a precise moment and then transported and analysed in a lab. For this reason, it cannot be used to continuously monitor odour emissions.

Dynamic olfactometry cannot be used to gain information about odour quality, thus it cannot identify odours or distinguish between different odours.

Dynamic olfactometry provides information about odour emissions. Thus, it cannot give information about the presence of odours in ambient air (immissions). For this purpose, data from olfactometric analysis should be combined with meteorological and geographical information in a specific dispersion model to estimate the average annual odour impact.

Examples of relevant applications

The objective determination of odour concentration provided by dynamic olfactometry makes this odour measurement method a useful tool for the assessment of the overall performance and the efficiency of abatement systems in removing odours and volatile organic compounds (VOCs).

For example, Gutierrez et al. in 2015 and Sowka et al. in 2017 proposed the adoption of this technique to test the efficiency of industrial biofilters by means of the characterization of

samples collected upstream and downstream the abatement units. Gutierrez et al. proposed also the combination of dynamic olfactometry with the GC-TOFMS with the aim to identify, among the VOCs analysed, the compounds responsible for the odour emission.

The most common application of dynamic olfactometry entails the combination with **dispersion modelling**, since determining the odour concentration alone is not sufficient to assess the odour impact on citizens. This approach involves the determination of the **odour emission rate** (OER) of the odour emission sources, which represents the odour flux emitted to the atmosphere. The OER is expressed in ou_E/s and is obtained as the product of the odour concentration by the air flow associated with the source. The method adopted for estimating OER depends on the source type, i.e. point, volume or surface sources (Sironi et al., 2014). This datum can be used as input for dispersion models, which, combining source characteristics, meteorological and geographical data, estimate the average odour impact of the monitored activity on surrounding territories, usually as annual values estimated for a specific percentile (i.e. Percentile 98).

In 2010, Sironi et al. presented a case study regarding the assessment of the odour impact in presence of multiple similar sources, i.e. four rendering plants. Based on the results of olfactometric surveys carried out in different seasons, the authors estimated the overall odour emission rates emitted by each plant and identified the major contributor to the odour impact on the monitored area. Furthermore, the CALPUFF model application allowed to quantify the odour impact relevant to the four monitored plants on the surroundings.

In 2019, Romanik et al. presented the comparative analysis, based on the combination of dynamic olfactometry and dispersion modelling, of the emission scenario relevant to an industrial activity before and after the installation of abatement equipment. The study had the twofold purpose to assess the odour impact at the sensible receptors and evaluate the efficiency of the technical intervention.

Relevant publications (links)

Hove, N. C., Demeyer, P., Van der Heyden, C., Van Weyenberg, S., & Van Langenhove, H. (2017). Improving the repeatability of dynamic olfactometry according to EN 13725: A case study for pig odour. Biosystems engineering, 161, 70-79.
https://doi.org/10.1016/j.scitotenv.2014.09.003

Akdeniz, N., Jacobson, L. D., Hetchler, B. P., Bereznicki, S. D., Heber, A. J., Koziel, J. A., ... & Parker, D. B. (2012). Odour and odorous chemical emissions from animal buildings: Part 2. Odour emissions. Transactions of the ASABE, 55(6), 2335-2345.
https://elibrary.asabe.org/abstract.asp?aid=42495

Capelli, L., Sironi, S., Del Rosso, R., & Céntola, P. (2009). Predicting odour emissions from wastewater treatment plants by means of odour emission factors. Water research, 43(7), 1977-1985.
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Capelli, L., Sironi, S., Del Rosso, R., Céntola, P., Rossi, A., & Austeri, C. (2011). Olfactometric approach for the evaluation of citizens' exposure to industrial emissions in the city of Terni, Italy. Science of the Total Environment, 409(3), 595-603.
https://doi.org/10.1016/j.scitotenv.2010.10.054

Gutierrez, M. C., MArtin, M. A., Pagans, E., Garcia-Olmo, J., Chica, A. F. (2015). Dynamic olfactometry and GC-TOFMS to monitor the efficiency of an industrial biofilter. Science of the Total Environment, 512-513, 572,581.
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https://doi.org/10.3155/1047-3289.58.6.806

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https://doi.org/10.1051/e3sconf /2019100000

Sironi, S., Capelli, L., Céntola, P., Del Rosso, R., & Grande, M. I. (2006). Odour emission factors for the prediction of odour emissions from plants for the mechanical and biological treatment of MSW. Atmospheric Environment, 40(39), 7632-7643.
https://doi.org/10.1016/j.atmosenv.2006.06.052

Sironi, S., Capelli, L., Céntola, P., Del Rosso, R., & Pierucci, S. (2010). Odour impact assessment by means of dynamic olfactometry, dispersion modelling and social participation. Atmospheric Environment, 44(3), 354-360.
https://doi.org/10.1016/j.atmosenv.2009.10.029

Sironi, S., Capelli, L., Del Rosso, R. (2014). Odour Emissions. Reference Module in Chemistry, Molecular Science and Chemical Engineering. Waltham, MA: Elsevier.
https://doi.org/10.1016/B978-0-12-409547-2.11042-X

Sowka, I., Miller, U., Grzelka, A. (2017). The application of dynamic olfactometry in evaluating the efficiency of purifying odorous gases by biofltration. Environment Protection Engineering, 43 (4), 233.242.
https://doi.org/10.5277/epel70418

CHEMICAL ANALYSIS - WITH SPECIATION

What is it? (Method description)
The chemical analysis (with speciation) of odorous emissions consists in the complete identification and quantification of odorous chemical compounds in an odour sample. It is an "instrumental analysis" because it investigates odour using instruments. Sensitive and powerful tools are required for odour analysis. Different instrumentation can be applied for this purpose: the main technique **Gas Chromatography coupled with Mass Spectrometry (GC-MS)**. GC - MS is a technique that combines the separation capability of gas chromatography (GC) with mass spectrometry (MS), which allows for the identification of the separated compounds (Figure 4).
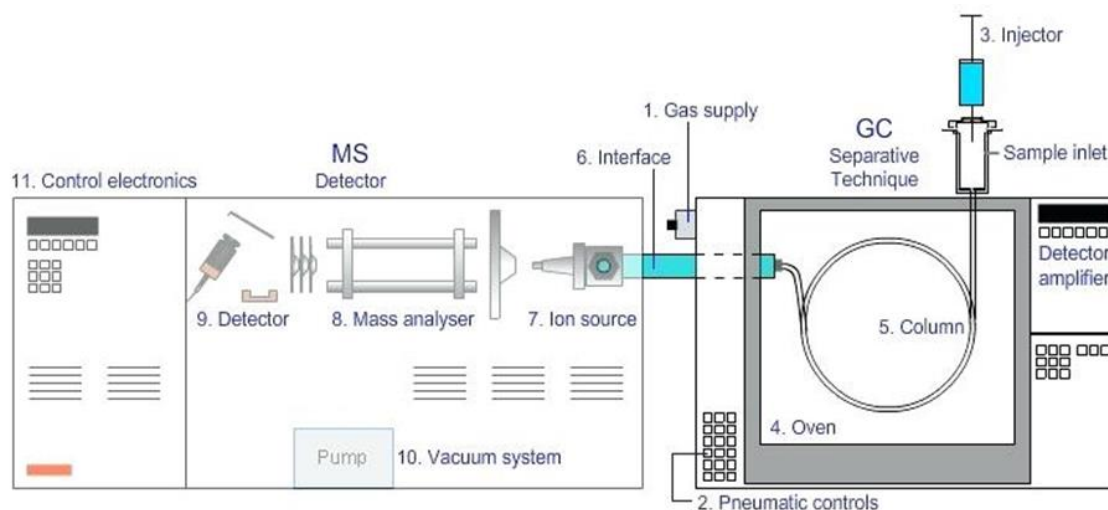
Figure 4: Schematization of a GC - MS analysis system

Gas chromatography can separate molecules depending on their chemical-physical properties: such as a foot race, molecules run along the GC column and they reach the MS detector in different time (called retention time), according to their chemical characteristics. This separation allows the MS to analyse molecules separately: indeed, mass spectrometer breaks each molecule into ionized fragments, obtaining a mass spectrum. A mass spectrum is a molecule fingerprint, which is characteristic and allows to identify uniquely a substance.

So, we obtain a chromatogram, a diagram where we can observe different peaks, each peak attributable to the different molecules separated by the GC column in function of time (Figure 5). Under every chromatographic peak, it is possible to analyse the mass spectrum and identify every substance.
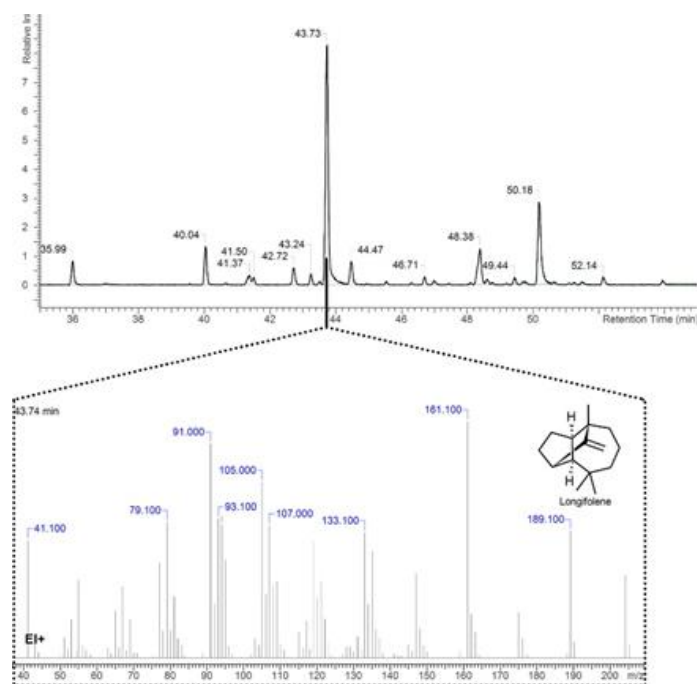
Figure 5: Example of chromatogram (top) and mass spectrum (bottom) for the identification of the molecules separated by GC

Background

Since chemical analysis with GC-MS is an "old" and consolidated technique, it is historically the first method that has been applied for odour analysis. However, it cannot be considered as a method developed specifically for odour measurement, which implies that the type of information that can be obtained with this kind of analysis may be very accurate, though not directly related to odour perception.

What can it be used for? (Applicability)

At the emission level, GC-MS can be applied in order to obtain information about the chemical composition of odour emissions.

As already mentioned, GC-MS allows for the identification and quantification of complex odour emissions. Identification and quantification of the chemical compounds that are present in an odour emission are fundamental to evaluate the impact of emitted compounds on the environment and human health.

Chemical characterization also allows to evaluate compliance of the emissions with regulatory concentration or flux limits that are fixed by the competent authorities in order to protect workers and citizens from exposure to hazardous or toxic compounds.

What can it NOT be used for? (Limitations)

Chemical analysis can turn out to be very difficult and not always effective, especially in the characterization of complex odours.

Odours are not additive: in odorous mixtures, synergistic and masking effects between different odorants may occur, giving that the chemical composition of an odorous sample cannot be related to its odour concentration.

One way to relate the chemical composition of an odorous mixture to its odour concentration is to evaluate the so called "**Odour Activity Value**" (OAV), which is calculated as the sum of the ratio between the chemical concentration of each compound in the mixture and its odour threshold concentration:

$$OAV = \sum_{i=1}^{n} \frac{C_i}{OT_i}$$

OAV $\quad$ = $\quad$ Odour Activity Value (ou_E m^{-3})
C_i $\quad$ = $\quad$ Concentration of compound i (mg m^{-3})
OT_i $\quad$ = $\quad$ Odour Threshold of compound i (mg ou_E^{-1})

However, the odour concentration calculated through the OAV can be very imprecise. One reason for this imprecision is the difficulty of finding reliable OT values, given that the values that are found in literature for a single odorous compound often differ by several orders of magnitude. Moreover, if synergic effects of odorous compounds are present, such a calculation will underestimate the odour concentration of the odorous mixture.

Finally, analytical techniques are not as sensitive as human nose to detect all malodorous compounds. Indeed, there are some odorous compounds, such as mercaptans, that have odour threshold concentrations in the range of ppb (parts per billion) o even ppt (parts per trillion), which are levels that are hardly detected by instrumental methods.

Examples of relevant applications

Although chemical analysis does not provide information directly related to odour perception, many literary papers proposed this technique for the characterization of odorous emissions (Zhu et al., 2016, Fisher et al., 2017).

For example, in 2017, Wu et al. proposed the adoption of gas chromatography to assess the odour impact of a landfill in Beijing (China). Odorous samples collected seasonally were analysed by both chemical analysis and olfactometer to correlate the measured odour concentration with the calculated odour concentration by means of the Odour Activity Value (OAV). Aware of the variability of odour thresholds (OT) reported in the scientific literature, authors measured the OT using a uniform methodology with the aim to minimize the imprecision of calculated and measured odour concentration, which resulted in a relatively higher correlation coefficient (r=0.9194). The speciation of odour samples collected at the main landfill odour sources highlighted that hydrogen sulphide, dimethyl sulphide and trimethylamine contributed the most to odour emissions.

In 2019, Gonzalez et al. involved the TD GC-MS to characterize odorous emissions of a full-scale sewage composting plant located in Majorca (Spain). In particular, 34 gaseous samples representative of different points of the treatment processes were analysed with the aim to monitor the odorous emissions during the composting process and evaluate the possibility to define a correlation between the odour concentrations estimated by means of OAVs and those assessed by field olfactometry. The study highlighted that the odorous emissions tended to decrease as the biological stability of the material increased and allowed to identify the compounds most responsible for the emission of odour. However, a weak correlation was found between the OAVs and the odour concentration values.

Chemical analysis with speciation can be used also to monitor the efficiency of abatement systems. As an example, Gutierrez et al. in 2015 used GC-TOFMS in conjunction with dynamic olfactometry to monitor the performance of an industrial scale biofilter. The speciation allowed to identify compounds most responsible for odour emissions and families that have similar influence on the variance of the measure to minimize the number or suggest possible intervention to limit the odour emission.

Relevant publications (links)

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Gutierrez, M. C., Martin, M. A., Pagans, E., Vera, L., Garcia-Olmo, J., Chica, A. F. (2015). Dynamic olfactometry and GC-TOFMS to monitor the efficiency of an industrial biofilter. Science of the Total Environment, 512-513, 572-581.
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Rincón, C. A., De Guardia, A., Couvert, A., Wolbert, D., Le Roux, S., Soutrel, I., & Nunes, G. (2019). Odour concentration (OC) prediction based on odour activity values (OAVs) during composting of solid wastes and digestates. Atmospheric Environment, 201, 1-12.
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Rincón, C. A., De Guardia, A., Couvert, A., Le Roux, S., Soutrel, I., Daumoin, M., & Benoist, J. C. (2019). Chemical and odour characterization of gas emissions released during composting of solid wastes and digestates. Journal of environmental management, 233, 39-53.
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Wu, C., Liu, J., Zhao, P., Li, W., Yan, L., Piringer, M., Schauberger, G. (2017). Evaluation of the chemical composition and correlation between the calculated and measured odour concentration of odorous gases from a landfill in Beijing, China. Atmospheric Environment, 164, 337-347.
https://dx.doi.org/10.1016/j.atmosenv.2017.06.010

CHEMICAL ANALYSIS - NON SPECIFIC

What is it? (Method description)
In those cases in which the odour problem is specifically related to hydrocarbon molecules (this can be typically the case for refineries), a non-specific gas analysis can be applied as a

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preliminary screening tool to assess the total amount of hydrocarbon compounds. This kind of technique is conducted with easy transportable and quite cheap tools, like **FID (Flame Ionization Detector)** or **PID (Photo Ionization Detector)**.

The principle on which these tools are based is the pyrolysis of the organic compounds that are present in the analysed gas. This pyrolysis (which is conceptually similar to a combustion) is made possible by the presence of an energy source, which produces ions detectable by an electric sensor.

The main difference between these two kind of sensors is that the FID needs an hydrogen bottle to maintain an hydrogen flame as energy source, while the PID uses an UV lamp.

Because of this different ionization mechanism, a FID is able to detect also methane, which is odourless, while a PID, which has a weaker energy source, is useful to detect NMHC (Non-Methanic HydroCarbons).

The main drawback of this method is that the total hydrocarbon concentration that is measured cannot be related directly to the odour concentration. The output of these type of instruments is a total VOC concentration expressed in terms of a concentration equivalent to a calibration gas concentration. Indeed, there are several scientific papers proving that the correlation between total VOC concentration and odour concentration of gas samples is generally non-existent. Moreover, these instruments do not take into consideration the different odour threshold of different compounds, the response factors of the electric sensor, and the mixing effects.

What can it be used for? (Applicability)

This type of analysis can be extremely useful for the detection of gas leaks, which are potentially associated with diffuse odour emissions.

One typical example is the case of refineries, where fugitive emissions from equipment and piping can be detected by means of the measurement of the total VOC concentration. Where a concentration of total VOC above a certain value (e.g. 10,000 ppm) is measured, a leak is present. The same approach is used in landfills in order to identify the presence of leaks in the landfill cover, through which landfill is emitted into the atmosphere.

What can it NOT be used for? (Limitations)

This technique doesn't give any information about the odour properties of the analysed gas.

Examples of relevant applications

Non-specific chemical analysis is commonly adopted for estimating fugitive emissions. Many authors proposed different techniques in the scientific literature for the detection and quantification of gas leaks.

For example, in 2005, Rao et al. presented the application of Leak Detection and Repair (LDAR) program in a refinery to estimate fugitive emissions in and around different process units, tanks, truck loading and treatment plants by involving a Photo Ionization Detector (PID). PID detections were processed according to specific correlations to estimate the emitted fluxes.

In 2008, Chambers et al. proposed the adoption of differential absorption light detection and ranging (DIAL) to remotely measure concentration profiles of hydrocarbons in the atmosphere up to several hundred meters from the instrument. When combined with wind speed and direction, downwind vertical DIAL scans can be used to calculate mass fluxes of the measured gas leaving the site. This rapid estimation of fugitive leaks would improve the effectiveness of

efforts to reduce emissions, quantify the reduction in emissions, and improve the accuracy of emissions data that are reported to regulators and the public.

Similar approaches were proposed in the scientific literature also for the estimation of landfill fugitive emissions. In 2018, Kormi et al. proposed the adoption of genetic algorithms based optimization combined with standard Gaussian dispersion model to estimate fugitive landfill methane emissions by identifying locations and emissions rates. The authors presented four case studies, which were carried out to evaluate the performance of the proposed methodology.

Relevant publications (links)

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https://doi.org/10.3155/1047-3289.58.8.1047

Kormi, T., Mhadhebi, S., Ali, N. B. H., Abichou, T., & Green, R. (2018). Estimation of fugitive landfill methane emissions using surface emission monitoring and Genetic Algorithms optimization. Waste Management, 72, 313-328.
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Kormi, T., Ali, N. B. H., Abichou, T., & Green, R. (2017). Estimation of landfill methane emissions using stochastic search methods. Atmospheric Pollution Research, 8(4), 597-605.
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CHEMICAL ANALYSIS - SINGLE GASES

What is it? (Method description)
There are some rare cases in which the odour pollution problem is due mainly to a single compound, such as ammonia or hydrogen sulphide. In such cases, by assessing the concentration of these single gases in emissions, it is possible to obtain a reliable quantification of odour emissions.

In general, for the measurement of single gases in emissions, such as ammonia and hydrogen sulphide, specific technical norms exist defining the sampling and analysis method.

Since concentrations are usually quite high (tens or hundreds of ppm), it is also possible to use electrochemical sensors, which are easy-to-use and cheap.

When determining the concentration of single gases in emissions or immissions, it is important that the most suitable method is chosen in function of the expected concentration.

What can it be used for? (Applicability)

This type of chemical analysis allows the quantification of the concentration of single gases in emissions. This can be used to verify compliance to emission limits relevant of specific compounds.

In those rare cases in which the emitted odour is directly correlated to one specific compound (tracer), then the determination of the compound concentration can be used to estimate the emitted odour concentration. In such cases, this datum can be used as input for dispersion modelling on order to evaluate odour impacts on the communities. For this purpose, it is necessary that a correlation between the compound concentration and the odour concentration has been preliminarily assessed.

What can it NOT be used for? (Limitations)

The chemical characterization of single gases is useless in the case of complex odorous mixtures, whereby odour concentration is not related to the concentration of one single component. This represents unfortunately the majority of the cases, since environmental odours typically are mixtures of hundreds of different compounds.

This analysis doesn't give information about the composition of complex mixtures.

Examples of relevant applications

In 2007, Qu et al. proposed use of an integrated system, including an electronic nose, a H_2S detector and a NH_3 detector, to predict odour concentration. The study involved the analysis of odorous samples from swine manure sources. Both linear regression and artificial neural networks were applied to develop correlations. Single detectors proved to be capable to predict odour concentration with poor accuracy (i.e. about 50%), whereas the integrated system achieved a good performance (R^2=0.75).

In 2018, Cangialosi et al. presented a case study involving the installation of a Jerome H_2S analyser for the continuous monitoring of odour emissions at a landfill boundary. The H_2S analyser was integrated with an automatic air sampler, which was activated in case of alert of the H_2S detector to withdraw samples to be sent to olfactometric analysis. However, no correlation was found between H_2S continuous measurements by Jerome J605 analyser and ou_E/m^3 values obtained by dynamic olfactometry.

Relevant publications (links)

Cangialosi, F., Intini, G., & Colucci, D. (2018). On Line Monitoring of Odour Nuisance at a Sanitary Landfill for Non-Hazardous Waste. Chemical Engineering Transactions, 68, 127-132.
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Qu, G., Omotoso, M. M., El-Din, M. G., & Feddes, J. J. (2008). Development of an integrated sensor to measure odours. Environmental monitoring and assessment, 144(1-3), 277-283.

GAS CHROMATOGRAPHY-OLFACTOMETRY (GC-O)

What is it? (Method description)
Gas-chromatography-Olfactometry (GC-O) is a method to combine the information supplied by chemical characterization and by odour perception. Indeed, GC-O utilises a GC-MS system equipped with an olfactory detection port: at the outlet of the GC there is a sniffer mask, where a trained panellist can smell the gas and provide information about the presence of odour in it. At the end of the GC column, after separation of the chemical compound sin the gas mixture, the sample is divided and an equal flux of it reaches the MS detector and the panellist. The panellist sniffs the gas, and every time he/she sniffs an odorous substance, he/she supplies a sensorial response, in terms of presence and type of odour. Indeed, every time the panellist perceives an odour, he/she shall push a button and describe the odour. Intensity values can also be added to the description of the odour types. This way, an olfactogram is obtained, which allows to correlate the chemical information supplied by the chromatogram and the sensorial perceptions of the panellist. Thus, GC-O consists in the combination of instrumental capacities and human nose and supplies both sensorial and chemical information.
One drawback of GC-O is that it is affected by subjectivity and inattention of the panellist. Indeed, panellist distraction can provoke important errors, in particular when odorous stimulus is short or weak, thus a proper training and measurement procedure to avoid fatigue of the panellist are of outmost importance.
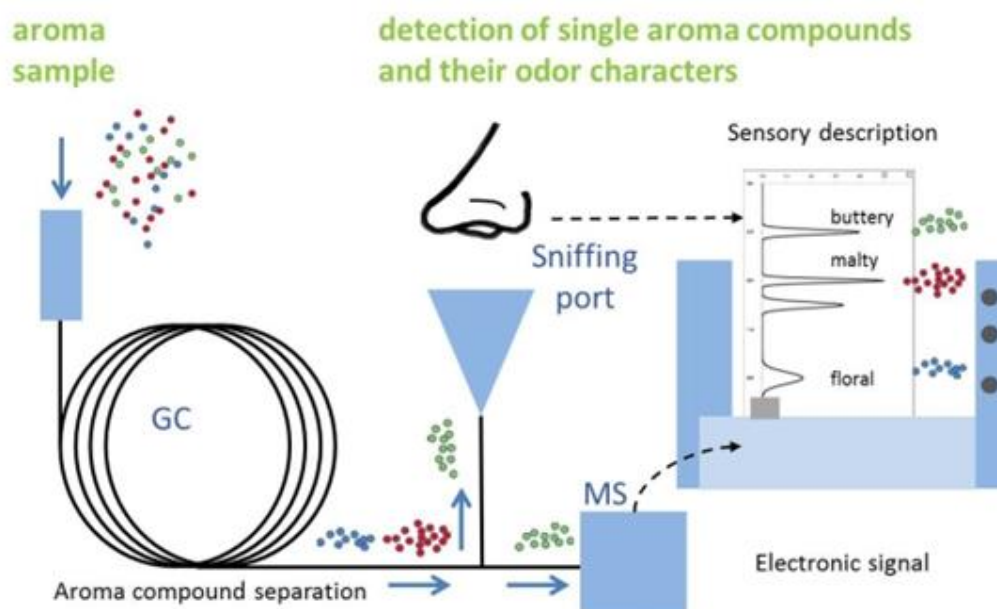

Figure 6: Schematization of the GC-O method

What can it be used for? (Applicability)
GC-O can be used to provide important information about the odour character associated with the different molecules contained in an odour sample. Thus, it allows to obtain information about odour quality. This technique is particularly suited to the analysis of odours due to the

use of human nose, which is way more sensitive than an instrumental detector: the human nose is sometimes able to detect the presence of odours also where the chromatogram doesn't show any peak.

What can it NOT be used for? (Limitations)
This technique doesn't provide any information about the odour concentration of the sample. Since it operates a separation of the sample in its single components, the olfactory properties of the sample as a whole are not considered. For this reason, data from GC-O analysis cannot provide information about the odour impact, and neither can it be used directly as input for dispersion modelling.

Examples of relevant applications
In 2010, Zhang et al. focused on the development of an odour characterization method for quantitative analysis of the key odorants responsible for livestock odour by means of TD-MDGC-MS/O. Target compounds were separated in GC column and isolated compounds were split into mass detector and sniff port in order to assess their concentration and their olfactory properties (odour character, intensity, duration time and hedonic). In 2015, the authors extended the study of 15 typical VOCs associated with livestock odour, identified the most significant gases that contribute to relative odour impacts of livestock buildings, and estimated a correlation between odour intensity and chemical concentration.
In 2018, Fisher et al. proposed the adoption of gas chromatography/olfactometry to characterize odour emissions from wastewater treatment plants. This technique allowed to identify compounds responsible for emission odour throughout biosolid processing and a description of their odour properties was provided by odour wheels.

Relevant publications (links)

Di Gilio, A., Palmisani, J., De Gennario, G. (2018). An innovative methodological approach for monitoring and chemical characterization of odours around industrial sites. Advances in Meteorology.
https://doi.org/10.1155/2018/1567146

Fisher, R. M., Barczak, R. J., Suffet, I. H. M., Hayes, J. E., Stuetz, R. M. (2018). Framework for the use of odour wheels to manage odorous throughout wastewater biosolids processing. Science of the Total Environment, 634, 214-223.
https://doi.org/10.1016/j.scitotenv.2018.03.352

Zhang, S., Cai, L., Koziel, A. K., Hoff, S. J., Schmidt, D. R., Clanton, C., Jacobon, L. D., Parker, D. B., Heber, A. J. (2010). Field air sampling and simultaneous chemical and sensory analysis of livestock odorants with sorbent tubes and GC-MS/olfactometry. Bioproducts and Biosystem Engineering, 146 (2), 427-432.
https://doi.org/10.1016/j.snb.2009.11.028

Zhang, S., Koziel, J. A., Cai, L., Hoff, S. J. (2015). Odour and odorous chemical emissions from animal buildings: part 5. Simultaneous chemical and sensory analysis with gas chromatography-mass spectrometry-olfactometry. Agricultural and Biosystem Engineering, 58 (5), 1349-1359.

INSTRUMENTAL ODOUR MONITORING (E-NOSES)

What is it? (Method description)

An electronic nose, or E-nose, is a piece of scientific equipment designed to mimic the mammalian olfaction in the detection and characterization of simple or complex odours.

These devices allow the identification of mixtures of organic samples as a whole, providing their olfactory fingerprint (identifiable to sources that released the mixture), without recognizing the individual odour-generating compounds, exactly as the human nose doesn't need to identify each single odorant molecule to distinguish the odour of an apple from rotten eggs.

To do this, the instrument must be trained: it must be provided with a database of olfactory fingerprints relating to the odours to which it may be exposed to during the analysis. That database is put together by analysing air samples with known olfactory qualities at different odour concentration and thus defining the olfactory classes (odour types) to be recognized.

The e-nose is made up of three different components:

- a series of chemical sensors which react to a wide range of odours (volatile organic compounds responsible for odours interact with the sensor surface and cause a change in certain chemical and physical properties);
- a sensor signal processing system which organises the information from the sensors;
- an odour recognition system which compares this information received to a catalogue of pre-stored datasets (i.e. the training set) to identify the odours detected.

Each odour has a unique 'fingerprint' related to its chemical composition, allowing the E-nose to compare and identify each odour detected, in the same way a human nose would first detect an odour and then process the stimuli and use memory to identify the odour type.

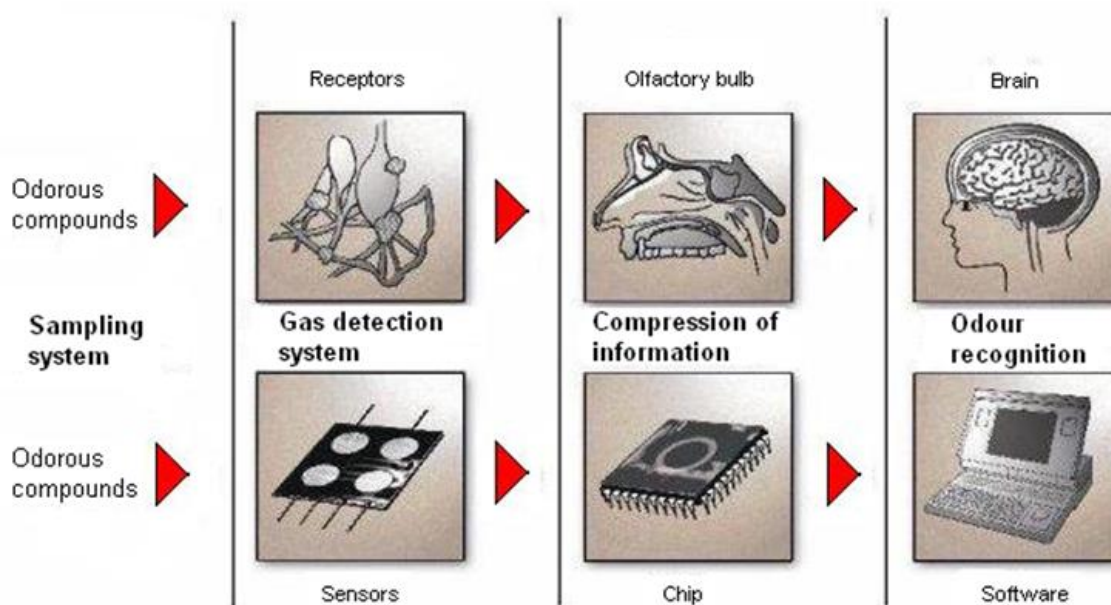A nice and easy explanation of how an electronic nose works is given in this video: https://youtu.be/3-lHCkK5faM

Figure 7: Schematization of an e-nose structure compared to the human olfactory system

Background

The name "electronic nose", which was introduced in scholarly literature in the early 1980s comes from a certain parallel of the measurement concept of the instrument and that of the mammalian olfactory system.

What can it be used for? (Applicability)

Electronic noses have the enormous advantage that they can be used for continuous determination of odour concentration at emissions.

In the case of emissions, they can also be used in order to monitor the efficiency of odour abatement systems continuously.

When applied to emission monitoring, e-nose data can be used as input data for dispersion modelling.

What can it NOT be used for? (Limitations)

E-noses cannot measure the intensity and the pleasantness of the odour (hedonic tone).

When used for the estimation of odour concentration at emissions, electronic noses shall be trained with samples that are analysed by dynamic olfactometry. For this reason, they cannot substitute dynamic olfactometry.

Examples of relevant applications

Electronic nose can be used also to monitor industrial processes. For example, in 2002, Figueiredo and Stentiford used an e-nose to monitor the composting process and detect the transition from aerobic to anaerobic conditions, using a laboratory reactor with controlled temperature.

In 2012, Delgado-Rodriguez et al. evaluated the use of an electronic nose as on-line, rapid method to quantify the gases from Municipal Solid Waste (MSW) composting. The electronic nose detected a clear difference in volatile compounds profiles relevant to the gases emitted during composting, using Principal Component Analysis (PCA). PCA reduced the dataset from the sensors to two principal components, which accounted for 74.5%, 68.8% and 62.8% of the total variance by using patterns for initial, thermophilic and mesophilic composting phases, respectively.

E-noses can be used at emission also to monitor continuously industrial emissions. In 2018, Cangialosi et al. investigated the possibility to use a multisensory electronic nose and a H_2S continuous analyser to continuously monitor the malodours form a sanitary landfill for non-hazardous waste, located in the Southern Italy. The electronic nose was trained towards landfill odours and, after installation, it proved its effectiveness for on-line monitoring, quantifying and identifying the odour produced by the landfill. On the contrary, the detections of the H_2S continuous analyses were poorly correlated with odour concentration in ambient air measured by dynamic olfactometry.

Relevant publications (links)

Blanco-Rodríguez, A., Camara, V. F., Campo, F., Becherán, L., Durán, A., Vieira, V. D., & Garcia-Ramirez, A. R. (2018). Development of an electronic nose to characterize odours emitted from different stages in a wastewater treatment plant. Water research, 134, 92-100.
https://doi.org/10.1016/j.watres.2018.01.067

Cangialosi, F., Intini, G., & Colucci, D. (2018). On Line Monitoring of Odour Nuisance at a Sanitary Landfill for Non-Hazardous Waste. Chemical Engineering Transactions, 68, 127-132.
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Capelli, L., Sironi, S., & Del Rosso, R. (2014). Electronic noses for environmental monitoring applications. Sensors, 14(11), 19979-20007.
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Chirmata, A., Ichou, I. A., & Page, T. (2015). A continuous electronic nose odour monitoring system in the city of Agadir Morocco. Journal of Environmental Protection, 6(01), 54.
http://dx.doi.org/10.4236/jep.2015.61007

Deledo-Rodriguez, M., Ruiz-Montoya, M., Giraldez, I., Lopez, R., Madejon, E., Diaz, M. J. (2012). Atmospheric Environment, 51, 278-285.
https://doi.org/10.1016/j.atmosenv.2012.01.006

Deshmukh, S., Bandyopadhyay, R., Bhattacharyya, N., Pandey, R. A., & Jana, A. (2015). Application of electronic nose for industrial odours and gaseous emissions measurement and monitoring–An overview. Talanta, 144, 329-340.
https://doi.org/10.1016/j.talanta.2015.06.050

Figueiredo, S., Stentiford, E. (2002). Evaluating the potential of an electronic nose for detecting the onset of anaerobic conditions during composting. Bioprocess Solid Waste Sludge, 2, 1-17.

2.4 Receptor level

FIELD INSPECTION

What is it? (Method description)
Dynamic olfactometry should be limited to source sampling. In order to assess the presence of ambient odours it is possible to use **human "sensors"** directly in the field. It is possible to rely on trained assessors by running field inspections such as grid or plume measurements to evaluate the extent of the area impacted.

The main idea of field inspections is to estimate the degree of annoyance in a determined problematic area by means of the olfactory capacities of a group of people (panel) specially trained and "calibrated" for this purpose.

Two different approaches for field inspection can be applied:
- **grid method,** which uses direct assessment of ambient air by panel members to characterize odour exposure in a defined assessment area.
- **plume method** for determining the extent of the downwind odour plume of a source (there is no direct relation between the presence of recognizable odours and the occurrence of odour annoyance).

Background

Although field inspections have been applied for a long time especially in Belgium, their standardization at European level is quite recent. Two European standards were published in 2016: **EN 16841-1** "Ambient air - Determination of odour in ambient air by using field inspection - Part 1: Grid method" and the **EN 16841-2** "Ambient air - Determination of odour in ambient air by using field inspection - Part 2: Plume method".

What can it be used for? (Applicability)

The "grid method" allows to estimate the degree of annoyance in terms of time percent of "odour hours" in a determined problematic area.

With the "plume method", it is possible to determine the extent of the odour plume from a facility under specific meteorological conditions.

With a suitable training, assessors carrying out field inspections may provide some information about odour quality and recognize its provenance.

What can it NOT be used for? (Limitations)

It can't give us information about odour concentration.

Examples of relevant applications

In 2018, Oettl et al. compared the odour-hours based on field inspections carried out in the vicinity of a pig-fattening farm with modelled ones using Lagrangian particle model GRAL. Field inspections were carried out in 12 measurement points between February and July 2017 according to the plume method. Authors reported good correlations between the two different methodologies.

In 2017, Yacoof et al. proposed the comparison between field inspection and CALPUFF dispersion model adopted for the assessment of the odour impact relevant to a palm oil mill. 18 possible receptors, including residential area, institution and public area, were considered for the comparison. The field inspection, carried out by 5 panellists according to the plume method, and the CALPUFF model were compared by running the process on the same area for three alternate days. The outcomes of the two methods differed in odour concentration values, but they showed the same trends over the monitoring period.

In 2016, Mannebeck et al. presented the results of a case study carried out in the German cities of Mainz and Wiesbaden, characterized by the presence of several commercial and industrial areas in close neighborhood to living area. 21 panel assessors, trained towards the typical odours of industrial activity to be monitored, were involved. The study lasted six months for a total of 157 measurements, which were managed by means of a central online platform OFIM. The perceived odours shown the complete range of industrial odours during measurements. The odour frequency exceeded the limit of 10% for the majority of the grid area, and near the industrial areas the determined values exceeded 40%.

Relevant publications (links)

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https://doi.org/10.2166/wst.2013.387

Guillot, J. M., Bilsen, I., Both, R., Hangartner, M., Kost, W. J., Kunz, W., & Van Elst, T. (2012). The future European standard to determine odour in ambient air by using field inspection. Water Science and Technology, 66(8), 1691-1698.
https://doi.org/10.2166/wst.2012.375

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Oettl, D., Kropsch, M., Mandl, M. (2018). Odours assessment in the vicinity of pig-fatting farm using field inspection (EN 16841.1) and dispersion modelling. Atmospheric Environment, 181, 54-60.
https://doi.org/10.1016/j.atmosenv.2018.03.029

Ranzato, L., Barausse, A., Mantovani, A., Pittarello, A., Benzo, M., & Palmeri, L. (2012). A comparison of methods for the assessment of odour impacts on air quality: Field inspection (VDI 3940) and the air dispersion model CALPUFF. Atmospheric environment, 61, 570-579.
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https://doi.org/10.3303/CET1654030

Yaacof, N., Qamaruzzaman, N., Yusuo, Y. (2018). Comparison method of odour impact evaluation using calpuff dispersion modelling and on-site monitoring. Engineering Heritage Journal, 1, 01-05.
https://doi.org/10.26480/gwk.01.2017.01.05

FIELD OLFACTOMETRY

What is it? (Method description)
Field olfactometer are portable devices that create a series of discrete dilutions by mixing the odorous ambient air with clean air (odour-free). In this case, panellists are moved to the problematic area and use this device to create several dilutions to know the "Dilution-to-Threshold," D/T ratio. The "Dilution-to-Threshold" ratio is a measure of the number of dilutions needed to make the odorous ambient air "non-detectable".

What can it be used for? (Applicability)
It can be used to give an indication of the number of times that air needs to be diluted to make it non odorous close to an odour source.

What can it NOT be used for? (Limitations)

It doesn't provide odour concentration in ou_E/m^3. Odour concentration is only measured by the reference method (i.e. dynamic olfactometry according to EN 13725:2003) at emissions. It is not recommended to be used at the fenceline or near the population affected. Results obtained entail high variability, which is due to several factors, and that implies that results of field olfactometry are not comparable with any reference method. The calibration of the assessors is a key element, and sniffing sticks are not suitable for this calibration.

Examples of relevant applications

In 2016, Barczak et al. used field olfactometry to assess the odour concentration at potential emission sources of a wastewater treatment plant, located in Poland, and determine their range of impact. In order to determine the range of the impact of odour sources receptor points were localized downwind to the source depending on the wind speed and direction and the altitude of the emission sources. All measurements were performed by two trained assessors, and for each measurement point at least two replicates were carried out. This study allowed to identify the emission sources most responsible for the odour impact.

In 2017, Vieira et al. investigated the possibility to combine field olfactometry with plume method measurements to monitor diffuse and discontinuous odour emission sources. The study was carried out in Flanders and involved the field measurements around five industrial sites, which were carried out by two panellists. The response time proved to be a critical aspect for field olfactometry, especially at plume boundaries and far away from the odour sources (intermittent odour). Moreover, panellist fatigue and high dilution gas consumption compromise in-field odour-measuring devices to determine different odour intensity levels within the odour plume. Nevertheless, near the odour sources (with relatively constant odour and steady conditions), measurements could be easily performed and odour strength assessed. In conclusion, field olfactometry seems not suitable, in a general manner, for determining different odour intensity levels within the global odour plume. However, it may provide useful information to characterize the odour level at few points and then to validate dispersion modelling results.

In 2018, Badach et al. proposed the use of field olfactometry to measure odour concentrations in the vicinity of a municipal landfill, located in Gdank (Poland). The results of field olfactometry were used as input for the CALPUFF model, which provided useful information in the process of local spatial planning. The study involved four panellists, who carried out field measurements in five measurement points situated along the landfill perimeter. The measurements were carried out simultaneously by all panel members in triplicate. The authors suggested the possible integration of this approach with the qualitative characterization of odours.

Relevant publications (links)

Badach, J., Kolasinska, P., Paciorek, M., Wojnowski, W., Dymerski, T., Gebeki, J., Dymnicka, M., NAmiesnik, J. (2018). A case study of odour nuisance evaluation in the contect of integrated urban planning. Journal of Environmental Management, 231, 417-424.
https://doi.org/10.1016/j.jenvman.2018.02.086

Barczak, R., Kulig, A. (2016). Odour monitoring of a municipal wastewater treatment plant in Poland by field olfactometry. Chemical Engineering Transaction, 54.
https://doi.org/10.3303/CET1654056

Vieira, M., Guillot, J.M., Filho, P. B., Romai, A. C., Adam, G., Delva, J., Baron, M., Van ELst, T. (2017). IWA ODOUR 2017.
 http://hdl.handle.net/2268/220315

CITIZEN SCIENCE

What is it? (Method description)
The Citizen Science approach to monitoring odour brings together the power of many, using one of the most effective odour sensors - the human nose – to generate new data sets (impossible to obtain otherwise) that allow the co-creation of collaborative odour maps in the impact area. Communities can record the frequency, intensity and type of odour that they experience and combine the individual observations of many to build a clear picture of the issue. As more citizens are involved in sharing their findings, or data, the level of subjectivity is reduced. The analysis of the plausibility of the gathered data can performed at different levels: 1) At individual level – To disregard potential fake observations; 2) At collective level – To identify odour episodes affecting more than one citizen in the same area at an specific period of time. Dispersion modelling can be used to evaluate the potential origins of the perceived odours.

Background
Citizen Science (CS) is a flexible, innovative and effective approach based on the engagement in scientific processes of people who do not work professionally in the relative field of study. Giving the citizens the opportunity to observe their environment and share information, CS projects create scientific knowledge outside institutionalized science, helping to align science with society, building trust and democratising science. CS projects in the field of environment have also the potential to inform new environmental policies through the gathered data, as reflected by the JRC report "An inventory of citizen science activities for environmental policies" from 2018 (https://doi.org/10.2779/961304), which is the ultimate goal of the D-NOSES Project.

What can it be used for? (Applicability)
When scientific standards are observed, CS allows to create large datasets and introduce innovative ideas, fosters the acceptance through transparent procedures, and verifies practical applicability in the field. It is an effective instrument to deal with complex social issues and strengthen the research methodology.
Co-creative approaches of CS include citizens at early stages of a project and enable the definition of questions or problems to be addressed, which are relevant for the affected communities. In the case of D-NOSES, the **Extreme Citizen Science model** derived from UCL (Haklay at al., 2018) has been adapted to fulfil the project objectives. This is a highly inclusive model that aims to involve all citizens, independently from their literacy levels, their gender, or their socio-cultural or socio-economic levels, in the research process, from the very definition of the research question, to data gathering, data analysis or the co-creation of an action plan.

CS often includes a wide variety of stakeholders from all areas, such as the public, policy makers, academics, industrial partners and NGOs. Through this inclusivity, CS allows collaborations without borders and fosters good relationships between citizens, science, governments and industries, increasing transparency and trust.

What can it NOT be used for? (Limitations)

It doesn't provide odour concentration in ou_E/m^3. Odour concentration is only measured by the reference method (i.e. dynamic olfactometry according to EN 13725:2003) at emissions.

CS is a scientific method with advantages and limitations, like every other approach. The inclusion of citizens in research can be difficult when the methods require special training or strenuous work. In addition, individual accuracies can vary, depending on the difficulty of the tasks. The element of variation in data collection and analysis done by citizens needs to be carefully incorporated into the final analysis and interpretation of the data/project.

Also, ethical issues may be taken into account when including citizens in CS projects, especially in relation to data protection and to the possibility of raising false expectations.

Examples of relevant applications

In 2018, Sowka et al. presented the results of field and sociological research aimed at identifying odour sources and odour nuisance in a selected urban area located in the southern part of Poland, on which many odour emission sources exist. Field measurements were carried out according to the German standard VDI 3940:2006. The measurement points were selected in the area where complaints were reported. Odour diaries with questions concerning the type and source of the odour, the assessment of the degree of odour nuisance in the form of a so-called thermometer scale, prevailing meteorological conditions and the duration of the 'odour situation', were distributed among the inhabitants of the area. The conducted research allowed the identification of prevalent emission sources and the extent of their impact on the area of the examined city and community.

In 2019, Eltarkawe and Miller proposed the combination of wind direction and social participation to identify odour sources in North Denver and Greeley (USA). Residents' signalling of odour occurrence were collected by a smartphone app, which recorded time, date, location and description of the odour perceived. The reporting tool provided a list of odour descriptions, developed based on the odour complaints received by the Denver Department of Public Health and Environment received in previous years. With the aim of obtaining reproducible results, randomly selected groups of 25 study participants were subjected to a sensitivity odour test, based on the psychophysical methodology of the ascending 3-Alternative Forced-Choice method, which involved St. Croix Sensory's odour sensitivity test kit. This type of investigation highlighted most reported odours in the area and allowed the identification of possible industrial activities responsible for them.

Relevant publications (links)

Balestrini, M., et al. (2017) "A city in common: a framework to orchestrate large-scale citizen engagement around urban issues." Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. ACM

Eltarkawe, M., Miller, S. (2019). Industrial odour source identification based on wind direction and social participation. International Journal of Environmental Research and Public Health, 16, 1242.
http://dx.doi.org/10.3390/ijerph16071242

Haklay, M., and Francis, L., (2018). Participatory GIS and community-based citizen science for environmental justice action, in Chakraborty, J., Walker, G. and Holifield, R. (eds.), The Routledge Handbook of Environmental Justice. Abingdon: Routledge, pp. 297-308.

Haklay M. (2013) Citizen Science and Volunteered Geographic Information: Overview and Typology of Participation. In: Sui D., Elwood S., Goodchild M. (eds.) Crowdsourcing Geographic Knowledge. Springer, Dordrecht.
https://link.springer.com/chapter/10.1007/978-94-007-4587-2_7

Sowka, I., Miller, U., Bezyk, Y., Nych, A., Grzelka, A., Dabrowski, L. (2018). Application of field inspection and odour observation diaries in the assessment of air quality and odour in urban areas. E3S Web of Conferences, 45, INFRAEKO 2018.
https://doi.org/10.1051/e3sconf/20184500086

CHEMICAL ANALYSIS - WITH SPECIATION

What is it? (Method description)
Chemical analysis (with speciation) can also be applied to ambient air.
Also in this case, the analysis consists in the complete identification and quantification of odorous chemical compounds in an odour sample. Different instrumentation can be applied for this purpose: the main technique **Gas Chromatography coupled with Mass Spectrometry** (GC-MS). GC - MS is a technique that combines the separation capability of gas chromatography (GC) with mass spectrometry (MS), which allows for the identification of the separated compounds. If ambient air is analysed instead of emissions, even more sensitive and powerful tools are required for odour analysis. For the analysis of ambient air, pre-concentration of the sample is needed in most cases.

Background
Since chemical analysis with GC-MS is an "old" and consolidated technique, it is historically the first method that has been applied for odour analysis. However, it cannot be considered as a method developed specifically for odour measurement, which makes that the type of information that can be obtained with this kind of analysis may be very accurate, though not directly related to odour perception.

What can it be used for? (Applicability)
At the receptor level, GC-MS can be applied in order to obtain information about the chemical composition of ambient air. As already mentioned, GC-MS allows for the identification and quantification of complex odour emissions. Identification and quantification of the chemical compounds that are present in ambient air can be used to evaluate the impact on the environment and human health.

What can it NOT be used for? (Limitations)

Chemical analysis can turn out to be very difficult and not always effective, especially in the characterization of complex odours. Odours are not additive: in odorous mixtures, synergistic and masking effects between different odorants may occur, giving that the chemical composition of an odorous sample cannot be related to its odour concentration.

Finally, analytical techniques are not as sensitive as human nose to detect all malodorous compounds. Indeed, there are some odorous compounds that have odour threshold concentrations in the range of ppb (parts per billion) o even ppt (parts per trillion), which are levels that are hardly detected by instrumental methods. Especially in the case of ambient air analysis, chemical analysis may be unable to detect odorous compounds that are present at very low concentration levels.

Examples of relevant applications

In 2017, Bylinsky et al. investigated the capability of two dimensional gas chromatography coupled with time of flight mass spectrometer and field olfactometry for the characterization of odour properties of atmospheric air in Gdansk, where a wastewater treatment plant (WWTP) and an oil refinery are located. The study involved the analysis of five samples collected by means of absorption tubes in ambient air around oil refinery and WWTP. This investigation allowed to identify the main pollutant present in the atmosphere in the area adjacent to the industrial activity. Authors' reports similar ranges for odour concentrations estimated from chemical composition and measured by dynamic olfactometry, but no specific correlation is reported in the paper.

Relevant publications (links)

Bylinsky, H., Kolasinka, P., Dymerski, T., Gebiki, J., Namiesnik, J. (2017). Determination of odour concentration by TD-GCxGC-TOF-MS and field olfactometry techniques. Manatach Chem, 148, 1651-1659.
https://doi.org/10.1007/s00706-017-2023-8

CHEMICAL ANALYSIS - SINGLE GASES

What is it? (Method description)

There are some rare cases in which the odour pollution problem is due mainly to a single compound, such as ammonia or hydrogen sulphide. In such cases, by assessing the concentration of these single gases in ambient air, it is possible to obtain reliable and good measure of the odour impact. There are different tools able to detect the concentration of these gases. When the concentration are quite high (1-10 ppm), it is possible to use electrochemical sensors, which are easy-to-use and cheap. By the way, when ambient air should be measured, the target concentrations are usually lower than the lower detection value of electrochemical sensors: in these case more complex and expensive tools are needed, like chemiluminescence analyser for ammonia or gold foil instruments for hydrogen sulphide.

In order to apply this type of analysis, it is very important that the measured compound is not ubiquitous, but that its source is clearly identifiable. Just to give a simple example, it would be

nonsense to search for compounds produced by a combustion plant close to a highway road, since the same compounds are likely to be emitted from car engines, and a chemical analysis would be unable to distinguish the provenance of the compound.

What can it be used for? (Applicability)
This type of chemical analysis allows the quantification of the concentration of single gases in ambient air.
In those rare cases in which the emitted odour is directly correlated to one specific compound (tracer), and if the source of this compound can be univocally identified in a determined area of study, then the determination of the compound concentration can be used to estimate the odour impact.
For this purpose, it is necessary that a correlation between the compound concentration and the odour concentration has been preliminarily assessed.

What can it NOT be used for? (Limitations)
The chemical characterization of single gases is useless in the case of complex odours, which is unfortunately the most common case.
Moreover, the measurement of one single compound in ambient air is also useless if the investigated compound is emitted by different sources. In such cases, the quantification of the component will provide no information about its provenance.

Examples of relevant applications
In 2011, Heaney et al. investigated health and quality of life concerns of neighbours related to air pollution caused by a landfill. Landfill neighbours were enrolled and kept twice-daily diaries for 14 days about odour intensity, alteration of daily activities, mood states, and irritant and other physical symptoms. Concurrently, hydrogen sulphide (H_2S) air measurements were recorded every 15 minutes. Relationships between H_2S, odour, and health outcomes were evaluated using conditional fixed effects regression models. Results highlighted that landfill odour increased 0.63 points (on 5-point Likert-type scale) for every 1 ppb increase in hourly average H_2S when the wind was blowing from the landfill towards the community, and that odour was strongly associated with reports of alterations of daily activities or healthy symptoms.
In 2012, Blanes-Vidal et al. investigated the association between regional and temporal variation of ammonia concentration in five Danish non-urban regions and environmental odour annoyance perceived by local residents. NH_3 concentration was obtained from air pollution monitoring stations. This study provided evidence that NH_3 concentration measured and modelled as part of the national air quality programs could be used as proxy of prevalence of odour annoyance in non-urban residential communities.

Relevant publications (links)

Blanes-Vidal, V., Nadimi, E. D., Ellermann, T., Andersen, H. V., Lofstrom, P. (2012). Perceived annoyance from environmental odours and association with atmospheric ammonia levels in non-urban residential communities: a cross-sectional study. Environ Health, 11, 27.
https://dx.doi.org/10.1186%2F1476-069X-11-27

Heaney, C. D., Wing, S., Campbell, R. L., Caldwell, D., Hopkins, B., Richardson, D., Yeatts, K. (2011). Relation between malodour, ambient hydrogen sulfide and healt in a community bordering a landfill. Environ Res, 111, 847-852.
https://dx.doi.org/10.1016%2Fj.envres.2011.05.021

INSTRUMENTAL ODOUR MONITORING (E-NOSES)

What is it? (Method description)
An electronic nose, or E-nose, is a piece of scientific equipment designed to mimic the mammalian olfaction in the detection and characterization of simple or complex odours.
These devices allow the identification of mixtures of organic samples as a whole, providing their olfactory fingerprint (identifiable to sources that released the mixture), without recognizing the individual odour-generating compounds, exactly as the human nose doesn't need to identify each single odorant molecule to distinguish the odour of an apple from rotten eggs.
To do this, the instrument must be trained: it must be provided with a database of olfactory fingerprints relating to the odours to which it may be exposed to during the analysis. That database is put together by analysing air samples with known olfactory qualities at different odour concentration and thus defining the olfactory classes (odour types) to be recognized.
The e-nose is made up of three different components:

- a series of chemical sensors which react to a wide range of odours (volatile organic compounds responsible for odours interact with the sensor surface and cause a change in certain chemical and physical properties);
- a sensor signal processing system which organises the information from the sensors;
- an odour recognition system which compares this information received to a catalogue of pre-stored datasets (i.e. the training set) to identify the odours detected.

Each odour has a unique 'fingerprint' related to its chemical composition, allowing the E-nose to compare and identify each odour detected, in the same way a human nose would first detect an odour and then process the stimuli and use memory to identify the odour type.
A nice and easy explanation of how an electronic nose works is given in this video: https://youtu.be/3-lHCkK5faM

Background
The name "electronic nose", which was introduced in scholarly literature in the early 1980s comes from a certain parallel of the measurement concept of the instrument and that of the mammalian olfactory system.

What can it be used for? (Applicability)
Electronic noses have the enormous advantage that they can be used for continuous analysis of ambient air in order to determine the odour impact of industrial activities at the receptor level. Moreover, in case of multiple sources, e-noses allow the identification of the sources that are most responsible for the perception of odours at receptors through the recognition of odour provenance.
Electronic noses are widely used for environmental odour monitoring, since it can create continuous and fast results with a limited budget.

What can it NOT be used for? (Limitations)
The electronic nose cannot be used for the determination of the hedonic tone.

Examples of relevant applications
The most common application of electronic nose in the environmental field concerns the assessment of the odour impact directly when the odour presence is lamented.

In 2007, Sironi et al. presented the monitoring of odours from composting plants by two electronic noses, which were installed in a nearby house and inside the perimeter of the composting plant to compare responses of both instruments. The instruments were trained with samples collected at odour sources. Samples were characterized by dynamic olfactometry and, depending on their odour concentration, diluted with odourless air with the aim to provide the instruments odour concentrations to which they might be exposed during the monitoring. The odour impact was assessed in terms of frequency of landfill odours detection by the electronic nose over the monitoring period.

In 2017, Deshmukh et al. investigated the real-time measurement of municipal solid waste odours using both electronic nose and chemical analysers with the aim to develop mathematical models to predict odour concentration. The samples collected at major odour sources over a period of 50 days were processed by Principal Component Analysis (PCA) to build the classification model and by Monte Carlo simulation and Multi Linear Regression (MLR) to build the correlation for estimating odour concentration.

In 2018, Licen et al. presented the e-nose monitoring of an integrated cycle steel plant in Trieste (Italy) and discussed the building of a classification model by means of chemometric approach based on Self Organizing Maps (SOM). The study involved an e-nose equipped with 4 MOS (Metal Oxide Sensor) and 15 polymer/black carbon composite sensors and chemical nitrogen and sulphur sensors, which was trained considering ambient air samples collected after citizens' calls and olfactometric characterization.

In 2018, Orzi et al. proposed the adoption of electronic noses for the assessment of the odour impact of untreated cow and pig slurries and treated (digestate and liquid fraction of digestate) manures when they were used on soil at field scale. The study involved the analysis by means of dynamic olfactometry and PEN3 electronic nose, equipped with 10 MOS sensors, of samples collected by means of a flux chamber both under lab conditions and in the field, and the comparison of results with the aim to investigate the effect of anaerobic digestion on odour emissions. The e-nose analysis highlighted that anaerobic digestion stabilizes slurries and reduces the variability among different matrices, independently of their origin.

Relevant publications (links)

Capelli, L., Sironi, S., & Del Rosso, R. (2014). Electronic noses for environmental monitoring applications. Sensors, 14(11), 19979-20007.
https://doi.org/10.3390/s141119979

Deshmukh, S., Purohit, H. J., Vaidaya, A. N., Romain, A. C. (2017). MSW odour quantification using electronic nose and chemical analysers; relative exploration of prediction capabilities and robust model development.017 ISOCS/IEEE International Symposium on Olfaction and Electronic Nose (ISOEN), Montreal, QC, 2017, pp. 1-3.

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7968853&isnumber=7968838

Licen, S., Barbieri, G., Fabbris, A., Briguglio, S. C., Pillon, A., Stel, F., Barbieri, P. (2018). Odour control map: Self organizing map built from electronic nose signals and integrated by different instrumental and sensorial data to obtain an assessment tool for real environmental scenarios. Sensor and Actuators (B), 263, 476-485.
https://doi.org./10.1016/j.snb.2018.02.144

Orzi, V., Riva, C., Scaglia, B., D'Imporzano, G., Tambone, F., Adani, F. (2018). Anaerobic digestion coupled with digestate injection reduced odour emissions from soil during manure distribution. Science of Total Environment, 621, 168-176.
https://doi.org/10.1016/j.scitotenv.2017.11.249

Sironi, S., Capelli, L., Centola, P., Del Rosso, R., & Grande, M. I. (2007). Continuous monitoring of odours from a composting plant using electronic noses. Waste Management, 27(3), 389-397.
https://doi.org/10.1016/j.wasman.2006.01.029

2.5 COMPARISON OF DIFFERENT METHODS

The above-mentioned methods are based on different principles and thus can be used to provide very different type of answers. For this reason, it is difficult to make a comparison of such methods. A limited comparison can be provided by stating the limits of applicability of each method, fixing clearly what they should or should not be used for. This type of information, which will be provided in the Odour Observatory, is summarized schematically in Table 1. This Table has been added to the paper "Odour Impact Assessment Methods Overview: The Odour Observatory as an Informative Tool for Citizen Science Based Approaches to Odour Management" by Laura Capelli, Rosa Arias, Jose Uribe, and Selena Sironi, presented at the Conference SARDINIA19, 17th International Waste Management and Landfill Symposium, 30 September-04 October 2019, Santa Margherita di Pula, Italy.

Measurement method	Applicable to emissions or ambient air	Applicability	Limitations
Dynamic olfactometry	Emissions	• Measure the concentration of odours emitted at the source • Ascertain if regulations are being breached • Provide information that can be used as input data for dispersion modelling in order to evaluate citizens' exposure to odours	• Non-continuous monitoring of odour emissions (discontinuous method) • No information about odour quality; it cannot identify odours or distinguish different odours • No information about presence of odours in ambient air (immissions): it only provides information about odour emissions

Chemical analysis – with speciation	Emissions and/ or ambient air	• Obtain information about the chemical composition of odours • Identification and quantification of the chemical compounds that are present in an odour emission or in ambient air can be used for the evaluation of the impact on the environment and human health	• Very difficult and not always effective, especially in the characterization of complex odours • Odours are not additive due to synergistic and masking effects between odorants, thus chemical composition of an odorous sample cannot be related to its odour concentration • Less sensitive than human nose for malodorous compounds with low odour threshold
Gas-chromatography-Olfactometry (GC-O)	Emissions	• Gain information about the odour character associated with the different molecules contained in an odour sample, and thus odour quality • High sensitivity: human nose is more sensitive than an instrumental detector; the human nose is sometimes able to detect the presence of odours also where the chromatogram doesn't show any peak	• No information about the odour concentration of the sample. • Because of the separation of the sample in its single components, the olfactory properties of the sample as a whole are not considered. • Cannot provide information about the odour impact, and neither can it be used directly as input for dispersion modelling
Chemical analysis – non-specific	Emissions	• Detection of gas leaks, which are potentially associated with diffuse odour emissions • Very useful in the detection of fugitive emissions from equipment or piping in refineries, or leaks in landfill soils	• No information about the odour properties of the analysed gas
Chemical analysis – single gases	Emissions and/ or ambient air	• Quantify the concentration of single gases in emissions or ambient air • Estimate the odour concentration in emissions, in those rare cases in which the emitted odour is directly correlated to one specific compound (tracer) • Measure the impact of odour in ambient air, in those rare cases in which the odour is directly correlated to one specific compound (tracer), and the source can be univocally identified	• Useless in the case of complex odorous mixtures, whereby odour concentration is not related to the concentration of one single component; this is the most common case, since environmental odours are mixtures of hundreds of different compounds. • No information about the composition of complex mixtures
Instrumental odour monitoring (E-noses)	Emissions and/ or ambient air	• Continuous and fast results with a limited budget • Continuous measurement of odour concentration at emissions, e.g. for continuous monitoring of odour abatement systems efficiency • Direct determination of the odour impact at receptors and potential identification of odour provenance	• No information about intensity and pleasantness of the odour • Cannot substitute dynamic olfactometry
Field inspections	Ambient air	• Estimate the degree of annoyance in terms of "odour hours" in a determined problematic area ("grid method") • Determine the extent of the odour plume from a facility under specific meteorological conditions ("plume method") • With a suitable training, assessors	• No information about odour concentration

		may provide information about odour quality	
Citizen science	Ambient air	• Involve citizens in the process of odour impact assessment • Estimate the degree of annoyance by directly referring to the effect on citizens • Provide new, real-time data sets that can be potentially correlated to daily industrial operations to reduce the impact on the population • Increase dialogue between the different stakeholders	• Risk of biased information • Hardly applicable in conflictual situations (e.g., law suits)

Table 1: Schematization of different odour measurement methods in terms of their applicability and limitations

3
ODOUR ABATEMENT TECHNIQUES

This section provides an overview of the methods that can be adopted in order to reduce odour emissions and their impact on communities. Brief descriptions of the methods are given, thereby focusing on their applicability to different types of odour emissions.

3.1 Introduction

There are several methods available to control odours - all with a variety of advantages, disadvantages and degrees of cost-effectiveness (Mills, 1995).

Some of the methods that are most commonly applied for controlling odour emissions include:
- Prevention
- Biofiltration
- Activated carbon
- Wet chemical scrubbing
- Thermal oxidation

There is not a univocal rule to choose the best odour control strategy, but, in general, since **prevention** is better than cure, prevention is by far the best strategy for odour control, if it can be implemented. In some cases it may cost more than other, end-of-pipe abatement techniques, but normally it has the advantage of leading to a better process control and operation, and an improved working environment (Mills, 1995).

Odour sources are typically classified into:

- **conveyed sources** (or point sources): emission sources of odorous gases through canalised ducts of defined dimension and flow rate (e.g., chimneys, vents)
- **diffuse sources**: generically not conveyed sources, which do not have a defined waste air flow, whereby the emission of odours occurs by diffusion/ convection from odorous surfaces exposed to the atmosphere ("area sources"), tanks or buildings ("volume sources"), or from gas leaks from non-airtight ducts or equipment (Figure 8).

Figure 8: Examples of diffuse odour sources

Odour abatement systems are typically applied to conveyed emissions, whereas for diffuse emissions, in absence of a defined air flow, traditional abatement equipment is not applicable. In the case of diffuse sources, odour emissions can be avoided by prevention, or other particular odour control strategies can be applied, as will be described in the last part of this document.

In general, **odour abatement technologies** can be divided in the following categories, depending on the type of process that is at the base of the abatement process:

- physical
- chemical
- biological

Physical/chemical technologies have been widely used because of their low empty bed residence time (EBRT), extensive experience in design and operation, and rapid startup. On the other hand, biotechnologies have been marketed as low-cost, environmentally friendly odour abatement methods (Estrada et al., 2011).

Table 2 reports an exhaustive list of different existing technologies (some more consolidated, other rather innovative) for odour abatement, belonging to the three above-mentioned categories.

Typology	Abatement method	Source type
Physical	Dry-Adsorption Systems (Activated carbon and other adsorbers)	Conveyed
	Thermal Oxidizers (Direct, Recuperative, Regenerative, Catalytic)	Conveyed
	Flares	Conveyed
	Cold plasma	Conveyed
	UV light	Conveyed
	Dispersion improvement (Conveying, flow acceleration/verticalization, stack height increase)	Conveyed/ diffuse
	Covers (for surfaces)	Diffuse
Chemical	Chemical scrubbers	Conveyed
	Ozonization	Conveyed
	Maskers/Neutralizers	Conveyed/ diffuse
Biological	Biofilters (open and closed)	Conveyed
	Suspended-growth bioreactors	Conveyed
	Bioscrubbers	Conveyed
	Biotrickling filters	Conveyed
	Rotating biological contactor	Conveyed
	Membrane bioreactors	Conveyed
	Air-lift bioreactor	Conveyed
	Two-liquid phase bioreactors	Conveyed

Table 2: List of existing odour abatement technologies

In recent years, the European Integrated Pollution Prevention & Control (IPPC) Bureau has done a great effort in drafting a reference document regarding the **Best Available Techniques** (BAT) for waste water and waste gas treatment in the chemical sector. This document is very exhaustive, and covers all up-to-date technologies existing for the control and abatement of odours and VOC emissions (it comprises specific sections dedicated to odour emissions). For this reason, the present report was compiled by taking this document (i.e. "Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector", dated June 2016), as a reference.

This document is open-access and can be downloaded at the following website:

https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/best-available-techniques-bat-reference-document-common-waste-water-and-waste-gas

Descriptions of the different techniques have been taken mainly from this European reference document, which refers to the abatement of VOCs and other pollutants, and re-adapted to the specific case of odour emissions.

Information about the different techniques have been further integrated with the data that can be found in the free-accessible database made available by the Belgian company Vito at:

https://emis.vito.be/en/luss-0

The website provides decision guidance system (LUSS) that can help in the initial screening of possible techniques for the treatment of industrial waste gas streams. The decision guidance system itself can only be consulted in Dutch, but the technical descriptions of the techniques are available in English as well.

Methods for the prevention/ reduction are described in detail in Section 3.5.4 of the aforementioned BAT Reference Document (BREF) for Common Waste Water and Waste Gas

Treatment/ Management Systems in the Chemical Sector, and will therefore not be discussed further in the present report.

3.2 End-of-pipe treatment techniques

OVERVIEW OF ODOUR ABATEMENT TECHNOLOGIES

As previously mentioned, end-of-pipe technologies are those applicable to conveyed odour emission sources.

Very high abatement efficiencies are required for the treatment of odorous emissions as humans are sensitive to very low concentrations of certain odorous substances.

There are a number of parameters to consider for selecting treatment techniques to minimise odour emissions:

- the flow rate of the odorous emissions;
- the concentration of the odorous pollutant(s);
- the physical and chemical properties of the odorous molecules, such as solubility, acidity, basicity, polarity, adsorbability, biodegradability;
- the efficiency of the techniques to abate the targeted odorous pollutants and the variability over time of this abatement efficiency (especially when catalysts are used);
- the generation of secondary pollutants;
- the energy consumption of the techniques;
- the technical limits/restrictions for the use of the techniques (e.g. temperature, maximum pollutants concentration, moisture content);
- the space requirements of the techniques;
- the operation and maintenance requirements of the techniques;
- the costs of the techniques.

These are the main end-of-pipe treatment techniques among those listed by the BREF for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector, in the section dedicated specifically to odour emissions (Section 3.5.5), which will therefore be described more in detail in the next paragraphs:

- Adsorption
- Thermal oxidation
- Catalytic oxidation   Physical
- Ionisation
- Photo/UV oxidation
- Wet scrubbers   Chemical
- Biofiltration
- Bioscrubbing   Biological
- Biotrickling

ADSORPTION

Description

Adsorption is a heterogeneous reaction in which gas molecules are retained on a solid or liquid surface (adsorbent also referred to as a molecular sieve) that prefers specific compounds to others and thus removes them from effluent streams. When the surface has adsorbed as much as it can, the adsorbed content is desorbed as part of the regeneration of the adsorbent. When desorbed, the contaminants are usually at a higher concentration and can either be recovered or disposed of.

Typical adsorbents include (EIPPCB; 2016):
- granular activated carbon (GAC), the most common adsorbent with a wide efficiency range and not restricted to polar or non-polar compounds; GAC can be impregnated, e.g. with oxidants such as potassium permanganate;
- zeolites, properties depending on their manufacturing, working either as mere molecular sieves, selective ion exchangers or hydrophobic VOC adsorbers;
- macroporous polymer particles, which are used as granules or beads, without being highly selective with respect to VOCs;
- silica gel;
- sodium-aluminium silicates.

Major types of adsorption systems are:
- fixed-bed adsorption;
- fluidised-bed adsorption;
- continuous moving-bed adsorption;
- pressure swing adsorption (PSA).

The most common adsorption systems for odour control are fixed-beds (Figure 10).
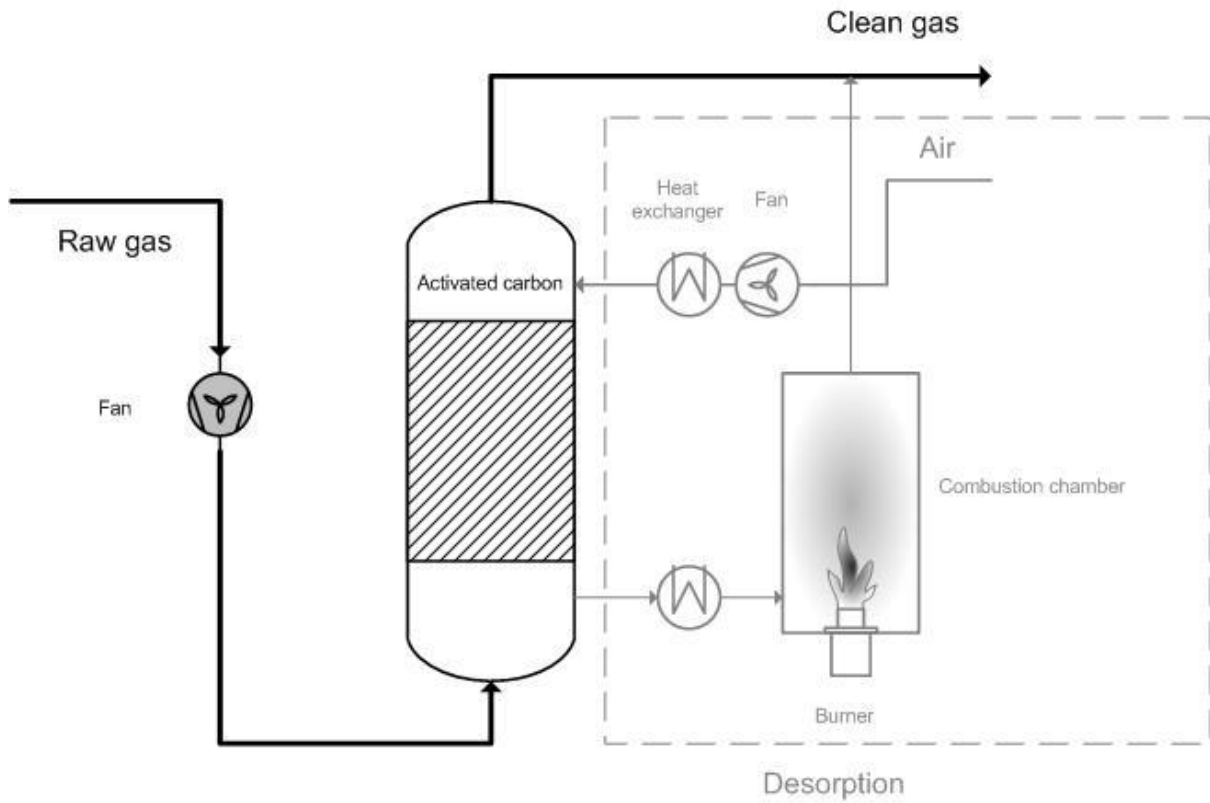
Active carbon adsorption

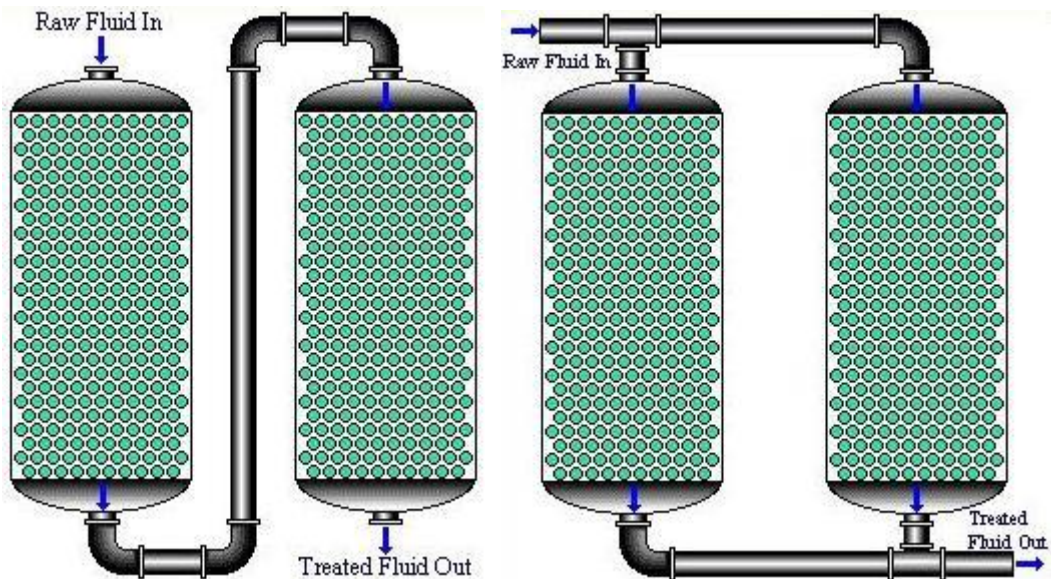*Figure 9: Diagram of active carbon adsorption system*

Figure 10: Examples of fixed bed columns: in series (left) and in parallel (right)

Design, maintenance and efficiency

Since all adsorption processes are exothermic, they cause a temperature rise, which is not desirable for the adsorption of organic compounds. Carbon or metals on GAC as well as zeolites can catalyse the oxidation of some compounds when the adsorbent is hot, resulting in bed fires that also consume part or all of the GAC, but not the zeolite. This is a hazard when adsorbing certain hydrocarbons (such as ketones or comparable active compounds) at ambient temperatures that are close to those that cause the organic compound to oxidise. Such a GAC bed fire can either alter the pore size of the remainder of the bed, or oxidise the bed to ash, which is a serious incident that may burn down the whole facility. These fires may be suppressed by humidification of the air and by intentional cooling of the GAC.

Temperature monitoring of the gas outlet of the GAC adsorber is required to prevent fire risk. Another important measurement is the pressure drop across the adsorbent bed. Across the bed, the pressure should remain roughly constant. There should be an alarm for high pressure.

Applicability

Table 3 shows application limits and restrictions associated with adsorption (adapted from EIPPCB, 2016, Table 3.166).

Issue	GAC	Zeolites
Gas flow (Nm^3/h)	100-100000	<100000
Temperature (°C)	15-80 (ideally about 20)	<250
Pressure (MPa)	0.1-2	Atmospheric
Pressure drop (mbar)	10 to 50	NI
Odour concentration (ou_E/m^3)	5000 - 100000	NI
Dust content (mg/Nm^3)	Low concentration to prevent obstruction	Low concentration to prevent obstruction
Relative humidity of the waste gas	max 70%	NI
NI = no information available		

Table 3: Application limits and restrictions associated with adsorption

THERMAL OXIDATION

Description

Thermal oxidation (also often referred to as 'incineration', 'thermal incineration' or 'oxidative combustion') is the oxidation process of combustible gases and odorants in a waste gas stream by heating a mixture of contaminants with air or oxygen above its auto ignition point in a combustion chamber and maintaining it at a high temperature for sufficient time to complete combustion to carbon dioxide and water.

After thermal oxidation, the main constituents of the treated waste gas are water vapour, nitrogen, carbon dioxide and oxygen. Depending on the pollutant content of the raw waste gas being incinerated and on the operating conditions of the thermal oxidiser, other pollutants may be present in the treated waste gas such as CO, HCl, HF, HBr, HI, NO_X, SO_2, VOCs,

PCDDs/PCDFs, PCBs, and heavy metal compounds (among others). It may require upstream treatment depending on the raw waste gas composition or additional downstream treatment of the treated waste gas. Depending on the combustion temperatures during the main stages of incineration, volatile heavy metals and inorganic compounds (e.g. salts) are totally or partially evaporated. These substances are transferred from the input waste to both the treated waste gas and the fly ash it contains. A mineral residue fly ash (dust) and heavier solid ash (bottom ash) are created.

Time, temperature (about 200–400 °C above auto ignition), turbulence (for mixing) and the availability of oxygen all affect the rate and efficiency of the combustion process. These factors provide the basic design parameters for VOC/ odour oxidation systems.

Several types of thermal oxidisers are operated:
- The **straight thermal oxidiser**, comprised of a combustion chamber and not including any heat recovery of flue-gas.
- The **regenerative thermal oxidiser**, using the following steps:
  - waste gas stream entering the oxidiser through the common inlet and passing into a regenerative chamber through a butterfly valve;
  - then passing through a ceramic heat exchange matrix, which raises the gas temperature almost to oxidation temperature;
  - then entering the combustion chamber, which is maintained at 800–1000 °C by burners, the released heat decreasing the fuel consumption of the burners;
  - then leaving the combustion chamber through a second ceramic heat exchanger matrix, transferring its thermal energy to be reused for preheating the next cycle;
  - releasing the clean gas stream through an outlet valve to discharge.

Due to the relatively high combustion space temperature, the large excess of air and the small influence of the flame, only small amounts of carbon monoxide and NO_X are formed.

This system is particularly suitable for waste gas streams with flow rates in the range of 5,000–10,000 Nm^3/h. Generally, 90–97% heat recovery (waste gas preheating) is achieved.

Regenerative Thermal Oxidizer
Airflow Diagram

Fuel Train

Exhaust to Atmosphere

Natural Gas Fired Burner

Combustion Blower

Heat Exchange Media

Airflow Switching Valves

Supply Fan

Process Exhaust Inlet
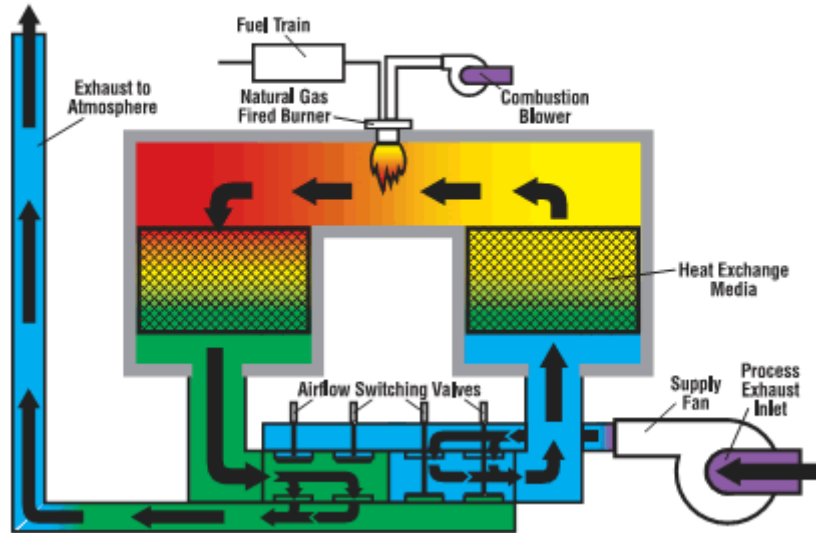
Figure 11: Scheme of a regenerative thermal oxidizer

- The **recuperative thermal oxidiser**, comprised of a combustion chamber, the waste gas preheater and, if appropriate, a secondary energy recovery heat exchanger, the heat continuously transferred to the preheater. This system is particularly suitable for waste gas stream flow rates in the range of 1000–50000 Nm^3/h. Generally, 50–80% heat recovery is achieved.

Thermal Recuperative Oxidizer
Airflow Diagram

Exhaust to Atmosphere

Process Exhaust Inlet

Supply Fan

Natural Gas Fired Burner

Combustion Chamber

High Efficiency Heat Exchanger

Figure 12: Scheme of a recuperative thermal oxidizer

- **Gas engines and/or steam boilers**, with 57–67% energy recovery. The waste gas is burnt in the engine. The concentration of the inlet gas has to be controlled to ensure that it is burnt efficiently in the engine. If necessary, natural gas can be added as support fuel or

the waste stream may need to be diluted. Downstream generators produce electricity. The engine contains a catalytic converter, princi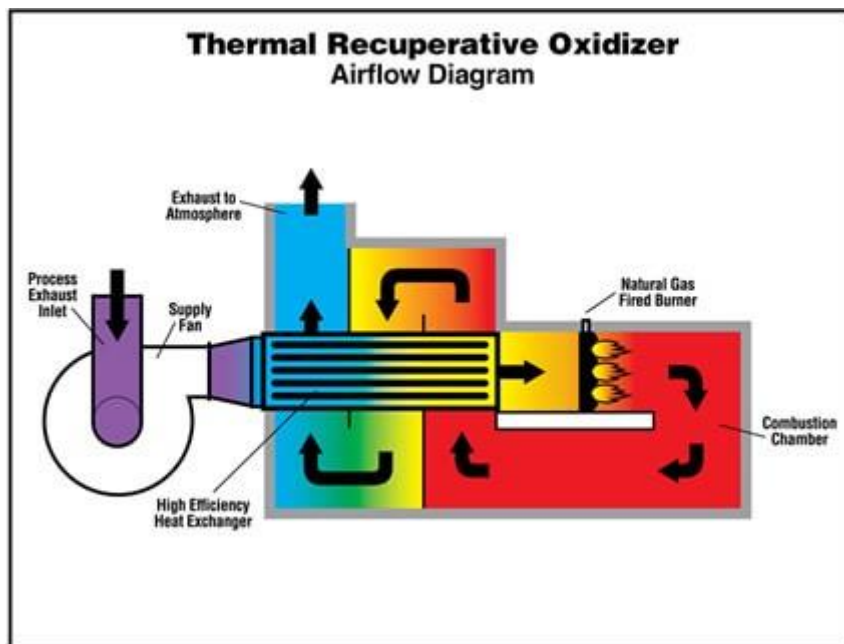pally to oxidise the carbon monoxide in the gas stream. The engine is coupled with a steam boiler to use the waste heat of the flue-gas for the production of steam. The boiler feed water is preheated by the engine cooling water. With low combustion temperatures, the formation of NO_X is low. The flue-gas leaving the gas engine is led over oxidation catalysts to reduce the carbon monoxide content.

Design, maintenance and efficiency

The design criteria for a thermal oxidiser system depend mainly on the nature of the waste gas stream (i.e. chemical and physical characteristics such as particle size, composition, and also thermal characteristics such as calorific value and moisture level), which determines the combustion conditions.

Thermal oxidisers should be inspected regularly and, if necessary, cleaned to maintain good performance and efficiency. When excess depositions occur, preventive actions have to be taken by cleaning the incoming gas before it enters the oxidiser.

Monitored parameters which should trigger an alarm when set values are exceeded include:
- combustion temperature;
- concentration of VOCs;
- concentration of carbon monoxide;
- pressure;
- feed of liquefied gas;
- feed of compressed air.

A further important parameter to monitor is the oxygen content of the effluent gas, which provides information about the combustion conditions. This is crucial when halogen compounds are thermally oxidised.

Applicability

Table 4 shows application limits and restrictions associated with thermal oxidation (adapted from EIPPCB, 2016, Table 3.204).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	900-86000 (straight and regenerative oxidiser) 90-86000 (recuperative thermal oxidiser)
Temperature (°C)	900-1200
Pressure	Atmospheric
Pressure drop (mbar)	10-50
Particulates content (mg/Nm^3)	<3
Residence time (s)	0.5-2

Table 4: Application limits and restrictions associated with thermal oxidation

CATALYTIC OXIDATION

Description

Catalytic oxidisers operate in a very similar way to thermal oxidisers, with the main difference being that the gas, after passing through the flame area, passes through a catalyst bed. The catalyst has the effect of increasing the oxidation reaction rate, enabling conversion at lower reaction temperatures than in thermal oxidation units. Catalysts, therefore, also allow smaller oxidisers to be used. The principle is illustrated in Figure 13.
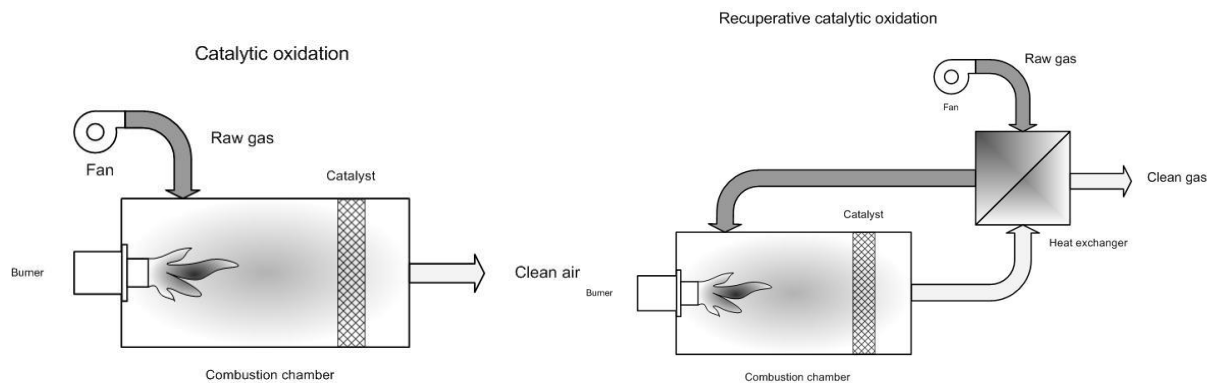

Figure 13: Principle of catalytic oxidation (left) and catalytic oxidation with heat recovery (right)

The waste gas is heated by auxiliary burners to approximately 300–500 °C before entering the catalyst bed. The maximum design waste gas temperature of the catalyst is typically 500–700 °C. There are low-temperature catalysts that work at temperatures of 200–250 °C.

The method of contacting the gas stream with the catalyst serves to distinguish catalytic oxidation systems. Both fixed-bed and fluidised-bed systems are used.

Catalysts for VOC oxidation are typically either precious metals, such as platinum, palladium and rhodium, supported on ceramic or metal, or base metals supported on ceramic pellets, single or mixed metal oxides, often supported by a mechanically strong carrier, such as oxides of copper, chromium, manganese, nickel, cobalt, etc. Platinum-based catalysts are active for the oxidation of sulphur-containing VOCs, whereas they are rapidly deactivated by the presence of chlorine.

The presence of catalyst poisons or masking (blinding) agents in the waste gas stream, such as particulates or reactive chemicals, can have a significant impact on the working life of the catalyst. Poisoning by blinding can be reversible, e.g. coating of the catalyst surface by oils or fats reduces its efficiency but the coating can be burnt off by raising the temperature. However, if certain chemicals are present, the poisoning of the catalyst becomes irreversible.

As with thermal oxidation, straight catalytic oxidisers, regenerative catalytic oxidisers and recuperative catalytic oxidisers are used.

Normal operating conditions for catalytic oxidisers include:
- natural gas as the preferred fuel (when additional fuel is needed);
- a distributed burner as a suitable burner;

- chambers constructed of stainless steel or carbon steel;
- a burner section with a sufficient length to provide an even flow and temperature distribution across the catalyst surface;
- flat flow profile across the catalyst surface;
- waste gas moving through the catalyst bed in 'plug flow' with minimum back mixing;
- a typical residence time of 0.3–0.5 seconds.

As with thermal oxidation, some waste gas pre-treatment can be necessary, such as condensing the water vapour from a wet waste gas, the removal of solids and liquids and – typical for the catalytic system – the removal of catalyst poisons.

Design, maintenance and efficiency
The catalytic oxidation should be designed in such a way as to facilitate the removal of the catalyst for cleaning or replacement purposes.

Catalytic oxidisers should be inspected regularly, and, if necessary, cleaned to maintain good performance and efficiency. When excess depositions occur, preventive actions should be taken by (partially) cleaning the incoming gas before it enters the oxidiser.
The catalyst bed temperature, the pressure drop across the catalyst bed, the combustion temperature and the carbon monoxide and oxygen content of the effluent gas stream should be monitored to maintain optimal combustion conditions.

Catalytic oxidation is most suited to systems with lower waste gas volumes, when there is little variation in the type and concentration of VOCs, and where catalyst poisons or other fouling contaminants are not present.

Applicability
Catalytic oxidation is mainly used for the removal of VOC from solvent evaporation. Implementation examples are:
- Bulk-loading fuel stations;
- Production of organic chemicals;
- Production of rubber and polymers;
- Resin production;
- Application and drying of solvent-laden coatings.

Table 5 shows application limits and restrictions associated with catalytic oxidation (adapted from EIPPCB, 2016, Table 3.209).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	1200-90000 (straight and regenerative cat. oxidiser) 90-90000 (recuperative catalytic oxidiser)
Temperature (°C)	300-500 before the catalyst 500-700 after the catalyst
Pressure	Atmospheric
Pressure drop (mbar)	10-50
Particulates content (mg/Nm^3)	<3

Table 5: Application limits and restrictions associated with catalytic oxidation

IONISATION

Description

In ionisation (also referred to as direct cold plasma technique), the air or the incoming gas flow is led through a reaction chamber where it is submitted to a very strong electrical field (20–30 kV) generated by electrodes, causing ions, free electrons, radicals and other highly reactive particles to be formed. However, no notable rise in temperature takes place. The highly reactive compounds cause the decomposition and (partial) oxidation of the pollutants present in the incoming gas. The most active particles in this process are the N, O and OH radicals. They are formed of nitrogen (N_2), oxygen (O_2) and water (H_2O). With direct treatment, the removal of organic chemicals is possible. In the case of injection of an ionised air stream, a modification of the odour molecules occurs and, to a lesser extent, a removal of the organic load.
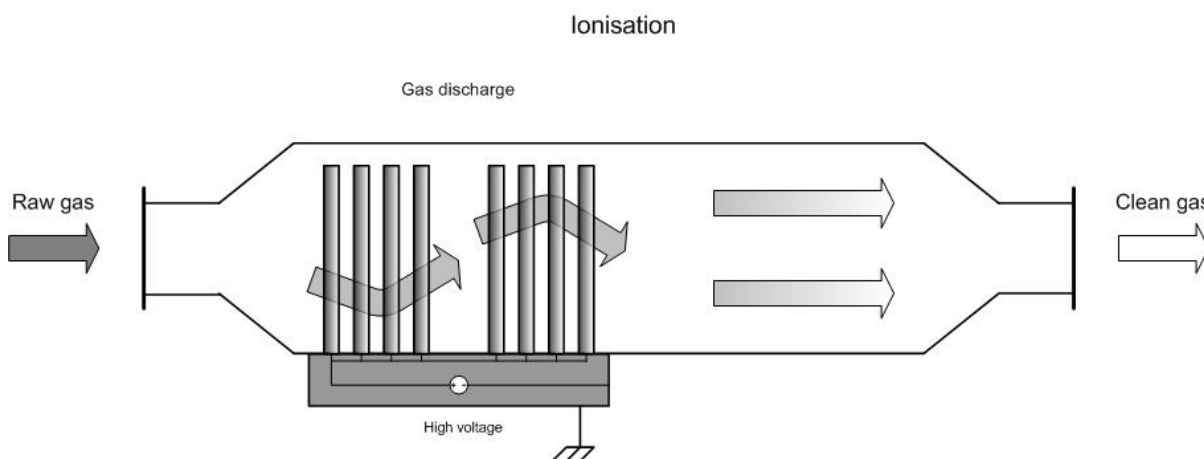

Figure 14: Diagram of an ionisation system

The decomposition of VOCs can generate emissions of CO_2, H_2O_2, CO, NO_X, etc. which can be treated using a catalyst system.

Ozone created in the electrical field is a side product. If it is not completely reacted it leads to ozone emissions. Ozone has a distinctive smell and can be harmful in high concentrations. Under normal atmospheric conditions, ozone is quickly transformed into oxygen. When placing a catalyst in series after the ioniser, the ozone is completely removed. In industrial applications, the ozone emission stays below one ppm.

Waste water is emitted as a small quantity of drainage water.

Design, maintenance and efficiency

The maintenance is minimal. If the unit is used to abate odour, a 'wash-down' once a week may be needed and an internal inspection once a month would be recommended.

Voltage is the main parameter that is to be monitored.

Applicability

Ionisation is normally used to treat waste gases with low concentrations of VOCs and in cases where thermal/catalytic oxidation is not effective.

The first prototype applications of plasma oxidation for air purification at an industrial scale date back to the late '80s. The technology has been fully commercialised since the mid-'90s. In the meantime, dozens of such installations are being used for odour control, including in the following sectors:

- Water purification (RWZI, food, chemicals and leather industry);
- Sludge composting;
- Tobacco industry;
- Foodstuffs industry;
- Fish-feed industry;
- Animal-feed industry;
- Slaughterhouses;
- Grain and soya processing;
- Potato processing (crisps production).

Besides odour control, the technique can also be useful for removing low solvent concentrations (including halogenated solvents), e.g. from a waste gas stream from the paint, varnish and printing ink industry. Though there is little experience of this at industrial scale.

Table 6 shows application limits and restrictions associated with ionisation (adapted from EIPPCB, 2016, Table 3.214).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	20-200000
Temperature (°C)	20-80; Higher temperatures are possible (up to 120) with plasma oxidation
Pressure	Atmospheric
Pressure drop (mbar)	Some
Relative humidity (%)	Not too high because of risks of condensation and short-circuiting. A heightened humidity improves the performance in a side stream set-up
Dust concentration	If applied directly into the gas stream, this should include relatively low amounts of dust. The ioniser will then act as an electrostatic precipitator
Energy	Ionisation is primarily suited for gas streams with low concentrations of VOCs because of the low energy consumption compared to thermal oxidisers

Table 6: Application limits and restrictions associated with ionisation

PHOTO/ UV OXIDATION

Description

The incoming waste gas stream is led through a reaction chamber and radiated with UV waves (100–280 nm). This radiation causes the decomposition of the undesired compounds. This decomposition takes place in two ways:

- photolysis: compounds such as VOCs, NH_3, H_2S and amines are directly broken down by the radiation;
- oxidation by reactive oxygen radicals: the presence of highly reactive oxygen radicals oxidises compounds that are not broken down by direct photolysis and reaction products from the photolysis.
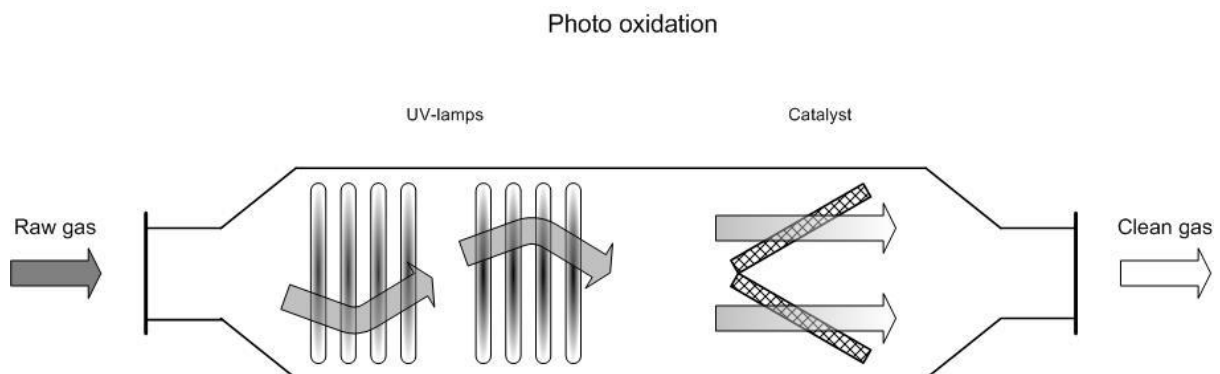

Figure 15: Diagram of a photo oxidation system

Design, maintenance and efficiency

Some suppliers install a catalyst, an adsorption system (activated carbon), or a second set of lamps with a different wavelength after the first photo oxidation phase to reach the highest possible removal rate. This extra phase also serves to break down the remaining ozone into oxygen.

Besides spent UV lamps (expected lifespan of about 8000 hours), no waste is created. The energy consumption is in the range of 0.3–1.5 kWh/1000 Nm^3.

Applicability

Photo oxidation is particularly suited to discontinuous processes with lower solvent concentrations (maximum 500 mg/Nm^3). The process reaches its steady-state removal yield almost immediately and has no extra start-up costs or disadvantages compared to continuous operation.

The first use of photo oxidation in air purification on an industrial scale dates back to the late '90s. Applications can be found in the following sectors:

- Coating installations;
- Wastewater treatment;
- Waste sorting/ processing installations;
- Fermentation processes, breweries;
- Foodstuffs industry (meat, fish);
- Kitchens.

Table 7 shows application limits and restrictions associated with photo/ UV oxidation (adapted from EIPPCB, 2016, Table 3.218).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	2000-58000 (in theory not very critical)
Temperature (°C)	< 60
Pressure	Atmospheric
Pressure drop (mbar)	NI
Relative humidity (%)	< 85 (max. dew point, no mist)
Dust concentration	Dust removal should preferably be carried out
NI = no information available	

Table 7: Application limits and restrictions associated with photo/ UV oxidation

WET GAS SCRUBBERS

Description

Wet scrubbing (or absorption) is a mass transfer between a soluble gas and a solvent – often water – in contact with each other. Physical scrubbing is preferred for chemical recovery, whereas chemical scrubbing is restricted to removing and abating gaseous compounds. Physico-chemical scrubbing takes an intermediate position. The compound is dissolved in the absorbing liquid and involved in a reversible chemical reaction, which enables the recovery of the gaseous compound.

Depending on the pollutants to be removed, several aqueous scrubbing liquids are used including the following:

- Water, to remove solvents and gases such as hydrogen halides or ammonia, with the main aim being to recover and reuse these contaminants.
- Alkaline solutions (e.g. caustic soda – i.e. sodium hydroxide – and sodium carbonate), to remove acidic compounds such as hydrogen halides, sulphur dioxide, hydrogen sulphide (H_2S), phenols, chlorine. The pH value of the alkaline scrubber depends on the pollutant to be removed; pH is often kept between 8.5 and 9.5 (for SO_2 removal a pH range of 6.5–7.5 is needed, whereas for H_2S removal a pH of 10 or more is required). The pH value should not be too high because of absorption of CO_2 in the water. A pH value of 10 and above will cause the dissolved CO_2 to be present in the water as carbonate, causing the alkaline consumption rate to increase dramatically. The calcium carbonate will also deposit on the gaskets, increasing the pressure drop. To avoid this, softened water can be used in an alkaline gas scrubber.
- Alkaline oxidative solutions, i.e. alkaline solutions with oxidants such as sodium hypochlorite ($NaOCl$), chlorine dioxide (ClO_2), ozone (O_3) or hydrogen peroxide (H_2O_2); these are particularly indicated for the removal of odours.
- Sodium hydrogen sulphite solutions, to remove odour (e.g. aldehydes).
- Acidic solutions, to remove alkaline compounds, e.g. ammonia, amines and esters. The dosing of the acid is done by means of pH regulation. In most cases, the pH is kept between 3 and 6. Sulphuric acid (H_2SO_4) is often the acid of choice for economic reasons. For specific applications, for example the removal of NH_3, nitric acid (HNO_3) is used.
- Monoethanolamine and diethanolamine solutions, suitable for the absorption and recovery of hydrogen sulphide.
- Organic solvents with low volatility, e.g. chilled nonane for the recovery of light VOCs such as butanes and pentanes.

Various types of scrubbers are operated, such as:

- fibrous packing scrubbers;
- moving-bed scrubbers;
- packed-bed scrubbers;
- impingement plate scrubbers;
- spray towers.

Their choice depends on the following:

- requirements for performance efficiency,
- energy needs,
- reagents,
- properties of the waste gas stream.

Design, maintenance and efficiency

An optimum design of scrubbing systems to achieve low exit concentrations includes high reliability, automatic operation and a countercurrent flow of liquid and gas. Scrubbers are commonly operated with precoolers (e.g. spray chambers and quenchers) to lower the inlet gas

temperature and simultaneously saturate the gas stream, thus avoiding reduced absorption rates and solvent evaporation. Such additional devices exert low pressure drops.

The abatement efficiency of gas scrubbers is dependent on the residence time of the gas in the absorption section, the type of packing used, the liquid to gas ratio (L/G), the refreshing rate, the temperature of the water and the addition of chemicals.

In the case of alkaline-oxidative scrubbers, abatement efficiency depends on the oxidisability of the compounds and the residence time in the scrubber.

An increase in the residence time requires larger installations and higher investment costs. Pilot tests are essential for achieving good design.

The consumption of scrubbing water depends to a great extent on the incoming and outgoing concentrations of gaseous compounds. Evaporation losses are primarily determined by the temperature and the humidity of the incoming gas stream. The outgoing gas stream is, in most cases, completely saturated with water vapour.

Scrubbing generates waste water which needs treatment, if the scrubbing liquid with its content is not otherwise used.

Routine measurement is necessary for:
- the pressure drop across the scrubber, as a means to discover operational anomalies that might require maintenance;
- the scrubber make-up water flow rate;
- the recycle water flow rate;
- the reagent flow rate;
- in some cases pH, temperature, electrical conductivity and reduction potential.

Wet scrubbers need regular inspection to identify any deterioration in the plant, such as corrosion or blockages. Access to the scrubber should be readily available. It is essential that operating failures be detected quickly, and adequate instrumentation with alarms be applied at the outlet vent of the absorption plant to ensure that warning is given if equipment fails.

When using an alkaline oxidative scrubber with NaOCl, toxic chlorine fumes might be formed at low pH values. An alkaline scrubber might then be placed in series to the alkaline oxidative scrubber to remove these chlorine fumes.

Absorption is enhanced by:
- larger contacting surfaces;
- higher liquid/gas ratios;
- higher concentrations in the gas stream;
- lower temperatures.

Applicability
Alkaline oxidative scrubbing is reported to be used in the sectors such as the food industry, slaughterhouses, flavouring agents production and the textiles industry.

Table 8 shows application limits and restrictions associated with wet scrubbing (adapted from EIPPCB, 2016, Table 3.307).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	50-500000
Temperature (°C)	5-80
Pressure	Atmospheric
Pressure drop (mbar)	~12
Particulates content (mg/Nm^3)	<10

Table 8: Application limits and restrictions associated with wet scrubbing

BIOFILTRATION

Description

The waste gas stream is passed through a bed of organic material (such as peat, heather, compost, root wood, tree bark, peat, compost, softwood and different kinds of combinations) or some inert material (such as clay, activated carbon, and polyurethane), where it is biologically oxidised by naturally occurring microorganisms into carbon dioxide, water, inorganic salts and biomass.
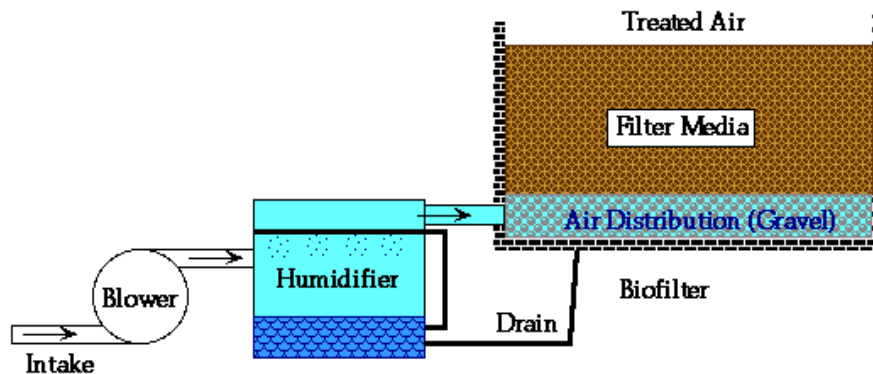

Figure 16: Scheme of a biofiltration system

Biofilters can be divided into:
- open biofilters;
- enclosed biofilters.

An open biofilter consists of a layer of porous biofiltering material underlaid by a network of pipes through which the contaminated air is blown to the filter. These filters require a long residence time and therefore tend to be large. They might be used for low gas rates. In areas with a cold climate (frost), the suitability of open biofilters is restricted.

An enclosed biofilter consists of a layer of material supporting a suitable microbial population and placed under a distribution system which supplies the contaminated waste gas stream to the filter uniformly. The gas stream is drawn to the filter by electric fans. Gas flow is from top to bottom or vice versa. The blower, ventilation system and biofilter construction materials should minimise the effects of corrosive waste gas, excess condensate and dust/sludge.

The majority of biofilters in operation are open-bed filters, which are less costly than enclosed biofilters but generally less efficient.

Design, maintenance and efficiency
The microorganisms are enclosed in a fixed bed. The height of the filter material is between 0.5 m and 1.5 m, with a maximum of two to three layers. The specific load of the filter bed is between 100 and 500 Nm^3/h per m^2 of filter surface.

Parameters such as biofilter media pH, moisture content (relative gas moisture of about 95% and more is required) and inlet gas temperatures affect odour removal capacity.
The moisture balance is regulated by a pre-connected humidifier or gas scrubber, at times in combination with a moistening of the filter material. The relative humidity of the filter material should be below 60% to avoid clogging. The moistening device needs protection against freezing in regions where temperatures are substantially below 0 °C.
For application to warm waste gas streams (> 35 °C), cooling is necessary, either by mixing with air or introducing a gas scrubber or heat exchanger. Wet scrubbing can be applied as a pre-treatment with the aim of decreasing excessive particulate content, inlet odour concentration and amount of pollutants not suitable for biofiltration.
The residence time to allow an effective abatement depends on the inlet concentration. As a rough guide, a minimum residence time of 30 s to 45 s should be aimed for.

For some odorous compounds (e.g. mercaptans, H$_2$S), abatement efficiencies of 75% are a minimum. Using a scrubber and biofilter in combination can increase performance. For other odorous compounds, the abatement efficiency is somewhat lower. Comparative research for odour abatement efficiencies between scrubbers and biofilters show that biofilters achieve higher efficiencies.

With open biofilters the filter material has to be regularly worked up and disposed of from time to time. Waste gas channelization can occur through the filter bed, thereby decreasing the biofilter efficiency.

The efficiency of biofiltration depends to a great extent on the composition of the waste gas stream. Also, sudden changes in biofilter media conditions (e.g. temperature) can adversely affect the performance of the system. If parameters do change slowly over time then the media become accustomed and efficiencies remain high.

Cooling is necessary for applications with hot airflows (> 38 °C). This can be realised by a mixture of outside air, a (single-pass) water scrubber or a heat exchanger/condenser.
The filtering material should be replaced periodically (every 0.5 – 5 years), depending on the type of packing material and the composition of the gases.

Although biofilters are static in principle and require little mechanical maintenance, experience shows that regular inspection and monitoring are necessary. The abatement efficiency can be excellent during the first few years, but can decrease drastically over a short period of time because of a lack of nutrients, problems with the fluid balance and/or the deterioration of the filter material.

The moisture balance has to be carefully examined because it is critical for the accurate operation of biofilters.

Applicability

Biofiltration is well-suited to low concentrations of pollutants that are easily soluble in water. It is normally not suitable, however, for waste gases containing many different and/or changing pollutants. Furthermore, methane is not abated, because the residence time needed would be too long for normal filter dimensions.

Biofiltration is primarily used for large flow rates and low solvent concentrations.

Typical areas for implementation are:
- Wastewater treatment plants
- Composting installations
- Flavourings industry
- Foundries
- Chemicals industry
- Plastic production
- Foodstuffs industry
- Meat and fish-processing industry

Table 9 shows application limits and restrictions associated with biofiltration (adapted from EIPPCB, 2016, Table 3.178).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	100-200000 100-400 per m^2 of filter surface
Temperature (°C)	15-38
Pressure	Atmospheric
Pressure drop (mbar)	5-20
Content of dust, grease and fat	Can cause clogging; pretreatment is necessary
Odour concentration (ou$_E$/m^3)	20000-200000
Climatic conditions	Frost, rain and high ambient temperatures affect the filter material and decrease efficiency

Table 9: Application limits and restrictions associated with biofiltration

BIOSCRUBBING

Description

Bioscrubbing combines wet gas scrubbing (absorption) and biodegradation; the scrubbing water contains a population of microorganisms suitable to oxidise noxious gaseous compounds. The microorganisms are suspended in water. Hence, the conditions to use bioscrubbers are:
- the existence of the possibility to wash out the waste gas constituents;
- the washed-out constituents must be biodegradable under aerobic conditions.
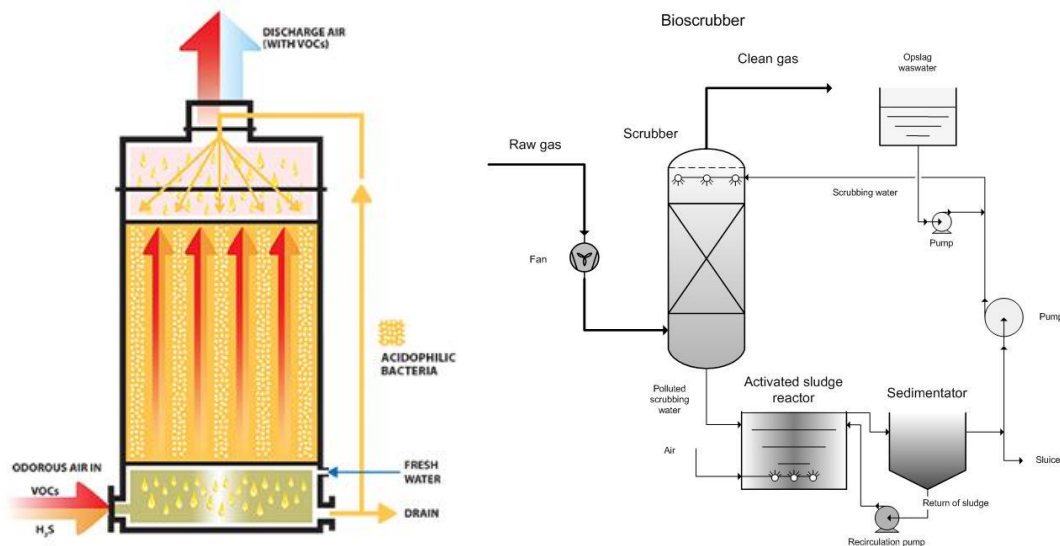
Figure 17: Scheme of a bioscrubber

The bioreactor design is founded on an activated sludge or a sludge-on-carrier system. The water sludge mixture is recirculated into the reactor. The absorbed pollutants are degraded in aerated sludge tanks.

Bioscrubbers are frequently inoculated with activated sludge, e.g. from a biological waste water treatment plant. Depending on the composition of the waste gas, the performance of the bioscrubber will only attain the desired level after some weeks of adaptation. Inoculation with cultures prepared in fermenters is particularly applied to contaminants that contain sulphur (mercaptans, hydrogen sulphide, dimethyl sulphide, etc.) or chlorine (chlorinated methanes or ethanes).

Design, maintenance and efficiency
The bioscrubber should be designed in such a way that the residence time of the gases is around one second. Depending on the solubility of the compounds, this may be slightly more or less. The bioscrubber requires a special open packing and special spray nozzles to prevent clogging due to the biological sludge. A hydraulic residence time of the scrubbing water of between 20 and 40 days gives the best results.

Applicability
Bioscrubbing is well-suited to low concentrations of pollutants that are easily soluble in water; it is well-suited to the abatement of alcohols, aldehydes and ketones, carboxylic acids and their esters, phenols, heterocyclic sulphur and nitrogen compounds, mercaptans, amines, chlorophenols, hydrogen sulphide, naphthalene, sulphides and ammonia.
It is not suited for aliphatic hydrocarbons, aromatic hydrocarbons, ethers and halogenated hydrocarbons.

Application of bioscrubbers for odour removal can be found in:
- Cigarette industry: Odour concentration is reduced by approximately 5000 ou_E/m^3 to 200 – 300 ou_E/m^3
- Wastewater treatment plants

- Production of enzymes
- Production of aromas
- Rubber industry
- Production of polymers
- Processing of paint residues

Table 10 shows application limits and restrictions associated with bioscrubbing (adapted from EIPPCB, 2016, Table 3.185).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	1000-3000 Nm^3/h per m^2 of column surface
Temperature (°C)	15-40 30-35 (optimum)
Pressure	Atmospheric
Pressure drop (mbar)	2-3
Sludge concentration	Maximum 15 g/l dry matter
Odour concentration (ou$_E$/m^3)	>10000

Table 10: Application limits and restrictions associated with bioscrubbing

BIOTRICKLING

Description

Biotrickling works under similar conditions to bioscrubbing but, in contrast to bioscrubbing, the microbes are fixed on supporting elements.
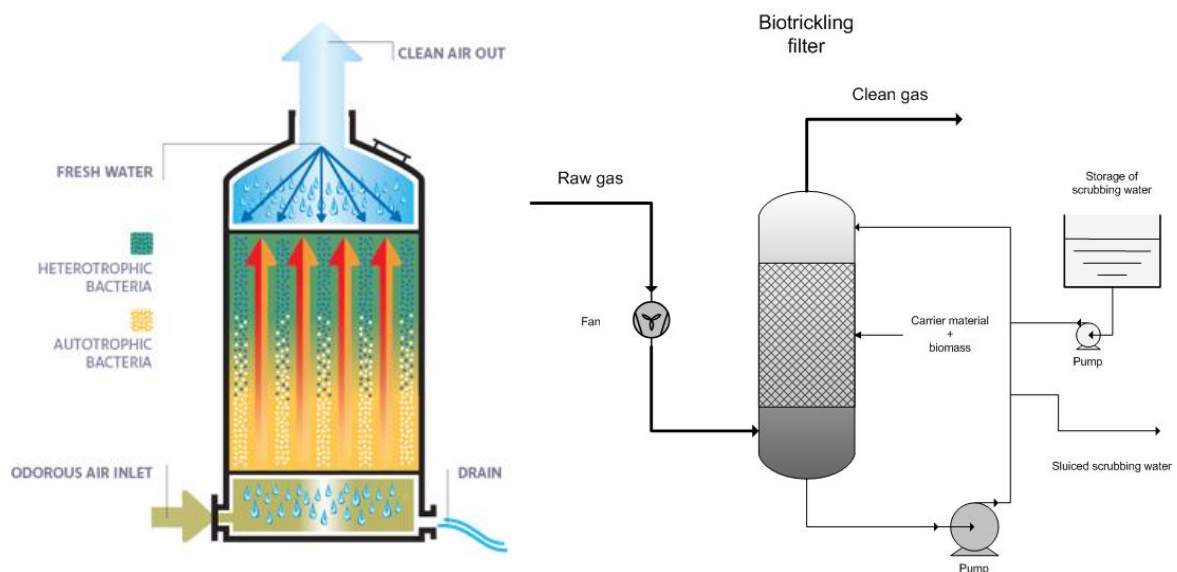

Figure 18: Scheme of the biotrickling process

In a biological trickle-bed reactor, an aqueous phase is continuously circulated through a bed of inert material. This packing can consist of irregular bulk material, such as rings, saddles, etc. or

of structured packing. When selecting the packing material, it is necessary in every single case to ensure that, even in the event of an anticipated excess sludge formation, the reactor will not become choked in the long term. The surface properties should be such that the biofilm adheres to it firmly. The pollutants in the waste gas and the oxygen are absorbed by the water phase and transported to the biofilm, where the biological transformation takes place. The quality of the mass transfer from the gas to the liquid phase and the elimination performance of the reactor essentially depend on the wetted surface area of the packing. In order to achieve optimum elimination results, i.e. to maximise the wetted surface area, the liquid phase should be distributed uniformly over the surface of the biofilm.

The immobilisation of the biomass and the formation of the biofilm are generally a naturally controlled process which starts after inoculation of the water phase. The continuously circulating liquid phase takes on the function of supplying the microbe population with the necessary nutrients. At the same time, excess activated sludge and reaction products which can also be inhibitors, e.g. hydrogen chloride during the degradation of dichloromethane, are washed out of the reactor. In the liquid phase, the essential conditions such as pH, nutrients and salt accumulation need to be controlled.

Design, maintenance and efficiency

The handling of the biological film layer (biofilm) of the packing is essential: too much growth can lead to (local) clogging that finally results in preferential streams, causing the size of the exchange surface and thus the performance of the biotrickling filter to worsen. The growth and thickness of the biofilm can be controlled by adjusting the thickness with mechanics (like varying the humidification) or by adjusting the growth of the microorganisms by varying the degree of acidity and/or the salt content.

Applicability

The application of biotrickling is comparable to that of bioscrubbing. Slight differences are found in the pollutant compounds for which both treatment techniques are suitable. Biotrickling filters are primarily used to remove gases with acidic components.

Table 11 shows application limits and restrictions associated with biotrickling (adapted from EIPPCB, 2016, Table 3.191).

Issue	Limits/ restrictions
Gas flow (Nm^3/h)	1000-500000
Temperature (°C)	15-40 30-35 (optimum)
Pressure	Atmospheric
Pressure drop (mbar)	1-10
Concentration of microorganisms	> 15 g/l dry matter
Odour concentration (ou_E/m^3)	>10000

Table 11: Application limits and restrictions associated with biotrickling

ABATEMENT EFFICIENCY

Determination of abatement efficiency

The abatement efficiency of the system is determined by monitoring the concentration of odour before and after the adsorption system. When referring to odour removal, abatement efficiencies are determined by taking grab samples at appropriate sampling points at the abatement system inlet and outlet, and subsequently analysing them by olfactometry according to EN 13725:2003.

Typical ranges of abatement efficiencies

The BREF for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector reports the ranges of abatement efficiencies specifically related to odour removal for the end-of-pipe odour treatment techniques reported in Section 3.5.5.4.2.1 (Table 12).

Technique	Reported odour abatement efficiency (%)
Adsorption	80-99
Thermal oxidation	98-99.9
Catalytic oxidation	80-95
Ionisation	80-98
Photo/UV oxidation	80-98
Wet scrubbers	60-85
Alkaline oxidative scrubbing	80-90
Biofiltration	70-99
Bioscrubbing	70-80
Biotrickling	70-90
Moving-bed trickling filter	>90
	Physical
	Chemical
	Biological

Table 12: Odour abatement efficiency ranges reported for different end-of-pipe odour treatment techniques

In the scientific literature, there are several research and/or review papers reporting abatement efficiencies for different systems. However, it is not always easy to find data about odour abatement efficiency in terms of odour units.

Another example of comparison of different techniques for the specific treatment of odour emissions from wastewater treatment plant as a function of the hydrophobicity of the odorous compounds to be abated is found in Estrada et al. (2011) (Table 13).

Technique	Reported odour abatement efficiency (%)		
	High Hydrophobicity	Medium Hydrophobicity	Low Hydrophobicity
Biofilter	75	95	99
Activated sludge	50	90	99
Biotrickling filter	50	90	99
Chemical scrubber	50	90	99
Impregnated AC	99.9	98	99
Incineration	99.9	99.9	99.9

Table 13: Odour abatement efficiency ranges reported by Estrada et al. (2011) for different odour treatment techniques in wastewater treatment plants as a function of the hydrophobicity of the compounds to be abated

APPLICABILITY: COMPARISON OF DIFFERENT TECHNIQUES

Table 14 summarizes a comparison of the applicability of the main odour treatment techniques in function of the flow rate (in Nm^3/h), the temperature, the relative humidity, the discontinuity, and the odour concentration (in ou_E/m^3) of the gas to be treated.

The information reported is extrapolated from the BREF for Common Waste Water and Waste Gas Treatment/Management Systems, and from the free-accessible database made available by the Belgian company Vito at https://emis.vito.be/en/luss-0.

Abatement method	Flow rate (Nm^3/h)	Temperature (°C)	Relative humidity (%)	Discontinuous flow	Odour concentration (ou_E/m^3)
Activated Carbon (Adsorption)	100-100000	15-80 (opt. <50)	< 70	Y	5000-100000
Thermal Oxidation	1000-100000	900-1200	n.s.	N	1000-1000000
Catalytic oxidation	1000-100000	300-600	n.s.	N	1000-1000000
Ionisation	20-200000	20-80	Low	Y	5000-100000
Photo oxidation	2000-60000 (not critical)	< 60 (opt. 20-40)	< 85	Y	500-10000
Alkalyne Oxidative Scrubbing	50-500000	5-80	0-100	Y/N	500-100000
Biofiltration	100-200000	15-38	> 95%	N	20000-200000
Bioscrubbing	n.s.	15-40 (opt. 30-35)	n.s.	N	> 10000
Biotrickling	1000-500000	15-40 (opt. 30-35)	n.s.	N	> 10000

n.s. = not specified

Table 14: Comparison of the conditions for the applicability of different odour treatment techniques

PROS AND CONS OF THE DIFFERENT ABATEMENT TECHNOLOGIES

Table 15 summarizes the main advantages and disadvantages related to the different odour treatment techniques here examined.
Also in this case, the information reported is extrapolated from the BREF for Common Waste Water and Waste Gas Treatment/Management Systems, and from the free-accessible database by the Belgian company Vito (https://emis.vito.be/en/luss-0).

Technique	Advantages	Disadvantages
Adsorption	- High efficiency for VOC removal and recovery - Simple and robust technology - High saturation level of the adsorbent - Simple installation - Relatively simple maintenance - Suitable for discontinuous processes	- Particulates in the waste gas stream can cause problems (i.e. clogging) - Not suitable for wet gases (less critical for impregnated activated carbon) - Risk of bed fires - Polymerisation risk for unsaturated hydrocarbons on the activated carbon (exothermal and causes blockages)
Thermal oxidation	- Good and constant performance - Simple principle - Reliable in operation - Recuperative and regenerative oxidation have a high thermal efficiency, with the effect of lowering extra fuel consumption and hence lowering carbon dioxide emission - Process integration of waste heat or steam generation is possible	- Emission of carbon monoxide and nitrogen oxides - Risk of dioxin formation, when chlorinated compounds are incinerated - Additional fuel needed, at least for start-up operations, and VOC concentration below auto-ignition point (not cost-effective with low concentrations and high flow)
Catalytic oxidation	- More compact than thermal oxidisers - Requires lower temperatures (i.e. less energy consumption and less isolation required) and less additional fuel than thermal oxidisers - Little or no NO_X produced from atmospheric fixation (about 20–30% of the amount formed by thermal oxidation) - CO in the waste gas stream is simultaneously abated by the catalyst - Good, constant and reliable performance is possible - Recuperative and regenerative oxidation have a high thermal efficiency, with the effect of lower extra fuel consumption and lower carbon dioxide emission - Process integration of residual heat or steam generation is possible - Little or no insulation requirements	- Higher investment costs than with thermal oxidation - Lower efficiency in VOC destruction than thermal oxidation - System sensitive to changes in the energy content of the waste gas - Risk of dioxin formation, when chlorinated compounds are present in the waste gas - All catalysts susceptible to poisoning agents, fouling agents and activity suppressants - Particulates must often be removed first - Spent catalyst that cannot be regenerated may need to be disposed of

Ionisation	• Low energy consumption compared to thermal oxidisers (for gas streams with low pollutant concentrations) • Very compact • Can be placed indoors and outdoors • May be turned on and off at will (almost no start-up time) • Relatively simple operation • Not sensitive to variations in the gas stream • Process takes place at a low temperature	• Electricity consumption • Preliminary testing before installation is recommended to examine whether the technique is suited to a specific emission problem • Only suitable for VOC removal when the system is applied directly to the gas stream • Risk of electromagnetic radiation. This risk is limited when the casing is made of metals
Photo/ UV Oxidation	• Compact and modular system • Close to no start-up time • Can be placed indoors and outdoors • Operation at low temperature • Low energy consumption • Noise-free	• Preliminary testing before installation is recommended to examine whether the technique is suited to a specific emission problem • Not suitable for high concentrations of pollutants (VOC > 500 mg/m^3)
Wet scrubbers	• Wide range of uses • Very high abatement efficiency can be achieved • Compact installation thanks to a favourable ratio between capacity and device volume • Simple and robust technology • Simple maintenance • Only few wear-sensitive components • Can handle flammable and explosive gases/dusts with little risk • Can also cool hot gas streams (quencher) • Can handle mists • Can be constructed in modules	• Water or diluted chemicals are required for the replacement of the purged water and the evaporation losses • Waste water needs treatment • Conditioning agents (e.g. acids, bases, oxidants, softeners) are required for many applications • For roof fitting, support structures are needed • Sensitive to corrosion. For outdoor fitting, frost protection is needed (depending on climate) • Packing material sensitive to clogging because of dust or grease • Off-gas may require reheating to avoid visible (steam) plume • Pilot-scale tests are required in order to evaluate the abatement potential of the system • Recirculation of scrubbing liquid may cause an increase in odour emission
Biofiltration	• Low investment and operating costs • Simple construction • In combination with adsorption and absorption, also suitable for barely soluble compounds • High efficiency for biodegradable compounds, e.g. odorous substances • Low amount of waste water (percolate water) and waste material	• Dried-out peat and compost filter beds are difficult to rewet • Relatively bulky design; high surfaces needed • Poisoning and acidification of the biomass must be prevented • Fluctuations in the waste gas stream conditions have a significant impact on performance • Packing is sensitive to dust clogging • Limited control (including pH) • Energy consumption where cooling of the incoming gas is necessary

Bioscrubbing	• High concentrations of easily degradable compounds can be abated owing to high microbial conversion • High concentrations of compounds containing sulphur, chlorine, and/or nitrogen can be abated by controlling the pH • Peak emissions can be controlled better than with a biofilter or biotrickling filter	• Biomass builds up, needs to be disposed of as waste and can result in blockage of the circulating water • Primarily suited for easily soluble compounds, poorly soluble compounds are more difficult to abate • Compounds must be biologically degradable • Fluctuations, e.g. changing concentrations and flow in the gas stream, have a significant impact on performance • Percolate water needs treatment
Biotrickling	• Biological decomposition of components; no VOC residual products • Suitable for medium concentrations of acidifying compounds which contain sulphur, chlorine and nitrogen • Suitable for decomposition of acid-forming components • Small pH corrections are possible • Low pressure drop • Average investment and operating costs • Compact construction and reasonable space requirements • Low energy consumption and thus limited CO_2 emissions • Little use of additives • Better reliability than a biofilter	• Fluctuations in intake air stream conditions (type and concentration of pollutants) have a significant impact on efficiency • Poorly soluble compounds are more difficult to abate • High concentrations of toxic and acidifying substances should be avoided • The biomass can obstruct the packing • More complex to construct than a biofilter, and more expensive • Production of waste water

Table 15: Advantages/ Disadvantages of the different odour treatment techniques

3.3 Other odour control methods

GENERAL CONSIDERATIONS

The abatement methods described in the previous section of the present report are so called "end-of-pipe" treatment techniques, which can be applied in order to reduce the odour concentration of a certain waste gas flow. Since such techniques require a channelled and defined air flow, they are only applicable to conveyed emissions.

For diffuse odour emissions, different strategies shall be adopted. Besides the methods for the prevention of VOC emissions described in section 3.5.4 of the BREF for Common Waste Water and Waste Gas Treatment/ Management Systems in the Chemical Sector, there are some technical expedients and interventions that can be implemented in order to reduce the odour impact related to diffuse odour emissions.

Such expedients, which will be shortly described in this section, include:
- Covers/ enclosures (for liquid/ solid surfaces)
- Improving the emission dispersion capability
- Nebulization of de-odourizing/ masking products

COVERS/ENCLOSURES

Passive area sources consist in extended solid or liquid surfaces without an outward airflow, which are exposed to the atmosphere and therefore may originate emissions of volatile odorous compounds.

Examples of passive area sources that typically are associated with odour emissions are for instance wastewater treatment tanks (liquid) or composting piles (solid).

One way to reduce emissions from this type of sources is to minimize the evaporation of odorous substances by reducing the portion of the odorous surface that is directly exposed to the atmosphere. This can be achieved by enclosing the emitting surface with specific covers.

There are many cover styles available on the market: fixed covers, floating covers, inflatable covers, retractable covers, covers made from flexible geomembranes, and covers made from rigid materials such as aluminum, fiberglass, or steel.

Covers can – in principle – be applied both to liquid and to solid surfaces. When evaluating the possibility to cover an odour source, some important factors shall be taken into consideration such as:

- Possibility of normal operation/ maintenance of the source after covering
- Oxygen demand for sources that require aerobic conditions (e.g., composting piles)
- Possibility that flammable conditions are reached under the cover

Some examples of covers are shown in Figure 19-Figure 20.

Figure 19: Examples of covered wastewater treatment tanks

Figure 20: Examples of covered composting piles

IMPROVING THE EMISSION DISPERSION CAPABILITY

The impact caused by an odour source on its surroundings is not only a function of the emitted odour concentration and of the gas flow rate (the product of the odour concentration and of the air flow rate is called "Odour Emission Rate" – OER), but also of how the emitted air flow is dispersed into the atmosphere before it reaches a certain receptor.

For this reason, an alternative effective strategy to reduce odour impacts is to improve the dispersion capability of an odour source.

This can be achieved basically (but not exclusively) with the following technical interventions.

- For non-conveyed emissions, by **conveying emissions into a stack** (Zanetti et al., 2010). One typical example where this solution is applicable is represented by sheds without forced ventilation, where the emissions occurs by diffusion through the openings (i.e. doors and windows). In such cases, if ventilation is forced through one (or more) stacks by fans, dispersion can be greatly improved, thereby reducing the odour impact significantly.

- **Verticalization of horizontal emissions**. In industrial applications, there are a lot of situations where emissions are horizontal, or where vertical stacks are equipped with "raincaps" (Figure 21). Despite the undeniable advantages of preventing the entrance of rainwater, and in some cases of facilitating the deposition of emitted dust in proximity of the source, such technical features inhibit the vertical component of the emission outlet velocity, thus worsening the dispersion capability significantly. For this reason, technical interventions aiming to "verticalize" such emissions, which increase the so called "plume rise" effect, can produce a significant benefit in terms of odour dispersion, thus resulting in a reduction of the odour impact. Figure 22 shows two odour dispersion maps comparing the odour impact related to a plant with horizontal emissions (left) with the odour impact produced if the same emissions are vertical instead of horizontal (right): indeed, a significant reduction of the odour impact is obtained without reducing the emitted odour concentration.

Figure 21: Examples of horizontal emissions (left) and stack with raincap (right)
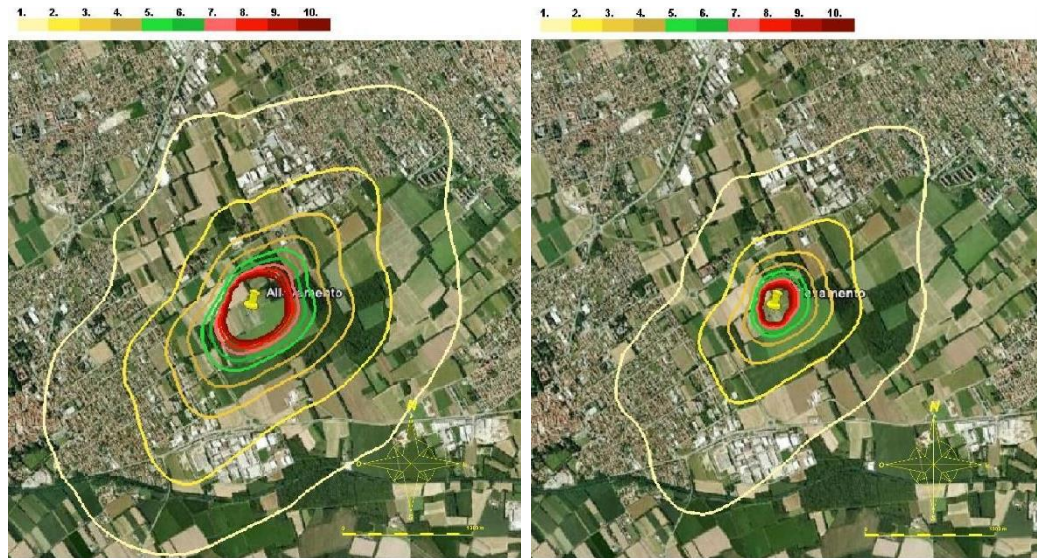
Figure 22: Comparison of a plant odour impact with horizontal emissions (left) and with verticalized emissions (right)

- **Increasing the stack height**. Another effective way of enhancing the dispersion capability of an emission, is increasing the height of the release point. In the case of point sources (through a stack), this means increasing the stack height. This solution is particularly effective if the emission point is raised at heights of about 50 m, for which the dispersion capability of the stack improve significantly. Figure 23 shows the odour impact related to a stack with a height of 27 m (left) with the odour impact produced by the same stack at a height of 50 m (right): indeed, a significant reduction of the odour impact is obtained without reducing the emitted odour concentration.

Figure 23: Comparison of the odour impact related to the emission from a stack with a height of 27 m (left) and 50 m (right)

These solutions, despite not necessarily banal, have the advantage of being generally more economic than others, involving the realization of a new abatement system. Indeed, the modification of a plant design for the improvement of the dispersion capability of an odour source usually involves (sometimes high) investment costs, but after that it has no operational

costs. And in many cases, they can produce very high benefits in terms of odour impact reduction. This type of solution is particularly indicated where the waste gas stream is hardly treated with the common technologies, or where abatement systems are already applied, and their abatement efficiency is not sufficient to meet odour impact criteria.

Another positive aspect is that the effect of such solutions can be preventively be verified before their implementation by applying dispersion modelling.

NEBULIZATION OF DE-ODOURIZING/ MASKING PRODUCTS

Another quite common solution for the reduction of odour emissions, which can be applied both to conveyed and to diffuse sources, is the nebulization of de-odorizing or masking products.

In the case of conveyed emissions, the nebulizing nozzles can be installed directly at the stack outlet, with the aim of reducing the odour concentration of the emitted air flow. In the case of diffuse emissions, such as wastewater treatment tanks, composting piles or landfills, the nebulization of the de-odorizing product can be realized with the purpose of creating a sort of "osmogenic barrier" for the abatement of the odours that diffuse into the atmosphere. Nebulization can also be implemented inside sheds (for instance, sheds for the receiving / treatment of solid wastes). Some examples of applications are illustrated in Figure 24.

Such de-odorizing products usually have an own, pleasant odour (typically fresh/ piny/ citrusy due to the presence of terpenic compounds) and are usually diluted at low (or very low) concentrations in water.

Indeed, the dosing of the de-odorizing product is critical in order to avoid the emission of odours due to the deodorizing product itself: this is usually less unpleasant than the odour to be treated, but if the concentration is high, then it might still become a source of odour nuisance.

This is one of the main reasons why preliminary tests are required in order to optimize the application for the specific case.

Figure 24: Example of nebulization of de-odorizing products for odour abatement

However, verification of the efficiency of the abatement, especially in the case of diffuse emissions is hardly applicable, thus requiring specific experimental setups (Dentoni et al., 2012) or field odour measurement campaigns.

Despite very appealing declarations about the capability of neutralizing odours that can be found on commercial material (i.e. websites and brochures), the functioning principle of such de-odorizing is not really understood. Some producers declare the presence of microorganisms that biologically degrade the odour, some others of encapsulating molecules that "trap" the odorous

molecules making them inoffensive. As already mentioned, since de-odorizing products are usually used diluted, the presence of the water surely has a scrubbing effect that adds to the reduction of the odour emissions, at least for hydrophilic odorous compounds. However, there are some examples, where the application of such products has been proven to be effective in reducing the odour perception outside the plant and the frequency of complaints (Culos et al., 2009).

This solution has the advantage of having low investment costs. The degree of the operational costs may be significant, depending on the cost and on the quantity of the nebulized product.

3.4 References

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