The need for electronic noses for environmental odour exposure assessment

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INTRODUCTION

Nowadays, odours are subject to control and regulation in many countries (Nicell 2009), thus entailing the need for specific methods for exposure assessment. At present, several odour regulation approaches are based on dispersion modelling. The first example of such an approach is represented by the Horizontal Guidance for Odour of the United Kingdom (UK Environmental Agency 2002), which establishes exposure criteria in terms of ground-level odour concentration at the 98th percentile, i.e. the maximum odour concentration that may only be exceeded for 2% of the hours in a year, whereby the limits are differentiated on the basis of the level of potential olfactory annoyance ('low', 'medium' or 'high') associated with the industrial category under consideration. Other examples are the French regu-lations for composting plants (JORF 2008) or the recent guidelines for Lombardy (Italy) (Regione Lombardia 2012), both fixing acceptability standards in terms of the frequency with which a given odour concentration is exceeded. Such regulatory approaches are based on the concept of accounting for the effective exposure of citizens to odour, thus overcom-ing older approaches based just on source characterisation.

Dispersion models, however, need dispersion data as inputs, thus requiring a detailed characterisation and quantification of the odour emissions in terms of the odour emission rate (OER), i.e. odour emitted per time unit (ou_E/s), for every hour of the simulation time domain. This step may in some cases entail serious difficulties, thus making dispersion modelling barely reliable, or even not applicable. Such cases include, for instance, diffuse sources, such as unventilated sheds, tanks, caissons, etc., whereby an estimate of the emitted air flow is very difficult to achieve (Figure 1).

Another critical case is represented by sources with variable emissions over time, whereby it is difficult to associate a given OER with every hour of the simulation time domain. Such variable emissions are typical of discontinuous production, including for instance plants working to order, which either work just a few hours a day (e.g. plants for the production of asphalts), or which manufacture different products depending on customers' requests (e.g. pharmaceuticals).

In such cases, where dispersion modelling is barely applicable, it might be useful to be free of the necessity to minutely characterise the emissions, and to determine the

Figure 1 | Examples of diffuse sources (from left to right): unventilated livestock shed, floating-roof oil storage tanks, partially covered wastewater treatment tank and sludge storage container.

exposure to odours directly where their presence is a nuisance. Electronic noses could be used for this purpose. The instruments need to be suitable for the continuous analysis of the ambient air by their receptors, thereby detecting the presence of odours, and possibly classifying and/or quantifying them as well.

This paper discusses the state-of-the-art electronic nose technology as far as its application to the environmental sector is concerned, and more specifically to the determination of odour exposure at receptors, focusing on the critical aspects connected to this kind of use.

Finally, an example of electronic nose application to the monitoring of odours from a municipal solid waste (MSW) landfill located in Northern Italy is reported, in order to discuss its potential and limits.

STATE OF THE ART OF ELECTRONIC NOSE APPLICATIONS TO ENVIRONMENTAL MONITORING

The electronic nose requirements

The electronic nose is a complex system with human nose-like attributes (Pearce 1997; Sankaran *et al.* 2012), and can be defined as 'an instrument which comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern recognition (PR) system, capable of recognising simple or complex odours' (Gardner & Bartlett 1994). The electronic nose does not perform a chemical analysis of a mixture, but the partially selective sensor array produces a kind of 'olfactory pattern', which can be subsequently classified based on a reference database acquired by the instrument in a previous training phase (Ampuero & Bosset 2003; Capelli *et al.* 2008).

Different sensor types can be used in electronic nose systems (James *et al.* 2005; Wilson & Baietto 2009). In general, an ideal sensing material to be integrated in an electronic nose should fulfil the following technical requirements: (i) high sensitivity to chemical compounds; (ii) low sensitivity to humidity and temperature; (iii) high selectivity; (iv) high stability; (v) high reproducibility; (vi) high reliability; (vii) short reaction and recovery period; (viii) robust and durable; (ix) easy calibration; and (x) small dimensions (Sankaran *et al.* 2012).

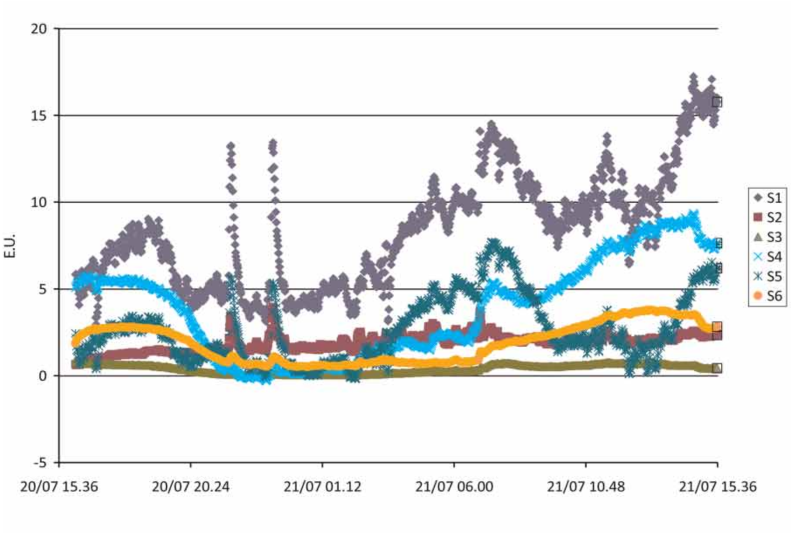
In more detail, an electronic nose for odour exposure assessment at specific receptors should be able to analyse the ambient air continuously (or repeatedly), to detect the presence of odours, and finally to classify them, i.e. to recognise odour provenance, and/or to estimate odour concentration.

Figure 2 illustrates an example of continuous monitoring of ambient air performed by an electronic nose. The right side of the figure shows a plot of the sensor responses, where the peaks correspond to potential odorous events; in this example, sensor responses are expressed in 'Eos Units' (E.U.) (Dentoni *et al.* 2012). The table on the right side of Figure 2 reports the olfactory classes attributed to the analysed air.

Electronic nose applications to environmental odour monitoring

Electronic noses are widely used in several sectors, especially in food analysis, i.e. process monitoring, shelf-life investigation, freshness evaluation and authenticity assessment (Peris & Escuder-Gilabert 2009). The use of electronic noses for environmental odour monitoring entails the necessity of continuous outdoor use at some distance from the odour source.

This kind of application is extremely challenging due to problems such as sensor drift over time (Romain *et al.* 2002); undesired sensor sensitivity to variable atmospheric conditions, e.g. temperature and humidity (Sohn *et al.* 2008), and the simultaneous required high sensitivity towards odours for detection at very low concentrations (Nicolas & Romain 2004; Dentoni *et al.* 2012). These problematic aspects are the reason for the slower distribution of



20/07	20:31	AIR
20/07	20:46	AIR
20/07	21:01	AIR
20/07	21:16	AIR
20/07	21:31	AIR
20/07	21:46	WWTP1
20/07	22:01	WWTP1
20/07	22:16	AIR
20/07	22:31	AIR
20/07	22:46	AIR
20/07	23:01	AIR
20/07	23:16	AIR
20/07	23:31	WWTP1
20/07	23:46	WWTP1
21/07	00:01	AIR
21/07	00:16	AIR
21/07	00:31	AIR
21/07	00:46	AIR
21/07	01:01	WWTP2
21/07	01:16	WWTP2
21/07	01:31	WWTP2
21/07	01:46	WWTP2

Figure 2 | Example of continuous analysis of ambient air and odour classification. The full colour version of this figure is available online at http://www.iwaponline.com/wst/toc.htm.

electronic noses in the environmental sector with respect to other laboratory applications.

Nonetheless, in recent years, some work regarding the application of electronic noses for environmental odour monitoring has been published.

An interesting example is given in a work by Nicolas *et al.* (2000), where very simple instruments based on tin oxide sensors were used for measurements around real odour sources in the environment, such as compost facilities, printing houses, paint shops, wastewater treatment plants, rendering plants, settling ponds of sugar factories, giving promising classification results with discriminant analysis (DA) and principal component analysis (PCA).

In a more recent work, the same authors (Nicolas *et al.* 2012) describe the application of a network of five home-made electronic noses, each comprising six metal oxide sensors from Figaro®, for the assessment of odour annoyance near a compost facility. Each electronic nose detects the odour events by classifying the odour types into five possible categories corresponding to the odour sources and to odour-free air. Then a quantitative model assesses the level of the odour and estimates the odour emission rate at the instrument location. Finally, according to the wind direction, the responses of the electronic noses in the right wind sector are used to assess the maximum downwind distance of odour perception. The study proves the system to be sufficiently efficient to predict in real time possible odour annoyance in the area around the plant, even though the approach suffers from various uncertainties, from the sensors to the final measurement of the distance of downwind annoyance.

Another study aiming to assess the odour exposure from a composting facility is described by Sironi *et al.* (2007), focusing especially on the training procedures and on the principles followed for data processing. One electronic nose equipped with six thin-film metal-oxide semiconductor (MOS) sensors was trained to recognise the odours from the plant and was then installed at receptors. The study proves the effectiveness of electronic noses as tools for the continuous monitoring of odour emissions and for odour exposure assessment in terms of relative recognition frequency of odours from the monitored plant, and highlights the problem of MOS sensor sensitivity to humidity.

Other interesting applications of electronic noses for environmental odour monitoring are reported by Sohn *et al.* (2009) and by Milan *et al.* (2012).

In the first one, in an effort to develop an appropriate tool for identifying major contributors to odour annoyance in areas with multiple odour emission sources, odour samples were collected on site at a piggery and an abattoir and in the surrounding areas, then analysed using a commercial non-specific chemical sensor array consisting of 32 organic conducting polymer (CP) sensors. The odour fingerprint database developed was analysed using two pattern recognition algorithms including a partial least squares-discriminant analysis (PLSDA) and a Kohonen self-organising map (KSOM). The KSOM performed better than the PLSDA, being able to identify odour samples sourced with mean percentage values of 45–90%.

The second study describes a huge monitoring programme to map the odour impact in the Port of Rotterdam by using 40 fixed and four mobile electronic noses for a

3-year period and comparing their responses with other sensorial observations (e.g. odour complaint reports and odour observations of experts). The objectives of investigating the electronic nose potential as an odour management tool for reducing odour exposure as well as a safety management tool for the fast recognition of accidental gases resulting in incidents gave promising results, although still require further development of the knowledge base and incremental improvements to the system.

Literature studies do not all deal just with the environmental applications of commercial (or almost commercial) electronic noses, but there is also very interesting work regarding the development of specific instruments for environmental odour monitoring. Such instruments are being improved, for instance by the use of innovative sensors (Suriano *et al.* 2012), or by the introduction of specific technical features for the compensation of variable atmospheric conditions, which typically occur in the field (Dentoni *et al.* 2012).

EXPERIMENTAL: ELECTRONIC NOSES FOR THE CONTINUOUS MONITORING OF ODOURS FROM A MSW LANDFILL

Materials and methods

Electronic noses developed at the Politecnico di Milano in collaboration with Sacmi s.c. were used to monitor the odour impact of a MSW landfill (Figure 3). The landfill is located in Northern Italy and has a surface of about 26 ha ($26{,}000\ m^2$), which makes it one of the biggest landfills of Northern Italy, and it receives about 500 t/day of MSW.

The electronic noses used for the study are equipped with six MOS sensors, which respond to the presence of odorous compounds in the air by changing their resistance with respect to specific reference conditions. A description of the innovative functioning principles with respect to other commercial instruments is given by Dentoni *et al.* (2012) (Figure 4).

In order to use electronic noses for the continuous monitoring and detection of odours from the landfill at issue, it is necessary to train the instruments to recognise all the landfill's potential odour emissions. The aim of the training phase, which is extremely delicate and yet of fundamental importance for successful application in the field, is to create a complete database that the instrument uses as a reference for subsequent pattern recognition. The training consists of the analysis of different gas samples of known olfactory quality diluted at different odour concentration values. Theoretical studies and experimental evidence prove that, in order to maximise the electronic nose ability to recognise diluted odours at receptors located at a certain distance from the emission source, it is necessary to dilute the samples collected directly at the emission source, thus obtaining training samples with odour concentration values that are more similar to the odour concentrations to which the instrument will be exposed in the field (Capelli *et al.* 2008).

Odour samples for electronic nose training were collected that corresponded to the landfill main odour sources, which are: landfill gas (LFG), fresh waste, leachate,

Figure 3 | The landfill studied.

Figure 4 | The electronic nose developed by Politecnico di Milano and Sacmi s.c., in the field (left) and in the laboratory (right).

and LFG combustion. Samples of the above-mentioned odour sources (i.e. olfactory classes) were collected from the extraction wells both on exhausted and active cells, on the surface of the fresh waste from the active cell, on the liquid surface of the oxygenated leachate collection tanks, and at the stack for the emission of the exhaust gas from the cogeneration plant that burns the extracted landfill gas.

Moreover, it was necessary to create a reference olfactory class, corresponding to non-odorous, i.e. 'neutral' air. For this reason some ambient air samples were collected at times when odours were not perceptible and then analysed.

The electronic nose training has also the aim of establishing a so-called threshold, calculated based on the sensor responses relevant to the neutral air measures, below which classification does not take place (Dentoni *et al.* 2012). This allows a detection limit for the electronic nose to be established, similar to the human detection limit.

As a general rule, the electronic nose locations should be chosen to provide a relevant representation of the monitored plant odour impact on the surroundings. For this reason, it is generally useful to place at least one instrument directly at the receptor(s) where odour nuisance is complained of. Moreover, another instrument may be placed at the plant boundaries in the direction of the chosen receptor, so as to verify that when odour from the plant is detected at the receptor, the same odour is present at the plant boundaries, thereby avoiding false positives. In this case, two instruments were placed in the field, one at the landfill boundary and the other at a receptor 2 km from the landfill. The instruments analysed the ambient air every 15 min for about 12 days. The monitoring data were then processed for classification of the air analysed.

RESULTS AND DISCUSSION

The monitoring results are expressed in terms of number of measures classified as belonging to the olfactory classes considered for electronic nose training (Table 1), thus allowing the odour exposure at each monitoring site to be determined as the frequency of detection of the different odours.

At the monitored receptor, the results of continuous odour monitoring by electronic noses show that odours from the landfill were detected for about 6.3% of the total duration of the monitoring time (10 days). As well as a quantification of the odour episodes, the use of electronic noses allowed the identification of the landfill's main

Table 1 | Odour detection frequencies at the landfill boundary and at the receptor

	Landfill boundary		Receptor	
Olfactory class	No. of measures	% of measures	No. of measures	% of measures
Neutral air	1,081	82.3	992	93.7
Landfill gas	217	16.5	61	5.7
Fresh waste	12	0.9	6	0.6
Leachate	4	0.3	0	0.0
LFG combustion	0	0.0	0	0.0

odour source, which turned out to be landfill gas (61 out of 67 total odour detections), probably emitted through the landfill surface, due to the fact that not all the landfill gas produced by the decomposing waste was effectively removed by the landfill gas extraction system.

These results are in agreement with citizens' records of odour perception near the monitored receptor, as well as with the meteorological conditions (i.e. wind speed and direction) registered during the monitoring period. Indeed, the electronic nose detected the presence of odours when the wind blew from the landfill towards the receptor.

The outcomes of the odour monitoring by electronic nose therefore allow effective odour exposure assessment at a receptor, without requiring a detailed characterisation of the emission source in terms of OER. This is particularly interesting in the case of a MSW landfill, given that, in general, even though there are several approaches for the quantification of landfill gas (or odour) emissions from a landfill body, such quantification is extremely complicated and may be highly inaccurate (Capelli *et al*. 2012). This may be because emissions from the landfill body are not constant, and that they are affected by different factors, e.g. the quantity of landfill gas produced, the quantity of landfill gas removed by suction system and the meteorological conditions.

Based on the results discussed, it is possible to make some generalisations about the opportunities for using electronic noses as odour exposure assessment tools at receptors.

As already discussed, one of the main advantages associated with the use of electronic noses is that they allow a direct determination of the presence/absence of odours at receptors, without requiring a minute (and in some cases difficult) characterisation of the emission. Moreover, besides the quantification of the odour episodes in terms of frequency of occurrence, electronic noses may also have a 'qualification' function: they may allow the identification of the main source of odours in the case of the coexistence of different potentially odour emitting plants, thereby giving useful indications to the plant operators as well as to environmental regulation bodies.

Another very important aspect is represented by the positive effect on the population, which, based on our experience, generally feels comforted by the presence of an instrument for the continuous monitoring of odours directly at their homes, which overcomes the problem of discontinuity of occasional olfactometric surveys.

Nonetheless, some drawbacks also have to be taken into consideration. First, as already mentioned, electronic noses allow the assessment of odour exposure as the frequency of occurrence of odour episodes, without giving precise information about their intensity. However, the most critical aspects relevant to the use of electronic noses are associated with the instrument complexity and the lack of specific regulation for their standardisation. As a matter of fact, the application of electronic noses for environmental odour monitoring entails a large number of degrees of freedom, regarding for instance the training and the data processing procedures. Actually, the definition and standardisation both of the instruments and of the procedures for their correct utilisation is a necessary requirement for their distribution as effective odour impact assessment tools. A first standardisation attempt, setting up the application of electronic noses in environmental monitoring, is represented by the NTA-905, a technical agreement document released in December 2012 by the Netherlands Standardization Institute (NEN 2012).

CONCLUSIONS

This paper focuses on the use of electronic noses for odour exposure assessment purposes, especially in cases where dispersion modelling is barely applicable, for instance in those cases where a detailed characterisation and quantification of the odour emissions in terms of OER, i.e. odour emitted per time unit (ou_E/s), for every hour of the simulation time domain may turn out to be particularly difficult, due to the nature of the source (e.g. diffuse source) or to the variability of the emission over time (e.g. discontinuous productions). In such cases, it might be useful to avoid a minute characterisation of the emission, and to determine the exposure to odours directly where the odour nuisance is perceived.

This paper discusses the state of the art of electronic nose technology as far as its application to the environmental sector is concerned, and more specifically to the determination of odour exposure at receptors, focusing on the critical aspects connected to this kind of use.

The reported example regarding the application of electronic noses to the continuous monitoring of odours from a MSW landfill proved the technology to be suitable for odour exposure assessment in terms of frequency of odour detections. Moreover, the instruments allowed the identification of the major odour source of the plant, as the source whose odours were most frequently recognised at the receptor.

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