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Review of Research Development on Environmental Odour in the Last Decade

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ABSTRACT

The latest research development of environmental odour was reviewed in terms of the source and emission, the generated annoyance and health impact, detection and measurement systems, the most advanced abatement technologies and the role of odour in forensic science. The review was based on more than one hundred of technical papers and articles related to environmental odours that were published during the last decade. The result of the study reveals that the research development of odour in the environment in the last decade (2001-2011) has achieved a significant step in which nowadays odour is not merely concerned as an environmental pollutant, but also as an important tool for product classification as well as an instrument utilized by police to investigate criminal scenes.

Keywords: Odour, emission, annoyance, measurement, odour abatement, forensic

INTRODUCTION

In the last decade (2001-2011) an enormous development of environmental odour research has been achieved by a lot of researchers in all over the world. It deals with the odour emission into environment, impact of odour annoyance on the change of ambient air quality, odour measurement techniques as well as environmental odour abatement technologies covering physical, chemical and biological approach methods. Furthermore, there is an increasing concern where odour has also been used in forensic science as a tool to investigate criminal scenes. The scope of the research development on odour is presented in **Figure 1**. The objective of the current paper is to overview briefly on odour research development within the last decade, i.e. in the period of time merely between 2001 and 2011.

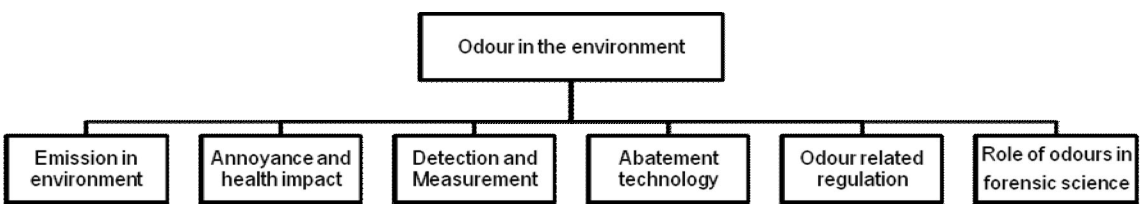

Figure 1: Scope of research development on environmental odour in 2001-2011 decade.

AN OVERVIEW OF ODOUR EMISSION IN THE ENVIRONMENT

Odour as a Classification Tool

A number of researches in the last decade (2001-2010) have shown that odour can be used as a tool to classify objects. Here are some examples of those study results:

- Classification of colour of wine, i.e. "red wine," "white wine," or "rosé wine" [1].
- Variability of olfactory functioning in children [2]. It involved the smelling of food dislike, family odour, people's natural odour, smell of clothes, smell self-odour, senses in nature, yesterday odour, outside odour, smelling cars, school tools, bathroom and tobacco.
- Quality of compost [3]. They evaluated the quality of food waste composting process by using the emitted odours.
- To functionally classify swine manure management system [4]. It was based on effluent chemical properties and emission rates of odour (NH_3 and H_2S), methane (CH_4) and VOC.

A demonstration by Stafford et al. [5] showed that certain odours are able to cue memory for odour-associated words. Participants (n=45 females in each experiment) were presented with words (two groups of odour-associated words and one neutral) on a computer screen and randomly assigned to one of three conditions where they recalled the words while inhaling from a bottle either rosemary, jasmine, or no odour (experiment 1)

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and peppermint, bergamot, or no odour (experiment 2). Experiment 1 revealed that, for those in the rosemary group, significantly more rosemary versus jasmine and neutral words were recalled. Experiment 2 replicated this effect for peppermint, though no odour-congruent effects were found in the lexical decision task (LDT). Other additional research [6] suggested that odour should be used as an important property that should be included in Material Safety Data Sheet (MSDS) of oil and gas products since a peculiar smell is the first indication that something has leaked.

Odour Emission in Ambient Air

A list of odours emitted from various sources in the outdoor environment is presented in Table 1. It includes swine confinement, dairy farm, swine composting plant and food waste composting plant. It reveals that most of odorous compounds belong to group of sulphur containing compounds and ammonia.

Kummer and Thiel [7] evaluated sources and control measures for odour in the environment. They addressed organizational and engineering measures for the mitigation of bioaerosol emissions including odour. In every field of activity where organic material is being handled, emission of dust, gases, odour as well as bioaerosols are bound to arise. For this reason, waste management facilities or else agricultural enterprises are potential emission sources of bioaerosols.

Teixeira et al. [8] developed a simulation of the evaporation/diffusion rate of small volumes of perfume liquid mixtures over time and distance based on Fick's Law. Thermodynamic UNIFAC model was used to predict the vapour–liquid equilibrium, since fragrance solutions were considered as non-ideal liquid mixtures. The diffusion model was applied to concentrated perfume mixtures but also to quaternary mixtures, considering the existence of a solvent matrix (ethanol). The PTD (Perfumery Ternary Diagram) methodology was applied to the study of the perfume evaporation and interpreted along with evaporation lines that traced the evaporation path of the perfume mixture.

Rappert and Müller [9] reviewed odour compounds in waste gas emissions from agricultural operations and food industries. The review was based on the available information regarding odour emissions from agricultural operations and food industries by giving an overview about odour problems, odour detection and quantification and identifying the sources and the mechanisms that contribute to the odour emissions. List of odour descriptions produced by microorganism from volatile substances as well as substance category was also included in this review, for example, hydrogen sulphide (H_2S) with its rotten egg like odour description can be produced by *Pseudomonas putifaciens* or *Pseudomonas mephitica* from sulphur compounds.

Table 1. Odour sources and its emitted compounds in the environment

Source	Identified emitted compounds or group of compounds	Reference
Outdoor sources		
Chemical fibre manufacturing plant	Sulphides, mercaptans, BTX, H_2S, CS_2	[10]
Swine confinement building	Ammonia, hydrogen sulphide, VOCs	[4]
	Ammonia, hydrogen sulphide	[11]
	-	[12]
Swine slurry handling	Hydrogen sulphide, dimethyl sulphide, dimethyl disulphide, dimethyl trisulphide	[13]
Dairy farm	Alcohols, aldehydes, ketones, esters, ethers, aromatic hydrocarbons, halogenated hydrocarbons, terpenes, other hydrocarbons, amines, other nitrogen containing compounds, sulphide-containing compounds. Lactating cow open stall: 82 VOCs. Slurry wastewater lagoon: 73 VOCs	[14]
Beef cattle housing	Sulphur-containing compounds, volatile fatty acids (VFA), phenols and indoles	[15]
Composting facility	22 odorous compounds. Three main components were 2-butanone, 2-butanol and ethyl acetate.	[16]
Composting of swine faeces	Key odour components: Ammonia, methyl mercaptan, dimethyl sulphide.	[17]
Food waste composting	Six critical odorants: Ethyl benzene, dimethyl sulphide, trimethyl amine, p-cymene, ammonia, acetic acid.	[18]
	29 compounds including ammonia, amines, acetic acid and multiple VOCs (hydrocarbons, ketones, esters, terpenes, S-compounds)	[3]
Biosolids (anaerobically digested)	Mayor odours: Ammonia, dimethyl disulphide. Lesser quantities: carbon disulphide, dimethyl sulphide, trimethyl amine, acetone, methyl ethyl ketone.	[19]
Lignosulfonate dust suppressant agents used on dirt roads	Sulphur dioxide, organic vapours	[20]
Plastic waste recycling plants	Toluene, ethyl benzene, 4-methyl- 2-pentanone, methyl methacrylate, acrolein	[105]
Urban traffic site	Hydrogen sulphide	[21]
Indoor sources		

Source	Identified emitted compounds or group of compounds	Reference
Paper, office partition, medium density fibre board in office furniture	Nonanal	[22]
Indoor sources	33 VOCs with the highest level were formaldehyde, acetic acid and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB)	[23]
	Nonanal, decanal	[24]
	VOCs and semi-VOCs	[25]
Floor oil	92 active odour VOCs	[26]

Industrial and Domestic Odours

The presence of odour in the environment can be contributed by industrial as well as domestic sources. A number of industrial odour sources cover food industries, wastewater treatment plant, municipal solid waste landfill site, composting plants and oil and gas refineries. Whereas domestic sources include household kitchen, toilet and waste bins. According to Nabais [27] the control and elimination of the emission of noxious odours in the food-processing industry is one of that industry's most difficult problems. The problem normally is exacerbated not only because of the multiple ways in which it can be approached, but also because, in spite of many efforts developed, there still is no universally accepted way to address its solution.

Another example of industrial odour was presented by Saral et al. [28] who assessed odorous volatile organic compounds (VOCs) released from municipal solid waste (MSW) landfill site in Istanbul – Turkey via a modelling approach. The atmospheric dispersion of hydrogen sulphide (H_2S) and 22 VOCs was modelled. Industrial Source Complex v3 Short Term (ISCST3) model was used to estimate hourly concentrations of odorous VOCs over the nearest residential area. Results showed that short term averages of three odorous VOCs, namely ethyl mercaptan, methyl mercaptan and hydrogen sulphide, exceeded their odour thresholds.

Household activity, in this case, can be concerned as source of odour as well as an object suffering from odour. A study was inisiated [10] in response to odour complaints from residents of neighbourhoods located adjacent to the largest chemical fibre manufacturing plant in Taiwan. Gas samples were analyzed for target sulphurous and volatile organic compounds, e.g., sulphides, mercaptans, BTX, etc. The resulting measured ambient air concentrations were compared to published odour threshold limits and Taiwan's regulatory standards for hazardous air pollutants. Although none of the detected sulphurous compounds exceeded the national limit, H_2S and CS_2 were occasionally present at levels higher than the odour threshold. Hence, the presence of these compounds probably triggered the residents to complain of the odour.

Outdoor (Ambient) and Indoor Odours

Presence of odour in ambient air can be indicated by using of a kind of mollusc as reported by Kholodkevich et al. [29] who studied bio-indication of air pollution based on biomarkers of the cardio-respiratory system of the mollusc *Achatina fulica.* The heart rate (HR) of the mollusc was used as parameter related to the concentration of ammonia (NH_3) in ambient air. In general, the biomarkers of *Achatina* cardiac activity have been demonstrated to be helpful for reliable detection of low concentrations of gas pollutants in the air.

Maddalena et al. [23] investigated odour emissions from indoor sources. Indoor concentrations of 33 volatile organic chemicals were measured in four unoccupied temporary housing units (THU) belonging to the U.S. Federal Emergency Management Administration (FEMA). The highest level contaminants in the THUs include formaldehyde, acetic acid and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB). Materials were collected from the THUs and emission factors were determined using small chambers to identify the potential source of indoor contaminants. Using material loading factors and ventilation rates that are relevant to the trailers, all of the material types we tested had at least two chemicals (formaldehyde and nonanal) with derived concentrations in excess of chronic reference exposure levels or odour thresholds. The extensive use of composite wood products, sealants and vinyl coverings, combined with the low air exchange rates relative to material surface areas, may explain the high concentrations of some VOCs and formaldehyde.

Another study on indoor odour was carried out by Peng et al. [24] that investigated indoor chemical pollutants and perceived odour in an area with complaints of unpleasant odours in terms of chemical and odour characteristics. Measurements are also taken in non-complaint areas within the same building to identify possible causes of malodours. By comparing chemical measurements of complaint and noncompliant areas, calculating odour indices and correlating odour and chemical measurements, possible odorous chemicals are detected and these are nonanal and decanal. This study provides a useful procedure to identify possible causes of malodours and can be applied to offices or buildings with odorous problems.

Odour can also be exhibited from paper, office partition and medium density fibre board that used in office furniture after building ozonation [22]. The by product of this ozonation is called as BOBP (building ozonation by product) such as nonanal that persists for months or more at emission rates large enough to result in indoor concentrations that exceed their odour threshold. Occurrence, dynamics and reactions of organic pollutants in the indoor environment that come from building materials, furnishing and other indoor materials was reviewed [25]. It includes complaints about odour that often emitted from floor coverings and furniture coatings.

Natural vs. Anthropogenic Odour Sources

The environmental behaviour of reduced sulphur compounds (RSCs: H_2S, DMS, CS_2, DMDS and CH_3SH) was investigated in an area influenced by strong anthropogenic processes based on a numerical modelling approach. The RSC emission concentrations were measured from multiple locations around the Ban-Wall industrial complex (BWIC) in the city of An San, Korea [30]. These emissions were then used as input for a CALPUFF dispersion model with the 34 dominant chemical reactions for RSCs. The model study indicated the possibility that RSCs emitted in and around the BWIC can exert a direct impact on the ambient SO_2 concentration levels in its surrounding areas with the most prominent effect observed during summer. The prediction indicated that a significant fraction of SO_2 was produced photochemically in and around the BWIC during the summer.

Shabtay et al. [15] studied on dynamics of offensive gas-phase odorants in fresh and aged faces throughout the development of beef cattle. Livestock odours are largely caused by several groups of volatile organic compounds (VOC), including sulphur-containing compounds, volatile fatty acids (VFA), phenols and indoles. Throughout the growth stages of cattle in the nursery and feedlot, distinctly different diets are formulated to meet the changing requirements of the animal. Because diet composition and manure management are two major factors affecting odour emissions, it was assumed that changes in diet composition along the development of calves would affect VOC emissions from fresh and stored manure. This study demonstrated that life stage and manure management affect odour emissions from beef fattening operations. Incorporation of the age and diet of calves in odour modelling could improve annoyance predictions.

Odour in Urban and Rural Areas

Kourtidis et al. [21] presented one full year of odour (hydrogen sulphide) measurements in an urban traffic site in the city of Thessaloniki, Greece. In this 1-million-population city the H_2S concentrations were surprisingly high, with a mean annual concentration of 8 $\mu g/m^3$ and wintertime mean monthly concentration up to 20 $\mu g/m^3$ (12.9 ppb). During calm (wind velocity <0.5 m/s) conditions, mainly encountered during night time hours, hourly values of H_2S were highly correlated with those of CO and SO_2, pointing to a common traffic source from catalytic converters. Annual mean concentrations are above the WHO recommendation for odour annoyance; Hence, H_2S might play a role to the malodorous episodes that the city occasionally experiences. The high ambient H_2S levels might also be relevant to the implementation of preservation efforts for outdoor marble and limestone historical monuments that have been targeting SO_2 emissions as an atmospheric acidity source, since the measurements presented here suggest that about 19% of the annual sulphur (SO_2 + H_2S) emissions in Thessaloniki are in the form of H_2S.

Odour emission from livestock production systems is a major nuisance in many rural areas [13]. A study was carried out that aim at determining the major airborne chemical compounds responsible for the unpleasant odour perceived in swine facilities during slurry handling and at proposing predictive models of odour concentration (OC) based on the concentrations of specific odour ants in the air. The result revealed that OC was found to have the highest correlation with the sulphur containing compounds (i.e. hydrogen sulphide, dimethyl sulphide, dimethyl disulphide, dimethyl trisulphide). The concentration of hydrogen sulphide accounted for 68% of the variation in OC above the stirred slurry samples. The highest concentrations of volatile organic compounds were observed for phenols and indoles, which made a significant contribution to the overall OC when the slurry was fresh. The contribution of ammonia to the OC was only significant in the absence of hydrogen sulphide. The precision of predictive models of OC based on the concentration of specific odorants in the air was satisfactory. Hence, this study suggests that monitoring of specific odour compounds released from agitated swine slurry can be used to predict the concentration of odour perceived close to the source (e.g. at storage units), allowing the assessment of odour nuisance potentials.

At the second study [31] the concentrations of odour and odorants above different types of stirred swine slurry were compared to analyze the relationships between concentrations of odour (and odorants) and physicochemical characteristics of the slurry (i.e. pH, temperature, dry matter, volatile solids and concentration of 22 chemical compounds); and to propose predictive models for the odour concentration (OC) based on these physicochemical characteristics (solely and in combination with concentrations of specific odorants in the air above the slurries). OC measured in the air above stirred swine slurry samples were not significantly different among production types or storage times. The physicochemical characteristics of the slurries were not useful for predicting OC or concentrations of hydrogen sulphide (or organic sulphides) above the slurry, but were related to concentrations of other emitted gases such as phenols and indoles, ammonia and carboxylic acids. There was good precision of predictive models of OC based on selected slurry characteristics (i.e. pH, dry matter, nitrogen content, sulphur content or concentrations of individual aromatic compounds and carboxylic acids) together with concentrations of specific odorants in the air (e.g. hydrogen sulphide). This study suggests that predictive models could be useful for evaluating odour nuisance potentials of swine slurry during handling.

ODOUR ANNOYANCE AND IMPACT OF ODOUR ON HEALTH

Odour annoyance encountered in the environment was assessed in term of the relationship between depression, anhedonia and olfactory hedonic estimates [32]. Odour identification was assessed for 16 common odours (orange, shoe leather, cinnamon, peppermint, banana, lemon, liquorice, turpentine, garlic, coffee, apple, clove, pineapple, rose, anise and fish). In summary, the study demonstrated a significant relationship between anhedonia and olfactory hedonics during depressive episodes. In contrast, there was no significant relation between olfactory hedonics and depressive symptoms. A schematic classification of odour annoyance and impact of odour on health is presented in Figure 2.

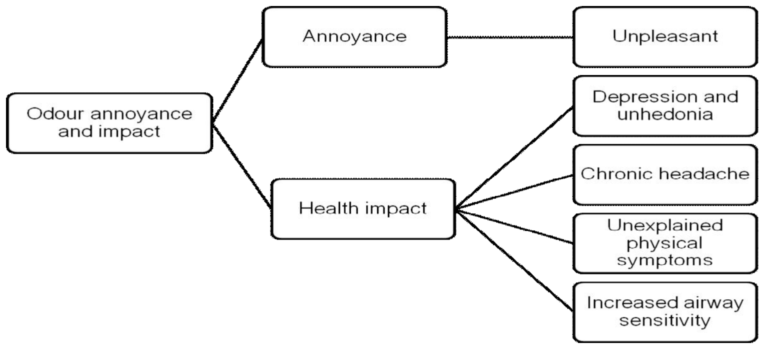

Figure 2: Classification of odour annoyance and odour impacts on health

Another study of odour annoyance was carried out by Collins et al. [33] and Al-Shammiri [34]. Collins et al. [33] presented nuisance odours associated with the site remediation that likely the result of naphthalene and possibly isomers of xylene. This was concluded from a study on ambient air quality in a site of a former manufactured gas plant. Air pollutant concentrations measured adjacent to the excavation area and at the site perimeter during remediation activities were less than the relevant occupational and environmental exposure limits. Al-Shammiri [34] investigated the emitted hydrogen sulphide (H_2S) in relation with the complaint from the citizens living around the Ardiyah Sewage Treatment Plant (ASTP) in Kuwait. Direct field measurement and the use of odour dispersion simulation were carried out simultaneously. The results from the dispersion model showed that the main problem exists inside the ASTP, where 6 ppm of H_2S concentration was reported by the simulator model, whereas outside the ASTP, there was no serious problem. The maximum concentration reported outside the ASTP at a distance in the x-direction (greater than 700 m) was 0.053 ppm. None of the concentrations predicted by the model exceeded the standard value as specified by the Occupational Safety and Health Administration (10 ppm), whereas some real sensor measurements at the ASTP exceeded the standard, reaching a value of 37 ppm. A compilation of odour annoyance and potential odour impact on health is presented in Table 2.

Table 2. Case study compilation of odour annoyance and potential health impact of odour

Case of odour annoyance or potential health impact of odour	Odour related supposed reasoning	Reference
Site remediation of former manufacturer gas plant	Naphthalene, isomers of xylene	[33]
Complaint from the citizens living around the sewage treatment plant	Hydrogen sulphide	[34]
Restoration work of an estuary called "Golden Horn" in Istanbul	Hydrogen sulphide	[35]
Road traffic exposure (dust/grime and exhaust/smell)	Smelly sense	[36]
Processes in large industrial complex in Korea	13 carbonyl compounds	[37]
Odour annoyance in the two Swedish communities: Oxeloesund (steel industry) and Vaernamo (biofuel refinement)	Organic substances, in particular terpenes	[38]
Disposal of wastewater on the land	Environmental odour nuisance	[39]
Somatic complaints in environmental health (medically unexplained physical symptoms)	Annoying odour exposure	[40]
Increased airway sensitivity to occupational chemicals and odours	Organic solvents; pyridine odour	[41]
Self-reported asthma symptoms and nasal allergies increased with self-reported odour annoyance	Animal feeding odour	[42]
Relationship between depression, anhedonia and olfactory hedonic estimates	n-butanol	[32; 43]

CURRENT DEVELOPMENT OF ODOUR DETECTION AND MEASUREMENT SYSTEMS

Recently, a review of odour detection methods by using olfactometry and chemical sensors was presented by Brattoli et al. [44]. It covered sampling methods of odour compounds, sensory methods, principles operation of electronic noses and olfaction systems, as well as comparison between olfactometry and electronic noses. Previously, an overview of odour detection instrumentation was described by Yuwono and Schulze Lammers [45] consisting of chemical sensor, olfactometry and gas chromatography, electronic nose, metal oxide sensor (MOS), conducting polymer sensor and quartz crystal microbalance sensor (QMB). Here, odour detection and measurement system is classified as follows (Figure 3) into olfactometry, electronic nose, chemical-analytical method and sniffing team. In the following parts each of those above mentioned methods will be de described briefly based on the current research development in the time period of 2001-2011.

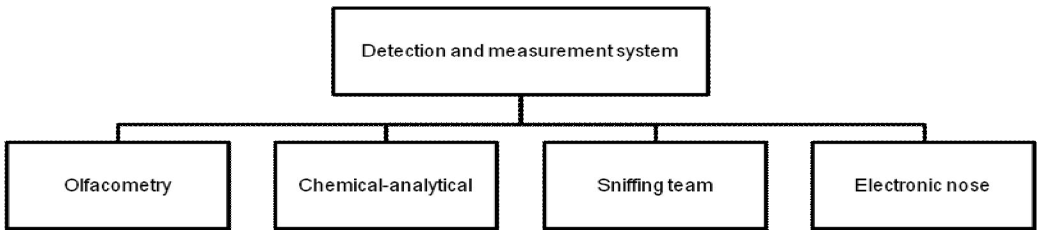

Figure 3: Schematic representation of odour detection and measurement system

Olfactometry

Odour measurement using olfactometry is today concerned as method that contains uncertainty due to variability of the biological sense of smell perceived by human being. The results of olfactometry show a large amount of scatter [46]. A Monte-Carlo simulation is the way to understand the source of uncertainty where the influence of every parameter and the influence of parameter on the overall uncertainty were studied. The results show that means of error band was between one third and the threefold of an actual measurement value.

A study on implementation of olfactometry was also carried out by Rosenfeld et al. [19] who measured odour emissions from three (3) different biosolids from King County (Washington) applied to forest soil by using dilution-to-threshold olfactometry and mass spectral analyses. The major odorous compounds volatilized from two anaerobically digested biosolids were ammonia and dimethyl disulphide, with lesser quantities of carbon disulphide, dimethyl sulphide, trimethyl amine, acetone and methyl ethyl ketone.

An additional study on the above result on olfactometry was reported [47] that described a vapour delivery system and its peripherals those instantiate good tools. The vapour delivery device 8 (VDD8) provides flexibility in range of delivered concentrations, offers definable stability of delivery, accommodates solvent-free delivery below a part per trillion, gives a realistic interface with subjects, has accessible and replaceable components and adapts to a variety of psychophysical methodologies. The device serves most often for measurement of absolute sensitivity, where its design encourages collection of thousands of judgments per day from subjects tested simultaneously. The results have shown humans to be more sensitive and less variable than has previous testing. The VDD8 can also serve for measurement of differential sensitivity, discrimination of quality and perception of mixtures and masking. The exposition seeks to transmit general lessons while it proffers some specifics of design to reproduce features of the device in a new or existing system.

Dincer and Muezzinoglu [48] compared two measurement techniques, i.e. by using olfactometry and chemical analysis. In this study, data for odours and H_2S measurements from two pumping stations of the wastewater collection system of Cesme, Izmir, Turkey were evaluated. Concentrations of H_2S were measured with chemical methods. Results indicated concentrations several orders of magnitude above the odour threshold level, which is generally accepted as $0.1 \mu g/m^3$ for pure H_2S in air. The statistical relationships between analytical and sensory odour data were established. Correlations indicated power law relationships between odour and H_2S concentrations (R^2 between 0.88–0.92). Steven's law between the intensity of human perception and concentration of stimulants was obeyed.

Electronic Nose

Studies on the electronic nose applications to detect and measure odour is presented as follows:

a. Burl et al. [49] studied the responses of a conducting polymer composite “electronic nose" detector array to predict human perceptual descriptors of odour quality for a selected test set of analytes. The single component odorants investigated in this work included molecules that are chemically quite distinct from each other, as well as molecules that are chemically similar to each other but which are perceived as having distinct odour qualities by humans.

b. Electronic nose (e-Nose) equipped with 12 different polypyrrole sensors was used [50] to classify sewage odour samples collected from different locations of a treatment plant. The main problem encountered with sewage samples was that the wastewater odours could vary considerably. There was an additional difficulty with the cluster analysis caused by the complexity of the odour data. The data produced by the e-Nose needed to be analyzed. For this purpose, clustering analysis was carried out using two techniques, neural networks (ANN) and fuzzy clustering. Although the number of data used was limited, ANN gave quite satisfactory results for the classification of sewage samples with a correlation of 99%.
c. Zanchettin and Ludermir [51] used Evolving Fuzzy Neural Networks as pattern recognition system for odour recognition in an artificial nose. In the classification of gases derived from the petroliferous industry, the method presented achieves better results (mean classification error of 0.88%) than those obtained by Multi-Layer Perceptron (13.88%) and Time Delay Neural Networks (10.54%).
d. Hamacher et al. [52] developed an online measurement system to monitor odorous gases close to odour threshold values by using a QMB (quartz crystal microbalance) sensor system with an integrated pre-concentration unit [53]. The system was highly sensitive to the main odorous components of waste gas, e.g. limonene, 2-butanone or ethyl acetate. A performance test of the basic configuration of this system to detect odour has been reported by Yuwono and Schulze Lammers [54].
e. A basic study towards implementation of electronic nose was conducted [55] where reduction of measuring gas dew point was assessed deeply. Furthermore, washing out of gas components, condensation process and washing out of odorous gas components were also analyzed as well in order to describe physico-chemical characteristics of odorous gases during measurement process.
f. Boeker et al. [56] elaborated a critical viewpoint of the current online odour measuring system. Here, methodology and technology to measure odours were assessed that covers also difference between the human reception of odours and the technical detection of gases.

Chemical-Analytical Measurement Technique

A successful and feasible method for online measurement of odour with a chemosensor system combined with olfactometry has been developed [57]. Here, the odour measurement system was installed at the outlet of a charcoal filter at a waste incineration plant. For a period of three (3) months the system operated unsupervised, taking odour samples continuously, calculating the odour concentration online and signalling odour events to a control centre.

Odour measurement at very low concentration (sub-part-per-trillion level) was achieved by Zhang et al. [58]. They developed a new method involving the large volume injection (LVI) GC/MS via programmable temperature vaporizing (PTV) inlet and continuous liquid–liquid extraction, to attain analytical sensitivity equal to or better than olfactory sensitivity. Six ‘‘earthy-musty’’ off-flavour organic compounds from water, i.e. 2-methylisoborneol (MIB), geosmin, 2,4,6-trichloroanisole, 2,3,6-trichloroanisole, 2,3,4-trichloroanisole and 2,4,6-tribromoanisole, were used as probes for this study. It was found that LVI via PTV could greatly improve system sensitivity towards off-flavour compound detection. This reliable and efficient method has been optimized and validated. The method has been successfully applied to test off-flavour compounds in different types of water samples with satisfactory results.

Cain and Schmidt [59] recheck the odour database of US-EPA in term of chemosensory properties of *t*- and *n*-butyl acetate. They found that the nose exhibits much higher sensitivity than the databases indicate. The collections rarely exhibit accuracy better than ±1000%. Collection of accurate data for a VOC can ironically bring on stricter regulation for just it, a situation that calls for a strategy to improve the database by collection of new data, importation of better data and development of quantitative structure–activity modelling.

Another chemical-analytical technique was reported by Kamadia et al. [60] who showed that compound concentration and aroma intensity bear a logarithmic relationship which is supported by the psychophysical law of Stevens. This relationship is more completely explained by Stevens Law than by dilution methods (flavour units), which state that there is a linear relationship between the perceived intensity of a compound and its concentration. Furthermore, results reveal that steepness of slopes of perceived intensity versus concentration was different for different odorants. The results also reveal that the assumption in dilution methods that steepness of slope for perceived intensity versus concentration is equal for all odorants was invalid even though this concept is still very useful in gas chromatography coupled with Osme technique (GCO) applications.

Clausen et al. [26] investigated the emission of odour active volatile organic compounds (VOCs) from floor oil based on linseed oil, the linseed oil itself and a low-odour linseed oil by thermal desorption gas chromatography combined with olfactometry and mass spectrometry (TD-GC–O/MS). They found that in total, 142 odour-active VOCs were detected in the emissions from the oils. About 50 of the odour active VOCs were identified or tentatively identified by GC–MS. While 92 VOCs were detected from the oil used in the floor oil, only 13 were detected in the low-odour linseed oil. The major odour active VOCs were aldehydes and carboxylic acids.

Sniffing Team Method

Odour emission rate from a landfill area was estimated by a sniffing team method [61]. The method is based on the field determination of odour perception points, followed by data processing with a bi-Gaussian-type model, adapted to handle the odours. In a first step, field observers delineate the region in which odour impact is experienced and then the emission rate is manipulated in a dispersion model until the predicted size of the impact zone matches that observed in the field. In a second step the adjusted emission rate is entered into the model to calculate the percentiles corresponding to the average annoyance zone. The originality of the proposed method is the introduction of all observation points and of all recorded meteorological data into the model.

Laor et al. [62] developed a screening tool for selection of field odour assessors to rate or describe several odor parameters, such as intensity, duration, offensiveness and character. They developed a three-part screening test for recruiting odor assessors: (1) distinguishing between different odorants by means of a triangular forced-choice test; (2) evaluating odor intensity; and (3) describing hedonic tone and odor character.

RESEARCH DEVELOPMENT ON ODOUR ABATEMENT TECHNOLOGIES

A review of methods to control odour and volatile organic compounds (VOC) was carried out by Revah and Segastume [63]. It consists of physical, chemical and biological control methods. A number of examples of physical-chemical methods reviewed are dilution, condensation, membranes, UV oxidation, plasma technology, adsorption, combustion, masking, caustic scrubbing, chemical precipitation, chlorine oxidation, ozone oxidation, etc. Whereas the biological methods reviewed are biofilter, biotrickling filter, bioscrubber, RBC (rotating biological contactor), membrane bioreactor and suspended cell bioreactor. Busca and Pistarino [64] summarized abatement technology for ammonia and amines from waste gas. They discussed advantages as well as drawbacks of thermal and catalytic oxidation processes, condensation, adsorption, scrubbing and biofiltration. Busca and Pistarino [65] overviewed the techniques that may be applied to the removal of sulphide compounds from gases. They concluded that scrubbing and adsorption on solids allow the recovery of sulphur either as such (H_2S or sulphide organics) or, after oxidation, as elemental sulphur or SO_2. When sulphur concentration is very low, techniques such as thermal and catalytic combustion, oxidative scrubbing and biofiltration might be preferable to attain deodorization. However, combustion converts sulphur into SO_2, while oxidative scrubbing gives rise to sulphate containing solutions. Biofiltration mineralizes sulphur in a natural environmental friendly way, without producing secondary contaminants.

Physico-Chemical Technology

An example of physico-chemical technique to control odour was shown by Misselbrook et al. [66] that introduced pilot scale abatement technique called "crusting formation" in order to reduce odour (ammonia) emitted from stored dairy slurry. In this pilot-scale study, slurry was stored in small tanks (500 L) and the effectiveness of natural crust development for reducing NH_3 emissions was assessed in a series of experiments. Generally, crusts began to form within the first 10 to 20 days of storage, at which time NH_3 emission rates would decrease. The formation of a natural crust reduced NH_3 emissions by approximately 50%. There was a large difference in crust formation between slurries from cattle fed a corn (*Zea mays* L.) silage–based diet and those fed a grass silage–based diet, although dietary differences were confounded with bedding differences. The inclusion of a corn starch and glucose additive has promoted crust formation and reduced NH_3 emission. A summary of the current research advancement on physico-chemical approach for odour abatement is presented in Table 3.

Table 3. Physico-chemical odour abatement technologies

Abatement Technology	Odour compounds	Result summary	References
Commercial products for use in automobile air-conditioning systems designated for abatement of malodours	Malodours presumably of microbial origin	Alleviation of associated microbial odours only in short-term effects.	[67]
"Crusting formation" on stored dairy slurry	Ammonia	Formation of a natural crust reduced NH_3 emissions ca. 50%.	[66]
Dielectric barrier discharge (DBD) reactor	Odour from pesticides factory: Dimethyl amine (DML), dimethyl sulphide	Conversion of DML of 761mg/m^3 reaches 100% at a peak voltage of 41.25 kV	[68]

Biological Approach Abatement Technology

A detailed description of biofilter and bioscrubber applications to control odours and air pollutants including developments, implementation issues and a number of case studies has been compiled by Kraakman [69] and Shareefdeen et al. [70]. They made an assessment on a lot of aspects covering the advantages and disadvantages of biofilter and bioscrubber, a number of full-scale application and onsite pilot studies, a compilation of case studies of H_2S removal, as well as a compilation of case studies of biotrickling filter treating waste gas at fungicide production plant. Current achievement of the biological odour abatement technologies is summarized in Table 4. Additional assessment on odour abatement technologies are as follows:

a. The experience of New Zealand where the use of biofilters is extremely widespread in this country for controlling industrial and municipal odour emissions [71].
b. A number of case studies about odour removal in municipal wastewater plants [72].
c. Detailed elaboration of future prospects of biofilters for odour control. The future prospects for biotechnology in odour control are bright. Certainly, the need for odour control will continue to expand [73].
d. The advantages of biological treatment to control odorous waste gases compared with physico-chemical gas cleaning techniques [74]. With biological waste treatment techniques, reactor engineering is often less complicated and consequently costs are less. In addition, usually no secondary wastes are produced. Biological methods are nonhazardous and benign for the environment.

Table 4. Summary of research development of biological odour abatement technologies

Abatement technology	Odour compounds	Result summary	References
Biofiltration	Phenol formaldehyde	Promising approach to purify gas emissions is general-purpose microbiological method.	[75]
	Hydrogen sulphide at high pH	H_2S removal > 98%; degradation end product was sulphate.	[76]
	Hydrogen sulphide	A quick start up in biofilters (≈80 h)	[77]
	Geosmin	75% removal through sand columns inoculated with geosmin-degrading bacteria.	[78]
	VOCs emitted from composting	97% VOC removal efficiency.	[79]
	Ammonia	Biodegradation rates 0.67 to 7.82 mg NH^3/kg media/d.	[80]
Membranes integrated within bioreactors (MBRs)	Dimethyl sulphide (DMS)	Max elimination cap. 4.8 kg of DMS.m^{-3}.d^{-1}, higher than any reported figure for biofilters and biotrickling filters.	[81]
Shelterbelt system	Livestock odour	Shelterbelts ameliorate livestock odour by impeding particulates movement from animal facilities.	[82]

Dispersion Technique in Ambient Air

Dispersion of odour in the ambient air was studied by developing software to model it [83]. It is based on the theory established by Högström on the odour dispersion of puff emissions. This theory is applied to Gaussian models and takes the frequency of values for odour intensity over any time period into account. Such a model is able to consider the instantaneous characteristics of odour perception by human beings.

Nicolas et al. [84] developed and validated a procedure of a formula to calculate a minimum separation distance from piggeries and poultry facilities to sensitive receptors. This was based on the fact that distance determination models for animal production farms are often based on some general considerations, on some survey and measurement outcomes and on different literature suggestions. Conclusions showed separation distance formula and percentile evaluation approaches are coherent. The validation method allows parameter adjustment but should need further refinements to examine separately piggeries and poultry facilities.

RESEARCH DEVELOPMENT ON ODOUR RELATED REGULATION

A number of regulations pertaining to odour are nowadays found in all over the world. Aldrich [85] summarized odour nuisance related regulations in selected states such as New York, Michigan, Arkansas and Massachusetts. Furthermore, odour related regulation in Japan, China and Canada was also described briefly [85]. Japan's odour control law is entitled "Offensive Odour Control Law" and was Law No. 91 of 1971. The latest amendment was made by Law No. 71 of 1995. Law 91 of 1971 applies to the odours generated in the course of business activities at factories or at other places of business. Law 91 of 1971 defines odour causing substances such as ammonia, methyl mercaptan and other substances likely to cause unpleasant odours and disrupt the living environment and applies in densely populated areas defined by the local governments. Additional research achievement during the last decade is summarized in the following parts.

- Odour was used as a point of interest included in "right-to-farm", a kind of anti-nuisance provision as reported by Centner [86]. For example, complaints about agricultural nuisances may be filed with the Michigan Department of Agriculture. When the director of this department receives a complaint concerning manure, waste products, odours, water pollution, or other enumerated problems of a farm, the director must notify the local government and make an on-site inspection. From the inspection, the director determines whether the farm is using generally accepted agricultural and management practices. For situations where the source of the problem at an operation is caused by the use of other than generally accepted agricultural and management practices, the farm operator is advised to make changes to resolve the problem.

- Repace et al. [87] quantified the air quality benefits of a smoke-free workplace law in Boston Massachusetts, USA, by measuring air pollution from second hand smoke (SHS) in 7 pubs before and after the law, comparing actual ventilation practices to engineering society (ASHRAE) recommendations and assessing SHS levels using health and comfort indices. Odour is one assessed parameter included in the research. The conclusion is that during smoking, although pub ventilation rates per occupant were within ASHRAE design parameters for the control of carbon dioxide levels for the number of occupants present, they failed to control SHS carcinogens or respirable particles (RSP). Non smokers' SHS odour and irritation sensory thresholds were massively exceeded. Post-ban air pollution measurements showed 90% to 95% reductions in PPAH (particulate polycyclic aromatic hydrocarbons) and RSP respectively, differing little from outdoor concentrations. Ventilation failed to control SHS, leading to increased risk of the diseases of air pollution for non-smoking workers and patrons. Boston's smoking ban eliminated this risk.
- Benzo et al. [88] determined the threshold odour concentration of main odorants in essential oils using gas chromatography–olfactometry incremental dilution technique. The result was that the first application of the GC–O technique to the determination of TOC (threshold odour concentration) values with the AEDA (aroma extract dilution analysis) method, through the use of dynamic olfactometry. They also found promising results coupling GC–O and AEDA techniques in the determination of TOC values of the constituents of complex mixtures.
- Bazen and Fleming [89] assessed the impact of Kentucky’s livestock production facility setbacks on the value of surrounding properties and farm financial management decisions. They developed a model of the benefits of livestock odour reduction and the livestock odour abatement cost associated with setback lengths paid by producers. The finding of the study was that the firm has no incentive to completely protect the legislated setback length. Livestock producers in compliance with the relevant setback length may feel protected from odour lawsuits despite damage being done to surrounding property.
- Özbek and Dietrich [90] developed a new method to measure Henry’s law constants at varying temperatures and from these data determine enthalpies of reactions for volatilization of aqueous compounds. The method was applied to 2-methylisoborneol (2-MIB), geosmin and trans-2,cis-6-nonadienal, which are three of the major odorous compounds found in natural and drinking water. Other investigation by Özbek and Dietrich [91] was a study on the conformity of n-Hexanal to being an odour reference standard. They concluded that n-Hexanal, a food additive of no known adverse health effects and has a pleasant grassy smell:
    a. Can be detected by a large percent of the population ($\approx$ 95.5%);
    b. is readily soluble in water and stable during sampling yielding similar intensities among the panellists;
    c. Gives reproducible results for different human panels;
    d. does not cause fatigue at higher concentrations or after a few sample evaluations; and,
    e. Has a linear Weber-Fechner plot indicating that the odour intensity increases with increasing odorant concentration.

Because n-Hexanal possesses all the necessary properties, it is proposed as an ideal odour reference standard to be used for FPA (flavour profile analysis) training and sensory panel assessment of water samples.

ROLE OF ODOUR IN FORENSIC SCIENCE

Studies on human corpses are restricted for many reasons, including ethics. Therefore, forensic entomologists use pig as animal model but very few information are available about the decompositional VOCs released by a decaying pig carcass. Dekeirsschieter et al. [92] tested a passive sampling technique, the Radiello diffusive sampler, to monitor the cadaveric VOCs released by decomposing pig carcasses in three biotopes (crop field, forest, urban site). A total of 104 chemical compounds, exclusively produced by the decompositional process, were identified by thermal desorption interfaced with gas chromatography and mass spectrometry (TDS-GC–MS). Ninety, 85 and 57 cadaveric VOCs were identified on pig carcasses lying on the agricultural site, the forest biotope and in the urban site, respectively. The main cadaveric VOCs are acids, cyclic hydrocarbons, oxygenated compounds, sulphur and nitrogen compounds. A better knowledge of the smell of death and their volatile constituents may have many applications in forensic sciences. **Table 5** summarizes forensic case studies using odour compounds or odour senses as a tool for forensic investigations.

Table 5. Odour compounds or odour sense and their role in forensic science

No	Case in forensic study	Odour related compounds/sense	Reference
1.	Odour of marijuana was used as probable cause for search packaged marijuana located in the trunk of an automobile	Odour from marijuana	[93]
2.	Effect of ageing of the odour trace collected at the crime scene on the performance of the dogs	Odour of a suspect at a crime scene	[94]
3.	Identification of dominant odours emanating from explosives for use in developing optimal training aid combinations and mimics for canine detection.	Common odour signature from TNT (trinitrotoluene), cast explosives, Composition 4 (C-4) and Detasheet; 2,4-dinitrotoluene and 2-ethyl-1-hexanol.	[95]
4.	Capturing volatiles profile over evidentiary items for subsequent canine presentation to assist law enforcement personnel	Odour or other volatile organic compounds trapped during an investigation	[96]
5.	Bloodhounds were used to trail fleeing felons and missing persons	Track of human odour (scent)	[97]
6.	Investigation on canine scent discriminations	Composition of human scent collected from the hands	[98]
7.	Identification of ‘‘odour signatures’’ unique to the decomposition of buried human remains	Odour of decomposing human buried remains	[99]
8.	Development of field portable analytical instruments to locate human remains in shallow burial sites	Odour of decomposing human buried remains	[99]
9.	Investigation the behaviour of fly in response to cadaver	Dead mouse odour	[100]
10.	Scent discrimination with specially trained canines	Human scent evidence	[101]
11.	Development of human scent barcode to determine a reproducible and individualizing profile stored in a searchable database for human scent concept as a biometric measure.	Odour (scent) evidence emitted from human body	[102]
12.	“Electronic body-tracking dog”: a kind of instrument to substitute the role of a tracker dog in forensic investigation	“Fingerprint” of the scent patterns	[103]

A strategic goal of the research [104] is to narrow the scope of identified VOCs in an effort to determine the appropriate odour chemicals required to train VR (victim recovery) canines. This study provides a VOC analysis using SPME (solid phase micro-extraction) of the headspace above 14 different and random decomposing human remains tissue types that have previously been used as VR canine training materials. This work is part of an on-going long-term FBI research strategy directed at the development and improvement of VR canine performance and the development of portable detection instrumentation. The 14 human remains samples evaluated in this study revealed 33 VOCs that included acids/acid esters, alcohols, aldehydes, halogens, aromatic hydrocarbons, ketones and sulphides. The results from this study support the premise that odours released by human decomposition share similarities across the body regions and types represented; however, there are enough differences to warrant an examination or determination of the proper tissue type(s) that would provide the highest number of target odour chemicals for VR canine training purposes.

GENERAL CONCLUSIONS

General conclusions that can be withdrawn are as follows:

a. There are a number of odour emission sources such as wastewater treatment plants, composting installations, industrial plants, as well as burials.
b. Odour is an important environmental parameter, especially in ambient air quality.
c. Odour in the environment can be measured by using various methods such as chemical-analytical methods, olfactometry, conventional chemical system, electronic nose as well as by using human being sniffing team.
d. Odour abatement techniques include physico-chemical abatement technologies, biological abatement technologies and dispersion in the atmosphere.
e. Odour evidence is an important tool utilized by police to investigate criminal scenes.

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