Review article

The use of gas chromatography combined with chemical and sensory analysis to evaluate nuisance odours in the air and water environment

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A B S T R A C T

Varieties of gas chromatography (GC) combined with chemical detection (CD) and sensory analysis at the odour detection port (ODP) for the evaluation of environmental odorants has steadily increased in application and sophistication; this has given rise to a plethora of techniques that cater to specific tasks. With this diversity of approaches in mind, there is a need to assess the critical points at which these approaches differ, as well as likely risks and factors that may affect them. These critical points explained within this review include sample preparation, GC separation techniques (with associated co-elution risks), how the elute is separated between CD and sensory analysis, the type of CD, the type of sensory analysis (with particular attention paid to its factors and guidelines), integrative data techniques, as well as how that data may be used. Additionally, this review provides commentary on the current state of the research space and makes recommendations based on how these analyses should be reported, the standardisation of nomenclature, as well as the impediments to the future goals of this research area. By careful consideration of the critical points of varying analytical processes and how best to communicate these findings, the quality of output within this area will improve. This review provides a benchmark for how GC-CD/sensory analysis should be undertaken and reported.

1. Introduction

Air quality has in developed countries has trended towards great improvements. However, complaints for nuisance odour affecting human health, quality of life, and working environments continue to occupy a large portion of the air quality problem (Fang et al., 2021; Conti et al., 2020). More than half of the complaints received by environmental control agencies around the world concern malodours (Bulliner et al., 2006; Pandey et al., 2016; Kaye and Jiang, 2000). Responding to odour complaints is complex because the odours characteristics, as well as the chemical species causing those odours, can be difficult to quantify (Jia et al., 2021). As a result, environmental quality control agencies struggle with setting measurable limits to control odour nuisances (Gostelow et al., 2001) by odour types and/or odorous compounds present.

The second main sector of malodours in the environment is connected with drinking water quality (Zhu et al., 2022). For decades odour issues within drinking water have occurred worldwide, presenting challenges to identify control and sufficient water treatment to remove the culprit chemicals causing the aesthetic issue (Wang et al., 2021). The identification of trace species causing odour problems whose composition and knowledge about them remains a continuing area of research.

Odorous emissions are usually derived from a mixture of volatile chemicals above their sensory thresholds and have the potential to adversely impact nearby communities (Sucker et al., 2008). Thus, the identification of the causes of odorous emissions at the low detection limits for odorants causing the nuisance odour makes the chemical identification of odours even more difficult.

Research into environmental malodour has steadily increased in sophistication as the demands on governing bodies is to define and remove nuisance odours (Bokowa et al. 2021). As the complexity of these methodologies has increased, varying types of information, such as analytical, sensorial, and community have provided disparate data streams (Hayes et al. 2014, Muñoz et al. 2010). One popular methodology adapted from food and perfume industries to combine some of these data streams has been the use of gas chromatography that

combines analytical chemical detection and sensorial olfaction (Acree and van Ruth 2003). This combined approach enhances the strengths of each data stream (Kim and Park 2008, Feng et al. 2022). Combined GC analytical/sensorial techniques has been extensively applied for aroma analysis of food and beverages (Chin and Marriott 2015, Laukaleja and Koppel 2021, Liu et al. 2022), perfume industries for the investigation of flavour and fragrance matrices (d'Acampora et al. 2007, Xiao et al. 2017), analysis of taste and odour in drinking water (Bruchet 2019), odorous characterisation of agriculture sources such as swine barns, poultry houses, dairy facilities, municipal waste, as well as wastewater management operations (Barczak et al. 2018, Kai and Schäfer 2004, Wang et al. 2010, Wright et al. 2005). The variations of nuisance odours is considerable and a non-exhaustive list includes volatile sulfur compounds (VSCs), terpenes, aldehydes, ketones, alcohols, general hydrocarbons, acids, lactones, esters, pyrazines, furans, amines, as well terpenoids (Fisher et al. 2018a, Czajka et al., 2020, Rappert and Muller 2005). The relationship between these chemicals and odours have begun to be defined via odour wheels (Fisher et al. 2018a, Suffet and Rosenfeld 2007). As a result, combined Sensory - GC techniques within environmental malodour applications use various technologies and report results in varying practices (Kim and Park 2008, Wang et al. 2010). This critical literature review will explain the components and design of the available combined GC-Chemical Detection/Olfaction (also called Sensory-GC) as well as the how this information is analysed and reported and discuss hitherto under-utilised environmental odour approaches that may offer new insights into odour characterisation.

2. The basis of GC-Chemical Detection/Olfaction

The overarching system of Gas Chromatography-Chemical Detection/Olfaction (GC-CD/ODP) is shown in Fig. 1 and some common odour analysis techniques are presented in Table 1. After sampling, the GC component separates a sample into its constituents (often by vapour pressure) which is then divided into two pathways. The chemical detector (CD) path provides chemical analysis of the samples constituents usually by mass spectrometry (MS), and usually by molecular weight (Brattoli et al. 2011). The olfaction path leads to a human assessor (also termed "panelist") who provides information pertaining to the constituent's olfactory qualities (Wang et al. 2010). By combining the two data streams simultaneously, an in-depth characterization of the odours sample is created (Fig. 2) (d'Acampora et al. 2008). For each separated constituent that emerges from the GC, a human assessor has the potential to detect compounds, to measure the duration and intensity of the odorous signal, as well as describe the quality of the odour perceived (Fig. 1) (Wang et al. 2022). Typically, a trained odour panelists describe the odour characteristics, as well as intensity level of the odorous signal related to chromatogram (Wang et al. 2010).

3. Procedure of GC-CD/ODP analysis

The procedure for GC chemical/sensory analysis typically consists of 6 steps: (1) sampling and sample preparation; (2) GC separation of the constituents; (3) the split of flow between olfactory detection port and mass spectroscopy/chemical analysis (4) chemical analysis; (5) sensory analysis and (6) interpretation of the acquired data (Fig. 1).

3.1. Sampling and sample preparation

Odorous environmental emissions usually are composed of a complex mixture of chemical compounds very often in the parts per billion (ppb) to parts per trillion (ppt) concentration range. This challenges the sensitivity of detectors and separation capacity of gas chromatography (Dou et al., 2022). In particular, odorous concentrations may be below the detection limits of many compounds; commonly in the nanogram range (Hudson and Ayoko 2008). As a result, choosing appropriate sample preparation methods can improve the detection of pertinent

analytes. Thus, sample preparation needs to be optimised to produce chromatograms with background peaks reduced to minimum (Agus et al. 2012). Then samples may have to be concentrated prior to GC analysis due to the very low abundance of analytes (Sadowska-Rociek et al. 2009). Both odour sampling device selection and the choice of an appropriate sample preparation methodology influences the composition of the resulting sample and must be considered for each sample (d'Acampora et al. 2007, Hudson and Ayoko 2008, Plutowska and Wardencki 2007). For example, sample loss as a result of permeation through sampling bags, or adsorption onto the bag surface must be considered (Kasper et al. 2018). Additionally, samples must be processed quickly- in some instances under 24 h, to reduce the impact of biodegradation of naturally volatile odorants; particularly VSCs (Le et al. 2013a, Le et al. 2015). The sampling techniques are divided into groups that use matrices of water, air, or both (Table 2, **Supplementary Table S1**).

As evinced, none of the many extraction techniques commonly used to isolate odorous compounds from complex matrices are able to completely reproduce a complete sensorial odour profile from the chemicals present. This is due to the varying mechanisms of extraction of each sampling procedure (d'Acampora et al. 2008, Plutowska and Wardencki 2011). For example, solvent extraction makes exclusive use of solubility, whereas headspace analysis relies on volatility (Biniecka and Caroli 2011). A potential solution is the use of different extraction procedures on an identical matrix enables a more extensive screening of the different methods to provide complementary information on the given odorous samples; however, this process quickly becomes expensive and time consuming (d'Acampora et al. 2008). Similarly, the use of different sorbents ensures that the compounds identified in subsequent analysis accurately represent the suite of odorous compounds that are being emitted from the source (Wang et al. 2010). For example, indole (a chemical with a septic odour character) could not be extracted by CLSA, yet had almost 50% recovery by SDE (Wang et al. 2010). Thus, to avoid bias at the beginning of analysis the sample collection methodology should be carefully considered (Dou et al., 2022). While multiple extraction techniques can reduce bias, their implementation still requires consideration. For example, various commercially available sorbents using air matrices may not be satisfactory for samples that are rich in sulfur compounds (Barczak et al. 2022a; Le et al. 2013b; Hayes et al. 2020).

The most popular sampling methodologies (SPME, canisters, sample bags, and sorbent tubes) require some discussion as to their specific advantages and disadvantages. Canisters, often known as SUMMA™ canisters, are used by varying government agencies to determine chemical concentrations (Koziel et al. 2005, McGlenny et al. 2012). Comparative prior research has shown canisters to have lower sample recoveries than other popular methods, and have logistical limitations compared to sorbent tubes and SPME (Koziel et al. 2005, Parcsi et al., 2012, Polvara et al. 2023). However, the technology for canisters continues to improve; Brown et al. (2015) discussed that careful consideration of sampling methodology, and use of newer canister designs resulted in excellent VSC retention.

Polymeric sample bags represent another popular choice for sampling environmental odours. While relatively inexpensive and some components are reusable, the bags themselves are not (Polvara et al. 2022a). Sample bags can be made of a variety of materials- Tedlar™, Nalophan™, and PTFE (Kasper et al. 2018, Woolfenden 2010). Within the application of GC-CD applications, bags usually have an additional, ancillary role for use by dynamic olfactometry panelists, but it must be noted that they are very good at storage of VSC samples (when not in small concentrations) making them useful in SCD analysis (Hayes et al. 2014, Khan et al. 2012, Hayes et al. 2020, Fisher et al., 2018b).

Sorbent tubes have some distinct advantages; capacity to measure high sampling versatility (i.e. odour samples with multitudes of different types of odorants), capacity to concentrate VOCs effectively, as well as an ability to absorb apolar and semi volatile odorants provides
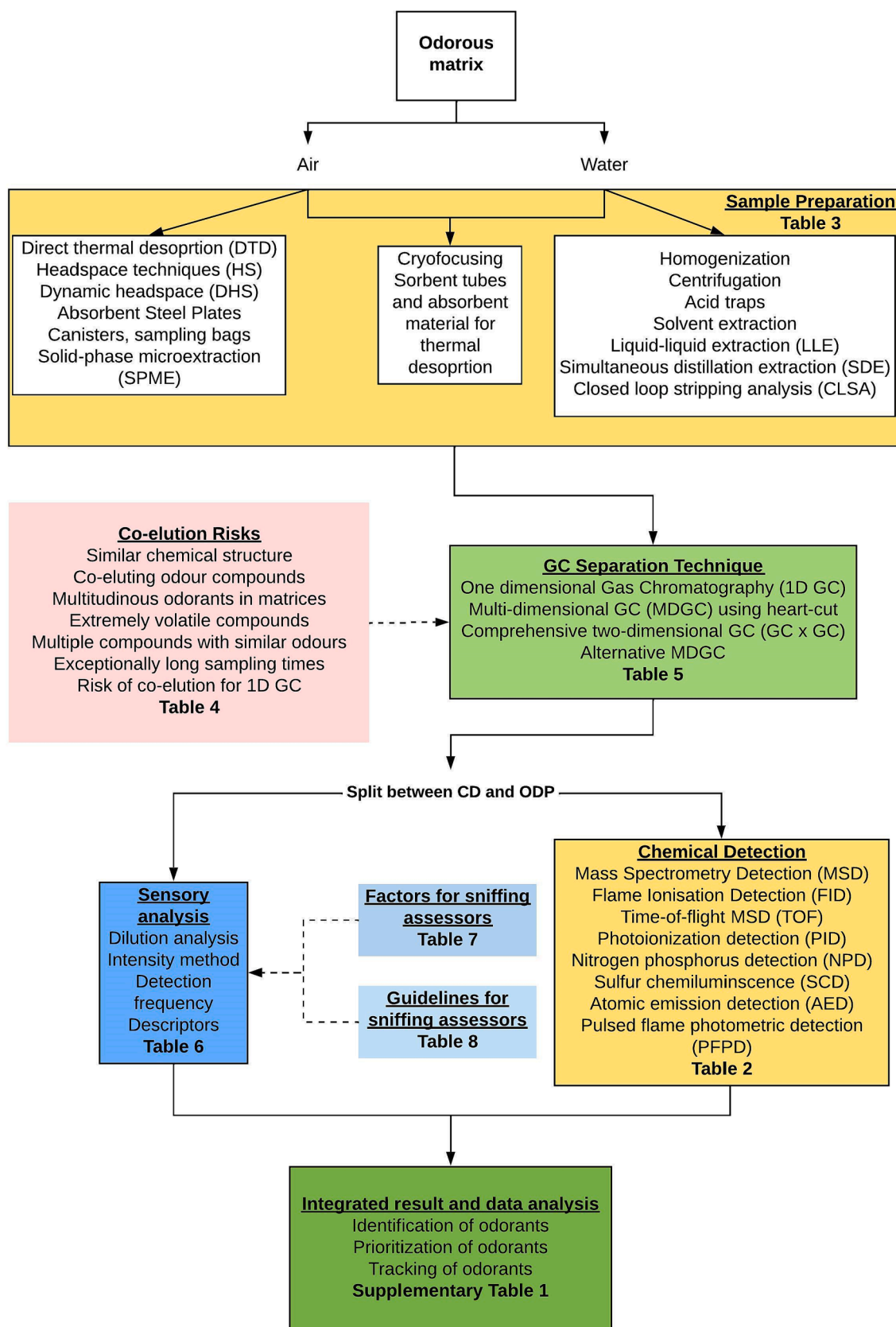
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                              ┌─────────────────┐
                              │    Odorous      │
                              │    matrix       │
                              └─────────────────┘
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Odorous matrix

Air   Water

Sample Preparation
Table 3

Direct thermal desoprtion (DTD)
Headspace techniques (HS)
Dynamic headspace (DHS)
Absorbent Steel Plates
Canisters, sampling bags
Solid-phase microextraction
(SPME)

Cryofocusing
Sorbent tubes
and absorbent
material for
thermal
desoprtion

Homogenization
Centrifugation
Acid traps
Solvent extraction
Liquid-liquid extraction (LLE)
Simultaneous distillation extraction (SDE)
Closed loop stripping analysis (CLSA)

Co-elution Risks
Similar chemical structure
Co-eluting odour compounds
Multitudinous odorants in matrices
Extremely volatile compounds
Multiple compounds with similar odours
Exceptionally long sampling times
Risk of co-elution for 1D GC
Table 4

GC Separation Technique
One dimensional Gas Chromatography (1D GC)
Multi-dimensional GC (MDGC) using heart-cut
Comprehensive two-dimensional GC (GC x GC)
Alternative MDGC
Table 5

Split between CD and ODP

Sensory analysis
Dilution analysis
Intensity method
Detection
frequency
Descriptors
Table 6

Factors for sniffing assessors
Table 7

Guidelines for sniffing assessors
Table 8

Chemical Detection
Mass Spectrometry Detection (MSD)
Flame Ionisation Detection (FID)
Time-of-flight MSD (TOF)
Photoionization detection (PID)
Nitrogen phosphorus detection (NPD)
Sulfur chemiluminscence (SCD)
Atomic emission detection (AED)
Pulsed flame photometric detection
(PFPD)
Table 2

Integrated result and data analysis
Identification of odorants
Prioritization of odorants
Tracking of odorants
Supplementary Table 1

Fig. 1. Flow chart of GC-CD/ODP odorous sample analysis and corresponding table guide for specific sections.

Table 1
Summary of abbreviations, functions, and descriptions of common analytical odour measurement devices.

Technique	Abbreviation	Summary	Application
Gas Chromatography	GC (Delahunty et al. 2006)	Gas Chromatography in odour research is used to separate volatile chemicals in the samples	– Almost all odour analysis begins with GC. – While GC includes a chemical detector to show the peaks that are separated.
Mass Spectrometry	MS (Kleeberg et al. 2005), MSD (Mass Spectrometry Detector) (Hobbs et al. 1995).	MS is used to determine the volatile constituents through mass and charge via ionization under high vacuum.	– Mass spectroscopy is very sensitive, yet the human nose for some odorants is more sensitive. (Muñoz et al. 2010, Kleeberg et al. 2005).
Olfactory (sensory)	O (Delahunty et al. 2006, Hayes et al. 2017), SNIFF (Hochereau and Bruchet 2004, Lehtinen and Veijanen 2011), Olf (Agus et al. 2012), ODP (Odour Detection Port) (Ranau and Steinhart 2004).	Refers to the use of a human detector as a part of a sensorial assessment.	– Required for sensorial analysis.
Chemical Detector	CD	Chemical Detector categories the detector as FID, MSD, and less often used time-of-flight (TOF) MS (Rochat et al. 2007, Eyres et al. 2005), photoionization detection (PID) (Wright et al. 2005), atomic emission detection (AED) (Wyllie et al. 2001), nitrogen phosphorus detection (NPD), pulsed flame photometric detection (PFPD) (Sasamoto and Ochiai 2010), sulfur chemiluminescence (SCD) (Shearer et al. 1990).	– The groups of chemical detectors that follows GC. – Every CD variant has different ranges of sensitivities and specificities which requires consideration with regards to their appropriateness for a study.
Flame Ionisation Detector	FID	FID detects ions through the combustion of compounds. They are unable to detect non-organic substances. FID works under atmospheric pressure.	– Effective shows the separation of volatile organic compounds (VOCs) but does not identify the chemicals as MS does (Muñoz et al. 2010).
Multi-dimensional Gas Chromatograph	MDGC	It uses the "heart-cut" of a sample; that is, picks out in mid-stream of a sample, a part of it for further separation of the heart-cut or analysis by a different detector.	– More effective separation than a standard GC (Bulliner et al. 2006).
Thermal desorption	TD	Using an increase in temperature to desorb the components absorbed on the porous bed during the sampling process.	– May degrade thermally unstable VOCs (Clausen et al. 2008). – May offer better recovery for volatile and hydrophobic odorants.
Two-dimensional gas chromatography	GC × GC	One GC column releases fractions of a sample to a second GC column. This produces a more detailed analysis that removes the requirements for heart-cut (Bulliner et al. 2006).	– Highly accurate and very effective at chemical separation.
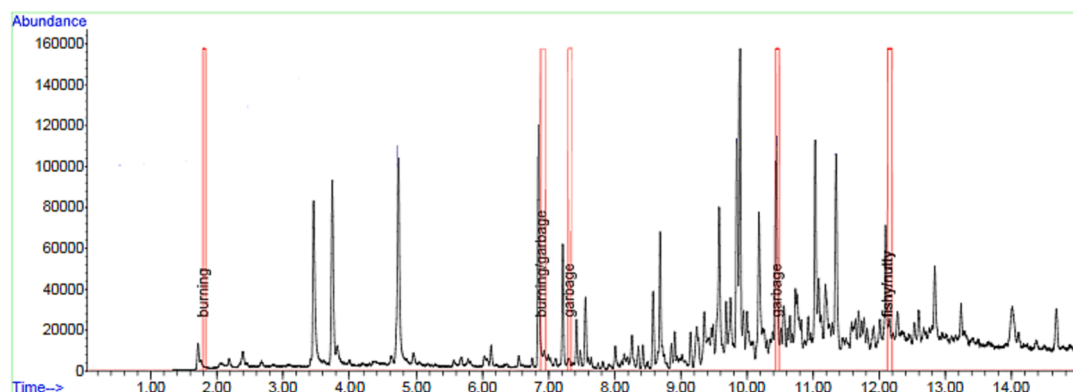
Fig. 2. Typical output of combining information received from CD and O simultaneously. The black line graph represents the CD's recording of the relative abundance of constituents of a sample. The red boxes and associated descriptors indicate the time and descriptive qualities of the odours experienced by the researcher (the aromagram). Note that high abundances of compounds do not always correlate with a human olfactory response and vice versa.

methodological benefits (Polvara et al. 2022b, Polvara et al. 2023, Ribes et al. 2007). From a logistical perspective, sorbent tubes are relatively low cost, easily transportable, resistant to degradation, have a low storage footprint and are reusable (Polvara et al. 2023, Ribes et al. 2007). Ribes et al. (2007) investigated the potential for multiple sorbent types in a single tube; while requiring additional effort and careful consideration, this methodology increased the range of accurately detected VOCs and may be a response to the issues of adopting multiple extraction procedures (Zhao et al. 2011). However, sorbent tubes are typically very selective of the VSCs it absorbs; this represents a significant issue given that VSCs are the prime malodour culprits (Zhao et al.

2011, Pandey and Kim 2009, Polvara et al. 2022a).

SPME is a methodology that is often compared favourably to others, but also provides examples of the risk of over-analysis (Koziel et al. 2005). Extraction time of sorbent materials as for SPME fibers is also a consideration as a greater mass uptake is a function of time (Cai et al. 2006). Usually, more volatile chemical species that are typically associated with low molecular weight and high vapor pressure reach equilibrium with SPME coatings more quickly relative to semi volatiles (Wright et al. 2005). For example, Laor et al. (2008) observed that from SPME six total ion chromatogram (TIC) peaks were recorded for a 15 s extraction, whereas 114 TIC peaks were obtained for an (admittedly

Table 2
Sampling and sample preparation techniques used in water and air matrices.

Matrix	Sampling/sample preparation techniques
Water	Homogenization [1]
	Centrifugation [1]
	Acid traps [1]
	Liquid-liquid extraction (LLE)[1], 6
	Simultaneous distillation extraction (SDE) [1]
	Closed loop stripping analysis (CLSA) [2]
Air, Water	Cryofocussing, sorbent tubes and adsorbent material for thermal desorption [3, 6, 8]
Air	Headspace techniques (static – HS and dynamic DHS) [2]
	Direct thermal desorption (DTD) [2]
	Adsorbent steel plates3
	Whole air sampling in canisters or sampling bags [4, 7, 8]
	Adsorptive fibres for solid phase microextraction (SPME) [4, 5, 6, 8]

[1] (Young and Suffet 1999).
[2] (Khiari et al. 1992).
[3] (Bulliner et al. 2006).
[4] (Hansen et al. 2011).
[5] (Chin and Marriott 2015, Kleeberg et al. 2005, Plutowska and Wardencki 2007, Hansen et al. 2011, Chin and Marriott 2014, Koziel et al. 2006, Plutowska and Wardencki 2011).
[6] (Agus et al. 2012).
[7] (Laor et al. 2008).
[8] (Koziel et al. 2006, Pawliszyn et al., 2001).

unrealistic in application)11 h extraction time (Laor et al. 2008). However, long extractions produce extremely complex chromatograms and aromagrams. This makes chemical identification of multiple peaks difficult for an assessor to resolve all odour events (Laor et al. 2008). Limitations also are an issue as the sensitivity and selectivity is restricted by the small volume and limited type of SPME fiber coatings that have limited sorptive capacity, as well as bias for sulfur compounds with relation to their molecular weight (Chin et al. 2012, Kabir and Kim 2012). Also, long extraction times can cause dynamic changes in sample composition by biodegradation that may interfere with the characterisation and possible competition and displacement on sorbent materials (Koziel et al. 2006, Laor et al. 2008). Additionally, extraction blanks are critical and resulted in identification and elimination of a number of odours are related to additives and impurities in the sampling and analysis process (Agus et al. 2012). Thus, SPME methods for specific odorous chemicals or screening for the presence of what are the major chemicals present must be carefully evaluated for use at specific locations.

3.2. GC separation

There is no difference in analysis between water and air analysis strategies; however, in the GC-CD/ODP methodology separation requires attention in much the same way of any Gas Chromatography separation method. Of particular consideration to GC-CD/ODP methodologies are the issues of co-elution, as well as opportunities for improved separation methods.

3.2.1. Co-elution

Co-elutions may cause some confusion for GC-CD/ODP separation. Co-elution of compounds that elute at similar retention time will confound odour peaks and the associated mass spectrum. Thus, co-elutes will mask odorants and the odorant's concentration (Ryan et al. 2008) (Table 3). Moreover, the co-eluted odorants might create an odorous signal with different odour character than any of the co-eluted odorants. Further discussion connecting co-elutions with odorant's properties and possible interactions among them is conducted in *3.5*.

3.2.2. Improved separation

In some cases, olfactory analysis from single dimensional GC can be imprecise due to co-elution, odour free zones being too short between

Table 3
Factors, risks, and remediation relating to co-elution.

Factor	Risk	Remediation
Similar chemical structure	Odourless compounds can mask odorants (Agus et al. 2012)	In these conditions, odour peaks can be tentatively identified (Agus et al. 2012)
Co-eluting odour compounds	Causes "odour clusters" that can be confusing to assessors as well as hiding particular olfactory contribution of the odorants. (Delahunty et al. 2006, Clausen et al. 2008)	Retention indices can be recorded from the onset to the end of each olfactory peak to assist in identification (Agus et al. 2012)
Numerous odorants in matrices	Co-eluting odour compounds can affect panelists sensitivity and capability to separate odour events (Laor et al. 2008).	Improving panellist training can improve results (Leonardos 1980, Van Harreveld 2003)Also the identification of typical culprits based on retention time improves diagnosis.
Extremely volatile compounds	Co-elution with the solvent, or have early eluting compounds which removes their ability to be detected (Agus et al. 2012).	Appropriate selection of sampling methodology.
Multiple compounds with similar odours	Separate contributing odorants are unrecognised where high odour detection threshold (ODT) may be masked by ones with low ODT (Clausen et al. 2008)	Pre-emptive identification of typical culprits.
Exceptionally long sampling times	Produces very complex chromatograms and aromagrams, running risk of co-elution (Laor et al., 2008).	Very long sampling times are often considered unnecessary and their implementation should be considered carefully (Laor et al., 2008).
Single-dimension GC	High risk of co-elution (Delahunty et al. 2006).	Pre-emptive identification of typical culprits or changing methodology to include more advanced GC instrumentation (Chin and Marriott 2014).

eluting compounds, as well as a potential lack of sufficient resolution power for characterisation (Begnaud et al. 2006). This leads to a possible masking of odour active trace level compounds by major interferences resulting in unreliable olfactory characterization (d'Acampora et al. 2007).

In order to increase the resolution of effluent regions with co-eluting compounds, multi-dimensional GC (MDGC) has gained popularity (Chin and Marriott 2015, Chin and Marriott 2014, Marriott et al. 2012, Shen et al. 2022, Xu et al. 2023). In MDGC-CD/ODP, particular compounds eluting at specific retention times and carrying characteristic odours can be diverted and separated from the entire sample on a second column of different phase selectivity (e.g., nonpolar and polar) (Koziel et al. 2009). MDGCs can be broadly divided into "heart-cut" and two-dimensional GC variations; each with their respective advantages and disadvantages as described in Table 4. (Biniecka and Caroli 2011).

Table 4 outlines several disadvantages of MDGC. This approach is considerably more expensive than their one-dimensional GC (Deans 1981, Maikhunthod et al. 2010). Long extractions using one-dimensional GC can provide information which is comparable with that gained by relatively short extractions using the MDGC capability (Laor et al. 2008). However, MDGC approaches can still been considered better alternatives for three reasons. First, more chromatogram peaks and odour events are resolved by MDGC–MS/O for relatively short extractions as compared with longer extractions followed by GC–MS/O. Second, long extractions can cause possible biodegradation of samples during extraction. Finally, MDGC has the potential to produce long extractions as well, thus potentially maximising odour-profile resolution (Laor et al. 2008, Tan et al. 2014).

An alternative is to operate two comparable GC columns, one to the

Table 4
Variations of multi-dimensional gas chromatography.

Name	Operation	Advantages	Disadvantages
Multi-dimensional GC (MDGC) using heart-cut	Selected compounds can be diverted and separated from the entire sample on a second column with a different phase selectivity (Koziel et al. 2009).	The method improves GC separation and resolutions of complex regions.	Technique becomes weaker if number of heart-cuts becomes too large and separation time is short (Biniecka and Caroli 2011).
Comprehensive two-dimensional GC (GCxGC, ²D)	Two directly coupled columns can provide orthogonal separation of compounds (d'Acampora et al. 2007).A modulator re-traps, refocuses and release fractions of the elute from the first GC column into the second one.	The whole sample is like a two dimensional GC.The sensitivity and accuracy compared to one-dimensional GC is improved by increasing peak resolution.	Reduces separation of odorous component as there is zone compression. Thus, narrow peaks may be too short for a human breathing cycle (Delahunty et al. 2006).In a very complex mixtures co-elution can still appear (Sasamoto and Ochiai 2010).
Alternative MDGC (Sakuma, Amano and Ohkochi 2000)	A particular component of the elute is collected using an adsorbent trap in a second GC with O attached (Sakuma et al. 2000, Nishimura 2001).	Specific sample components can be prioritised for analysis.The method shares similar advantages with standard MDGC.	The method shares similar disadvantages with standard MDGC.

sniffing port and one to the GC/MS. The retention times of the two GC columns must be carefully defined by relative retention times tests directly to the GC/MS and by standard chemicals of known odours to carefully verify the relative retention times (Khiari et al. 1995). This method minimises the pitfalls of the splitter technology and increases the concentrations received at both the GC/MS and the odour sniffer. However, by using this method, variations in column ageing, typical concerns with column humidity and temperatures, as well as potential homogeneity of varying sampling portions and/or sampling strategy may produce unpredictable results (Dettmer-Wilde and Engewald 2014, Gerretzen et al. 2015). These problems should be carefully addressed through consistent use of internal standards and a mixture of appropriate standard samples.

3.3. Split between CD and ODP

GC eluent column line is split into two separate lines with specific ratio of the streams relative to the constituents of the sample and the demands of an analysis (Hochereau and Bruchet 2004). Optimally the sniffing port line should allow low adsorption and small discrepancies between the CD and the odorous signals (Boeker et al. 2013a).

In the GC-CD/ODP, after GC separation the column flow split is typically achieved by a T-splitter with appropriate length and internal diameter capillary restrictors. The restrictors dimensions can affect the flow resistance with temperature changes; as a result, a 1:1 split ratio is only valid for a certain temperature (Boeker et al. 2013a, Grob 2001, Niessen 2001). At different GC temperatures, the split ratio will change due to asymmetries of the two flow paths (Boeker et al. 2013b, Grob 2001, Niessen 2001, Zhang et al. 2010). Care must also be taken due to potential differences in retention time between the detectors because of

the variation in pressure effects the sample flow (Brattoli et al. 2013). Fortunately, the installation and implementation of splitter variants can overcome these difficulties (Hochereau and Bruchet 2004, Brattoli et al. 2013). Variable splitting can be obtained by controlled pressure or flow control (Boeker et al. 2013a). Variable splitters are used with a 'live T' switching device, a Dean's switch, or a dome splitter (Boeker et al. 2013a). Since mass spectrometers operate under a high vacuum, care must be taken to avoid the carrier gas flow from the GC column to be entirely diverted to the MS. Also, outside air being sucked back into the MSD ion source must be avoided. This difficulty can be overcome by adding restrictors that regulate the pressure drop between the splitter, the ODP and the MSD, and by adjusting the carrier gas and make-up gas flow rates (Kozicki 2022). Split ratios can be calculated based on a column flow of the separation methodology (Wang et al. 2010).

Variable flow splitting to the sniffing port for GC-CD/ODP has benefits depending upon the odorant's odour threshold and concentration as less or more of the GC compounds eluting from the column can be directed to the sniffing port. This advantage in variability can be exploited with a high sensitivity detector such as time-of-flight mass spectrometry (TOF-MS) that only requires small percentage of the GC compounds eluting from the column. Additionally, if the retention times are not miss matched by the splitter (i.e., constant pressure in the lines) different split ratios can be set for an odorous mixture evaluation with higher sensitivity, both chemical and sensorial (Boeker et al. 2013a). The use of split-ratio for GC–MS has some technical concerns. Flow splitter runs the risk of poor precision, sample loss, and sample discrimination (Niessen 2001, Kozicki 2022). In addition, for trace analysis detector sensitivity may be decreased (Grob 2001, Niessen 2001). However, split ratio is currently the only methodology that allows GC–MS/O.

3.4. Chemical analysis of odorants

Predominantly, environmental chemical analysis GC-CD/ODP applications are MS and FID. Other chemical detectors are described in Table 1. Regardless of CD, there are considerations and restrictions regarding their measurements. Some compounds with very low odour thresholds might be present in such low concentrations that CDs cannot detect but assessors can (Acree et al. 1984, Barczak et al. 2022b). This means that the human nose can detect an odour even when there is no corresponding chromatogram peak (Khiari et al. 1992, Kai and Schäfer 2004, Knudsen et al. 2007, Wolkoff et al. 2006, Barczak et al. 2019). For example, a 2 ng/L concentration was considered as the limit of detection for geosmin by the MSD, while the odour could still be perceived at a level of 0.5 ng/L by human assessors (Hochereau and Bruchet 2004). Reverse situations may occur due to the compounds being extracted at concentrations below their odour detection thresholds but above their MSD detection limit (Laor et al. 2008).

3.5. Sensory analysis

Every odorant possesses qualities relating to their odour threshold and intensity (Rosenfeld et al. 2004). Both of those parameters varies for different compounds. The described by Weber–Fechner Law relation of the odour intensity of single odorant is proportional to the Log function of the odorant's concentration and can be calculated following Eq. (1) (Fechner, 1859).

$$\text{Odour Intensity} = k\text{Log}(\text{Concentration}) + b \qquad (1)$$

Whereas the concentrations are units such as ppb or $\mu g/m^3$, and k is a constant (named the Weber–Fechner coefficient) that is unique to each odorant. Fig. 3 shows the relationship between Odour Intensity and the Log (Concentration). The odour level of detection (1) and recognition (4) of the odour name are shown.

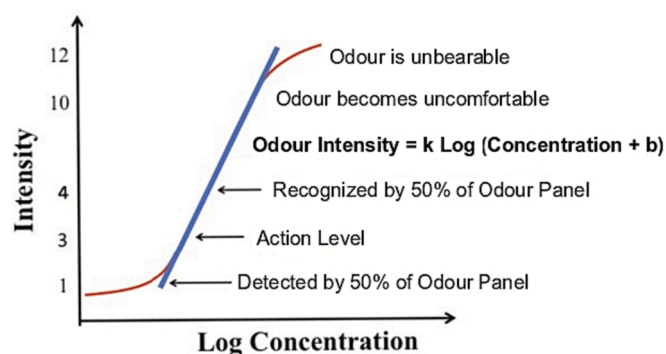Previous studies have demonstrated the odour gap between Odour

Fig. 3. Weber–Fechner curve showing intensity vs. concentration. Note: The straight line represents the Weber–Fechner Law.

Threshold Concentration (OTC) and Method Reporting Limit (MRL) (Curren et al. 2016, Zhou et al. 2023). OTC is the lowest concentration of a certain odorant that is perceivable by the human sense of smell. MRL refers to the threshold by which a specific sensor is capable of registering a specific stimulus; in this instance, where analytical methodologies can be expected to measure the concentration of a specific odorant. An odorant can still cause an odour nuisance when it has a concentration less than its MRL but higher than its OTC (Fig. 4). The odour gap can cause the situation where chemical analysis are not sensitive enough when determining odour-causing compounds. It is hardly possible to detect odour through chemical analysis if the affected area is in a distance from the emission source as the concentration of the odorants decreased as a results of air dilution and chemical degradation. In these situations, using an odour panel following the Odour Profile Method (OPM) practice is the most suitable approach.

Additional issues further complicate measures. Various studies have

evaluated the performance of some chemicals masking odours that would otherwise be detected by a participant. As an example, masking performance of specific chemicals was evaluated by chemical detection of reduced sulfur compounds concentration changes (Choi et al., 2012). However, analysing one group of compounds such as reduced sulfur compounds only does not represent odour evaluation (Abraham et al. 2015). To illustrate this problem, the relationship between the Weber-Fechner curves of odour masking agents and odorous compounds should be examined. However, since the sensitivity of odour varies among individuals, results from previous research should not be directly used. Detection curves for an odour mixture can provide supporting information on odour persistency at a further distance. The detection curves also illustrate a masking/unmasking effect that might be present in an odour mixture due to odour synergistic or antagonistic effects (Suffet et al. 2023, Zhou et al. 2023).

The complexity of odour analysis occurs due to the odour thresholds of the compounds that are mixed as well as their individual olfactory psychometric attributes: recognition threshold, odour character, hedonic tone (Yan et al. 2014, Xu et al. 2020). In some cases, synergies exist in mixtures of odorants; this is where the odour intensity of a compound is enhanced (or in some rare cases, modulated) by the presence of other compounds even below their OTC (Wyllie et al. 2001, Miyazawa et al. 2009, Trabue et al. 2011). For instance, Zahn et al. (2001) observed synergistic olfactory response when the concentration of acetic acid was increased relative to the concentration of other VOC odorants in standards (Zahn et al. 2001). Moreover, the relationship between concentration and intensity may be antagonistic for some compounds eluting together (Cocheo et al. 1991, Whelton and Dietrich 2004). For example, an antagonistic olfactory response was observed when the concentration of 4-ethyl phenol was increased relative to other VOC odorants (Zahn et al. 2001). These effects can occur when different odorants co-elute at similar time or can be missed due to the separation provided by the GC. Additionally, odour characteristics can change
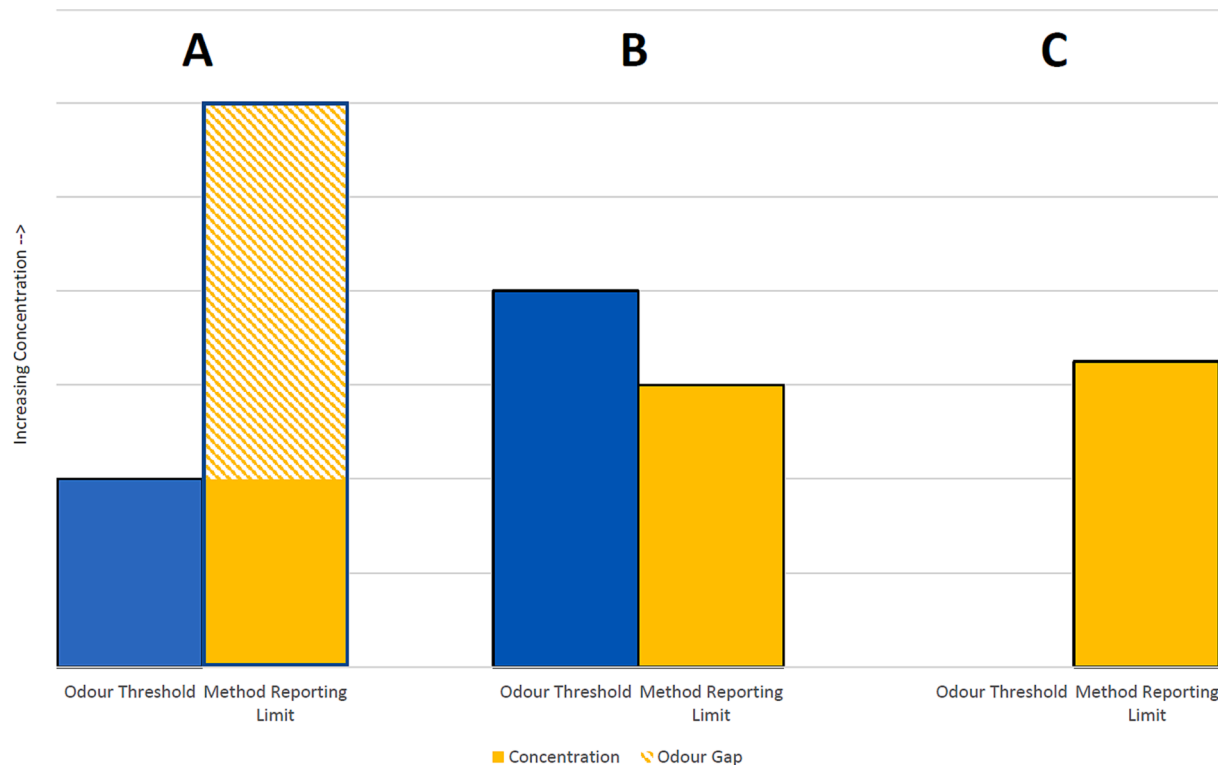

Fig. 4. Examples of the relationship between MRL and OTC. Column A is an example of when a panelist may detect an odour while the chemical detector may not; this is often the case with sulfurs and is represented by the odour gap. Conversely, column B represents the opposite, but an individual panelist's odour threshold for a specific odorant may be more sensitive than a documented average Odour Threshold. Column C represents the detection of compounds by the chemical detector but which are not detected by the specific type of olfaction. Note that for all compounds that the OTC and MRL vary in concentration.

based on concentrations. For example, the sulfur odour and the butyl mercaptan reference standard are either described as skunk or garlic based on the concentration of the reference standard (Agus et al. 2012). To overcome discussed here difficulties the technical solutions introduced in *3.2.2* were proposed.

Odour threshold values are far from established and in different reports can vary by orders of magnitude (Van Gemert, 2011). For example, 3-carene, allyl methyl sulfide, diethyl ether and hexanal caused odour perceptions in GC analytical/sensorial techniques, although their odour thresholds were not exceeded according to the measurement results (Lehtinen et al. 2013). This discrepancy is challenging to address; unless a comprehensive threshold measure applied to perhaps hundreds of participants is applied, it is likely that variation in odour thresholds will increase incrementally as more research contributes.

Human variability is not without concern. Using a number of assessors with a range of sensitivities and perceptions allows a wider variety of odorants to be identified and more readily elucidate the effect of intra and inter assessor variations (Barczak et al. 2018). Overall, the issues of sensory analysis are complex, and a standard method approach presented in the section 3.5.4. should be used by all odour panel to allow more consistency of results. Perhaps the greatest challenge with odour measurement strategies is a relative lack of inter-laboratory validity (Hayes et al. 2014). With appropriate standardization in presentation methods as well as methodology reporting methods, hitherto misunderstood odour qualities could be revealed, and greater reliance on odour measurement practices would be feasible for a variety of environmental, community-centric, and legislative applications. With these considerations in mind, there are also methodological issues with human sensory analysis that require careful monitoring.

3.5.1. Olfactory methods

Various GC-CD/ODP sensory methods have been proposed, reviewed, and classified into several categories including: dilution analysis, time-intensity methods, and detection frequency (DF) (Chin and Marriott 2015). Each GC-O technique has varying strengths and weaknesses (Table 5). Dilution methods are based on successive dilutions of an aroma extract until no odour is perceived at the sniffing port. There are not many applications for this method in environmental investigations involving GC-CD/ODP. However, the method is useful to establish the validity of assessors (Hayes et al. 2014). In intensity methods the odorous sample is injected once and the assessor, based on a scale, records the odour intensity of odours events eluted from GC column over the time (Pollien et al. 1997). Commonly, detection frequency and posterior intensity methods result in similar odour intensity/concentration relationships.

Dilution analysis was used to examine odour potencies, by measuring the relative importance, or the intensities of the odour in a single extract (d'Acampora et al. 2008). Ranking of identified odorants can be attempted by the applied sensory method (Kai and Schäfer 2004). The choice of methodology is critical for the correct evaluation of a matrix. This is because the use of different methods to a sample can indicate and rank the odorants according to their odour potency related to OTC and/or intensity. (Plutowska and Wardencki 2011). Indication odorant(-s) with lower OTC refer to its highest odour potencies.

3.5.2. Olfactory detection port

All ODP systems should not be referred to as olfactometers, unless the precise dilution of the GC effluent is established. Olfactometry, especially dynamic olfactometry, is a standardised methodology and using the term olfactometry in GC-CD/ODP can be considered misleading (Hochereau and Bruchet 2004, Brattoli et al. 2011).

All commercially available ODPs cones are made from PTFE or glass, with a nose shape fitting. To avoid the condensation of semi volatile analytes the effluent directed to the sniffing port flows through a heated transfer line. The auxiliary gas (humid air) is added to the eluate to prevent the nasal mucous membrane drying, what is critical in long time sniffing analysis (van Ruth and O'Connor 2001). A critical review of the sensitivity of available ODP devices would be valuable but has not yet been attempted.

3.5.3. Sniffing assessors

There are number of factors influenced analysis quality pertaining to sniffing assessors (Table 6). In particular, the number of assessors, their training, as well as factors relating to sensory fatigue. Unfortunately,

Table 5
Comparison of different GC-O techniques in odour assessment.

Method/principle based on	Subgroup	Strengths	Weakness	Opportunity examples
Dilution Analysis/ Potency as the Odor Activity Value which equals the ratio of concentration to odour detection threshold	CharmAnalysis™AEDA	– Minimum number of assessor(-s): 1	– Dilutions per sample 10–12 – Analyses required per sample min 10[a] – Time consuming for preparation dilutions and analysis – Low number of assessors makes results highly susceptible to the large variation in individual's sensitivities	– study the important aroma compounds in matrix, – determine the relative odour potency of compounds (odor active regions) in extract (Grosch 1993)
Intensity method/ Perception of odour intensity and duration	OSME, Finger Span Method, Posterior intensity method	– Minimum number of assessors: 3 – Analyses required per sample min 6[a] – Dilutions per sample: 1	– Training of assessors necessary (an OPM standardized training method is suggested) – Rapidly eluted peaks allow little time for odour characterization	– identify differences in the odour profiles in different conditions – identify the odorants and odorant contributions in matrix; – measures the odour activity values of odorants in matrix – identification important odorous active compounds and to assess their relative contributions to the unique odour of matrix (Fu et al. 2001)
Detection frequency/ Proportion of panel to detect an odour		– Training of assessors is not required – Dilutions per sample: 1 – Analyses required per sample min: 6[a]	– Minimum number of assessors 6 – No scale for intensity, above particular concentrations of odorants value of DF do not increase	– Identification and rank the odorants according to their OAV (Hanková et al. 2020)

[a] – based on combination of the number of dilutions × number of assessors × number of repetitions.

Table 6

Factors, risks, and remediations relating to sniffing assessors.

Factor	Risk	Remediation
Using low numbers of assessors	Makes results highly sensitive to individual olfactory variations, which can include idiosyncratic anosmias. This can underestimate the impact of specific odours (Delahunty et al. 2006, Warren et al., 2007)	Careful training and consideration of the number of assessors used (Muñoz et al. 2010) Replicated measurements of samples (Plutowska and Wardencki 2011)
An assessors ability to remember odour profiles	Assessors anticipate certain odours at later assessments, which produces bias (Plutowska and Wardencki 2011)	Motivation screening, and instruction that odours should be assessed appropriately (Agus et al. 2012, Brattoli et al. 2014)
Olfactory fatigue	Olfactory detection decreases, resulting in poor analysis (Doty, 1991a;b; Rabaud et al., 2002)	Sniff times should be reduced to 25–30 min (Brattoli et al. 2014). Time between assessments should be large, with a limit on number of assessments per day (Agus et al. 2012)
Breath cycle of assessor	Normal breath cycle is not efficient at detecting eluent from GC-O (Hanaoka et al. 2001)	More rapid breathing, as well as exhaling through mouth and inhaling through nose (Hanaoka et al. 2001)
Laboratory settings	Odours within laboratory can interfere with sampling (Delahunty et al. 2006) Variations in temperature can affect instrument reproducibility and assessor comfort (Delahunty et al. 2006) Extraneous noises (Delahunty et al. 2006)	Laboratory air should be filtered, and temperature controlled (Delahunty et al. 2006) Laboratories can be quiet, or in some cases soundproof headphones playing music is permitted (Delahunty et al. 2006)

prior research typically has limited or no information about the number of assessors or their training when reporting research (**Supplementary Table S1**). Future studies should consider the methodology described in more detail in section 3.5.4 and include how the odour assessors are trained e.g.: by Standard Method 2170 (APHA et al, 2017).

The number of assessors that are used to comprise a panel is debatable; dilution methodologies are often performed with only one to three assessors, whereas higher reliability is attained for detection frequency techniques with eight to ten assessors (Delahunty et al. 2006). A large number of trained panelists is also required for intensity evaluations since a high variability may be commonly observed within and between panelists (d'Acampora et al. 2008, Barczak et al. 2018). Requirements for high numbers of assessors are however time and cost consuming, and the transient nature of many VOCs often makes high numbers of assessors not feasible. Based upon the Standard Method 2170 (APHA et al, 2017), a minimum of four assessors are required and reports the odour character and the intensity +/- the standard deviation.

3.5.4. Screening test/training

There are only limited guidelines available for assessor training with GC-O technique (Vene et al. 2013) and there are only a few standardised protocols available for using sniffer assessors for research (Table 7) (Koziel 2013, Brattoli et al. 2014).

It is very difficult for an assessor to simultaneously detect an odour, find a descriptor, and register an intensity from a previously memorised scale, especially as peaks may elute rapidly and close to each other from a capillary column, as well as the "tip of the nose" phenomenon that makes describing odours inherently challenging (Pollien et al. 1997, Jönsson and Stevenson 2014, Stevenson 2001, Yeshurun and Sobel 2010). Rigorous selection and training of sniffing assessors will improve analyse performance, and as a consequence improve the accuracy and precision of collected results (Chambers and Koppel 2013). However,

Table 7

Guidelines for GC-CD/ODP assessors (Hayes et al. 2014, Delahunty et al. 2006, Agus, et al. Koziel 2013, Brattoli et al. 2014, Vene et al. 2013).

Protocol	Restrictions
During and before odour assessment	Not to wear aftershave, perfume, or strong –deodorants Good personal hygiene Not to eat strongly flavoured foods for 1 h up to analysis
Selection of panellists	Average sensitivity relative to population Screened for motivation Screened for concentration Ability to recall and recognise odour qualities- able to be trained effectively
Pre-screening	Age Smoking status Sinus related conditions Allergies Dentures Medication use

even with careful selection and training of analysts variability was still present due to the subjective nature of sensory analysis (Agus et al. 2012). In most published studies, there is missing information about assessors training, and then when it is stated that assessors are experienced in sensory analysis, the details of their expertise are not given (**Supplementary Table S1**).

Training methods for assessors have been proposed by numbers of authors (d'Acampora et al. 2007, Clausen et al. 2008, Barczak et al. 2018, Vene et al. 2013, Bianchi et al. 2009, Kamadia et al. 2006). Depending on the character of the research purposes and due to the inherent differences between GC-CD/ODP methods, different kinds of training procedures may be applied (Plutowska and Wardencki 2011, Vene et al. 2013). As an example, Pollien et al. (1997) reported that dilution frequency does not require training. On the other hand, Van Ruth and O'Connor showed that training did not affect the detection of the odour active compounds, but it decreased noise levels considerably (van Ruth and O'Connor 2001).

A method for training the sniffing assessors should be the OPM which is used by odour panelists to describe the odour and the intensity of the odour (Vitko et al. 2022). This method was successfully adopted into measure the odours of the odorous signals at the olfactory detection port (Khiari et al. 1992). OPM was based upon the Flavor Profile Analysis (FPA) method for the food and drinking water industries, specifically Standard Method 2170, the "Flavor Profile Analysis" of "Standard Methods of Water and Wastewater" (APHA et al, 2017, APHA, 1992). It has been used since 1992 and it is a standard method to evaluate odour problems and to serve as a quality control for specific odours in drinking water. The method was developed for air analysis studies by Burlingame (1999, 2009), Burlingame et al. (2004), and Curren et al. (2013). These methods helps determine what odours are present. The intensity of an odour obtained by the FPA or the OPM are proportional to the logarithm (base 10) of the concentration of the odorant, based on Weber- Fechner law. The OTC is defined as the concentration when intensity is 1 ($I = 1$) on the Weber-Fechner curve (Fig. 3). The breadth of OPM use includes identifying odour notes in the air sampled from the olfactory detection port as well as determining the odour intensity for each odour note. List of the OPM features is presented in the **Supplementary materials**. However, one of a disadvantage this training method is lack of matching with an intensity scale accessible in ODP hardware and software. In some of the popular ODP software and hardware there is 3 or 4 points intensity scale instead of the standard 12 points OPM scale.

During training, it is recommended to use compounds that are present in the sample of interest (Vene et al. 2013). Furthermore, if intensity measurements are to be carried out, the assessors should learn the appropriate scale (d'Acampora et al. 2008). Training depends also on separation technique. For example, requirements for an GC × GC-CD/

ODP assessor includes a high olfactory accuracy and dynamism in recording odour events (d'Acampora et al. 2007).

Additional physical and physiological scrutiny is also recommended. As with olfactory testing, panelists should be free of recent use of strong perfumes or other odour related products and have not eaten food or consumed any liquid beyond water (Doty 1991b). Over saturation of the olfactory system, or a drying out of the nasal mucosa can result in poor response (Doty 1991a). Additionally, panelists will likely perform sub-optimally if they are smokers, are of advanced age, or are experiencing certain diseases or conditions (Hayes and Jinks 2012, Doty 1991b, Stevenson et al. 2008). Additionally, the concept of olfactometry presenting as a health risk has emerged in recent years, however the actual potential of a health hazard appears to be low (Davoli et al. 2012, Davoli et al. 2016). As a response to this potential risk, measurement solutions for health have been provided in the literature (Polvara et al. 2021).

3.5.5. Descriptors

No universal odorant description table exists as it would be very difficult to describe every compound (especially considering variance between assessors), therefore for analysis it is often easier to limit the number of descriptors. Using descriptors strongly depends on the matrix and the purpose of the research. Most popular descriptors methods are based on a specific odour wheel (Aparicio et al. 1996). Odour wheels provide a framework to establish specific odours and patterns. Different variations of odour wheels depend on the matrix used. For example, there are odour wheels created for drinking water, wastewater, compost, landfill sites, biosolids processing (Suffet et al. 2004, Suffet et al. 2009, Suffet et al. 1999, Suffet and Rosenfeld 2007, Fisher et al. 2017).

For the analysis of odorous matrices where particular chemicals are expected in the samples the descriptors used should correspond with these expected compounds. In such analyses the assessors need to be familiar with these descriptors and the descriptors should be a part of training procedures.

However, in environmental studies most of the GC-CD/ODP analysis are carried out in order to support identification of chemical compounds which are often unknown (**Supplementary Table S1**). Thus, descriptors of the odorous events rely on the subjective opinion of the sniffing assessors (Fisher et al. 2018a). If more than one assessor take part in the analysis, it is valuable to discuss descriptors used among them to achieve congruence in the terminology. Without a training discussed in section 3.5.4 it is very likely that assessors will name the same odour event differently, particularly if they come from varied cultural backgrounds (Ferdenzi et al. 2013).

3.6. GC-CD/ODP results analysis

As what may be deduced, many factors influence the quality of the results obtained, such as the choice of the extraction procedure and the method of data collection (Plutowska and Wardencki 2011). However, there are also different approaches to report results. GC-CD/ODP analysis usually is presented in chromatogram and aromagram profiles (Fig. 1) (Koziel et al. 2009). The aromagram is a graphical representation of aroma or odour intensity and characterisation for chromatographically separated individual odorants from a complex matrix (Fig. 1) (Wright et al. 2005). As it was mentioned earlier, in many environmental analysis GC-CD/ODP methods are used for identification of new and/or unknown compounds (**Supplementary Table S1**). As a result, at least some of the odour events from the aromagram profiles do not correspond to the chromatogram peaks (Fig. 2) (Fisher et al. 2018b). Moreover, the character of the odour event does not always relate to the corresponding peaks of identified chemicals. However, those mismatches are of interest because understanding these phenomenon results with identification of chemical species and/or relationships between chemicals. If assessors are trained on odorant and an odorous signal that is different appears, that new odour belonging from new

potential odorant should be identified.

Interpretation of the results require multidisciplinary knowledge from variety of fields; for example: analytical chemistry for identification of chemical species occurs in low concentrations even in the ranges of ppt, chemometry to extract information from a large and highly complex datasets, sensory analysis to use human smell senses and even psychometrics as the measurement of human raters' judgement (Hayes et al. 2014).

3.6.1. Odorant characterisation

As discussed in section 3.5, there are several obstacles with regards to effective odour characterisation. Odorants usually are identified with three sets of criteria: (i) compared to previously reported odorous compounds or compound classes reported in peer-reviewed publications such as the Compilation of Odour Thresholds, Odour Qualities and Retention Indices of Key Food Odorants (Rychlik et al. 1998) and publicly available commercial odorant databases like LRI & Odour Database (Database), Flavornet (Acree 2014) or https://www.pherobase.com, (ii) matching mass spectra of unknown compounds with MS library search system and spectra of pure compounds like BenchTop/PBM (Palisade Mass Spectrometry, Ithaca, NY), NIST mass spectral library (Agilent, SantaClara, CA), Wiley275 (Wang et al. 2010); and (iii) matching of the retention time with the retention time of pure compounds run as standards (Agus et al. 2012, Bulliner et al. 2006, Koziel et al. 2006, Lehtinen et al. 2013, Brattoli et al. 2014, Lo et al. 2008, Yu et al. 2009). To unambiguously confirm existence of odorants in the matrix, its fragments and retention times as well as its odour character have to be compared with an authenticated standard (Clausen et al. 2008).

4. Applications of GC-CD/ODP

The various applications of GC-CD/ODP in environmental odour management are shown in **Supplementary Table S1**. Variations in methodology are mainly selected for identification and characterization of odorants from different sources. For example, identification and characterization of odorants in relation to different animal ages, nutritional diet, as well as different manure storage and management practices between dairies (Laor et al. 2008).

GC-CD/ODP can be a very useful tool for looking for compounds affecting taste and odour of water, especially when GC–MS alone is not able to explain the odour of the water samples. GC-CD/ODP can differentiate the odorous components of water to help understand the complexity of its odour profile. Because of the large differences between odour threshold concentrations of organic compounds in water, all of the chemicals identified by instrumental methods do not have the same contribution to the global aroma of the sample that would be evaluated by Flavour Profile Analysis (FPA) (Khiari et al. 1992). The methodology described in this paper includes the sensitive and precise methods for the determination of the odour of individual compounds. Moreover, it provides a means of screening which compounds merit quantitative analysis and monitoring. This methodology may be employed for other aqueous matrices as well as extracts of solids, which may contribute to aesthetic issues in water or air quality.

GC-CD/ODP analysis can offer potential benefits in identifying key chemical markers for odour abatement and mitigation system design. The identification of the key odour components responsible for the odour annoyance is important in the search for odour reducing methods and could be useful for quantitative purposes as well. Identification and quantitation of the major key odorants downwind of the sources can be helpful with developing and evaluating effective technologies and approaches to control odour (Wright et al. 2021, Vitko et al. 2022). The goal of these odour profile studies is to develop an approximate qualitative priority ranking of the individual odorants as emitted by the source. More recently inclusion of sensorial results in combination with analytical analyses improved the accuracy of the model prediction of odour concentrations for biosolids emission (Barczak et al. 2022b).

5. Conclusions

GC-CD/ODP is a useful and reliable tool for the detection and identification of odour active compounds. These approaches can be used for identification, defining, prioritizing, and tracking environmental odorants in the air in and around odour sources. From an analytical perspective, GC-CD/ODP is an invaluable tool to help identify unknown odorants. Moreover, GC-CD/ODP can be used to manifold determine both the psychometric function and absolute threshold of all odorants present in a multiplex environmental odour. In fact, this knowledge is necessary to extend our understanding of how individual chemical species combine to generate the odours that we are familiar with.

Thanks to a wide spectrum of analyzable samples, gas chromatography coupled with chemical and sensory analysis is becoming a popular methodology when investigating environmental issues. Odour character, odour intensity, and odour hedonic tone can be assessed for separated target odorants in parallel with chemical analyses to develop an understanding of how the odorants and their concentrations produced are connected to the total odour quality from the process. These factors are important in understanding the total odour production for evaluation of options for odour monitoring, process control and treatment. Cross tabulation of results between chemical and sensorial analysis can develop new insights into singular odorant contributions to overall odour.

However, there are still several limitations that exist when applying GC-CD/ODP technology to environmental malodour research. Firstly, understanding the link between the odour-active VOCs and the perceived air quality is still limited; the main limitation is related to the complexity of the odour mixture and to the lack of information regarding human perception. As a result, a correlation between identity and concentration of odour active compounds and the associated olfactory stimulus can be challenging. GC-CD/ODP methods cannot account for all possible interactions between odour components thus GC-CD/ODP methods may not result in the detection of all the key odour components. Due to GC separation, odorants cannot be analysed together, meaning that potential synergistic or antagonistic effects cannot be assessed. In some cases, this technique does not represent the complete screening of all possible odorous compounds from the matrix. As an example, some small amines that may be odorants were not detected by GC-CD/ODP (Lehtinen and Veijanen 2011). Moreover, larger molecules, the so-called semi-volatile organic compounds could not be measured by GC-CD/ODP focused to measure only VOCs (Lehtinen and Veijanen 2011). As a response, a version of multiple analyses involves the use of specific (and typically less expensive) measures for problematic odorants that are measured in tandem to a GC-CD/ODP setup. Commonly, this includes the use of PFPD or SCD for sulfur compounds, or NCD for nitrogenous compounds (Fisher et al. 2018b, Del Río et al. 2011, Polvara et al. 2022a, Polvara et al. 2022b). While these systems do not typically integrate with the GC-CD/ODP themselves, the complimentary data stream can help to improve odour impact assessments.

Issues relating to the limiting factors of implementation of GC-CD/ODP are centered around current practices. Analysis beyond identifying key odorants is very rare within environmental odour research, despite their otherwise wide appeal in other areas. More importantly, as **Supplementary Table S1** and Table 6 illustrate, there is a distinct lack of standardised tools, nomenclature, procedure, and reporting at every level of the GC-CD/ODP sequence which must be addressed if inter-laboratory comparisons (a veritable trove of research opportunity) are desired. Accomplishing this task may be difficult, however in similar fields a set of national or international standards, such as the VDI 3883 for odour impact establishment, has seen good progress in this regard (Sucker et al. 2008). Many of these challenges can be overcome through careful decision making with regards to any specific methodology to analyze environmental samples; as a result greater discussion and research into the varying merits and disadvantages of specific techniques represents a key goal in the research space.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108214.

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