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Odor Complaints, Health Impacts and Monitoring Methods

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EXECUTIVE SUMMARY

As a basic principle, odors are caused by airborne chemicals. Merely identifying a subset of compounds in air, however, does not indicate which are contributing to the odor problem. The odor description (odor note), intensity, and frequency plus duration of the occurrence need to be understood to identify the odor source and take corrective actions. In other words, these factors (odor note, odor intensity, odor frequency and duration) provide an indication of which chemical(s) cause the odor, which in turn informs the optimal mitigation steps or technology. The level of odor offensiveness (hedonic tone) as well as odor note (e.g., sewage) and intensity (e.g., high or strong) can help prioritize nuisance odors by indicating the severity to the complainant or impacted population, and highly offensive odors may require immediate shutdown of the operation or source.

Data management is the first challenge for any odor investigation. To gather the required information and assess trends, the following is recommended:
- Follow the example of Vancouver and educate the users of on-line forms by providing an odor wheel and pick lists to describe the odor (odor note, odor intensity, odor frequency and duration, and wind direction during odor episodes).
- Train call-center operators on these same odor descriptors.
- Replicate in other air districts the San Joaquin Valley AQMD database and its in-the-field functionality.
- Provide trend and complaint frequency data for the suspected odor source to air inspector prior to each new investigation.

For **initial screening** of a nuisance odor, two air inspectors, ideally, should respond to a complaint so they can corroborate the complainant's and each other's odor perception. If corroboration occurs, the source of the odor is usually identified by the complainant or the air inspectors' prior knowledge of the area. Standard practice is to move upwind of the likely source to assess whether another source contributes. Recording wind direction, details of the complaint and any action taken document the investigation.

Training air quality inspectors on how to better identify and consistently describe odors (odor note and odor intensity) would assist their work. For example, training on using an odor wheel (circular table of odor descriptions and potential culprit chemicals, see Appendix A) and scratch-n-sniff booklets will standardize odor vocabulary. Maintaining a log of complaints identifies trends. For many air districts, a lower level of training for the ability to sense "something" in the air at the complainant's location is sufficient, and odor intensity only need be noted as "weak," "moderate" or "strong" to help prioritize the nuisance. Initial training of new inspectors is required and refresher training every 2 to 3 years. More advanced training includes odor wheels and refined odor-intensity scaling. A local panel of residents, trained minimally, can help inspectors identify odors and their locations.

A wide range of **instrument and sensory techniques** are available, from sensors to questionnaires, for refining odor assessments. Unfortunately, no standard approach is followed today. For complex or unresolved odor exposures, sensory methods such as the Odor Profile Method (OPM) have been used to identify culprit odorants using an odor wheel, panel assessment of the intensity of the odor to prioritize those odorants, and frequency plus duration information to identify the odor source. Confirmation of the targeted odorants is provided by analytical techniques, such as gas chromatography with a sensory port and parallel mass spectrometry, within an OPM evaluation.

More expensive study (e.g., OPM plus selected ion flow tube mass spectrometry [SIFT-MS] or proton transfer mass spectrometry [PTR-MS]) may be needed to identify intermittent, faint odor sources. The use of the scanning reactive ion variant of PTR-MS on a mobile platform is an expensive but exciting addition to the confirmatory technology arsenal. The promise of e-noses that mimic the human sense of smell remains allusive, often failing to perform as well in the field as in the laboratory. The current path forward for environmental odor exposure assessment includes population-based metrics of odor, such as odor diaries and plume monitoring by OPM human panels, confirmed by advanced analytical techniques.

Odors add a substantial layer of complexity to conventional **human health risk assessment**. Two entwined senses, irritation and olfaction, are involved and their triggering can lead to either transitory or more permanent health effects. In addition, odorless co-pollutants can contribute to adverse effects, and their contribution is difficult to separate from that from the odorants. The variability in human responses to odors adds a large degree of uncertainty to any assessment. Nonetheless, several case studies demonstrate that odor thresholds and health hazard benchmarks can be applied to odorants to estimate sensory and health effects. How well this odorant-by-odorant approach addresses the health risks to communities, especially those suffering from environmental injustice, is an area in need of further research and objective methods.

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1. Introduction

Humans have around 5 million olfactory receptor neurons, and they connect to the most ancient, primitive part of the brain. By comparison, dogs have around 220 million olfactory receptor neurons and rabbits have around 100 million. It takes around 1 second to respond to an odor (Doty, 2015).

Olfaction relies on two routes of entry to the nasal cavity and two neural systems. Air enters either through the nostrils (orthonasally) or the mouth (retronasally). Volatile chemicals in the air (odorants) bind to olfactory neuron receptors (sense of smell) and to trigeminal neuron receptors (sense of temperature, pressure, pain and irritation). The combination of olfactory and trigeminal neuron receptors explains why menthol produces a minty smell as well as a tingling in the nose (Nagata et al., 2005). The human nose contains roughly 400 different types of receptor neurons, each sensitive to specific types of odorants (Malnic et al., 1999). The neural receptors signal the brain, which then associates the perceived odor with past experiences once the signal becomes strong enough.

Human olfactory mucosa occupies 3% (2.5 cm^2) of the nasal cavity and is protected high in the nasal vault (Dalton and Jaen, 2010), so only an estimated 5 to 10% of air entering the nostrils reaches this region (Johnson et al., 2006). The olfactory mucosa is composed of the olfactory epithelium and the underlying olfactory neurons. See Figure 1 for an overview.
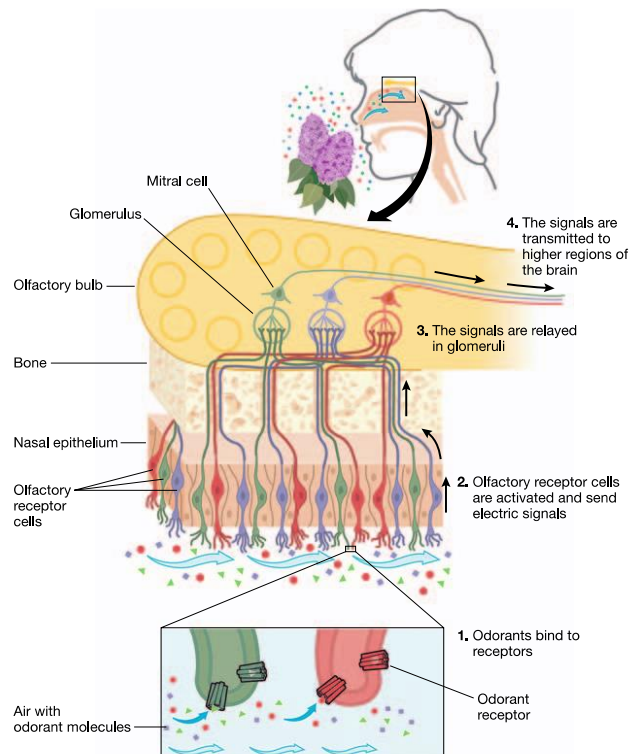

Figure 1. Human olfactory system (Rinaldi, 2007)

Environmental odors are typically complex mixtures of multiple odorants. Odorants can bind to one or more receptors, and receptors can bind to one or more odorants. Only a few odorants, however, are discerned within a mixture (Livermore and Laing, 1998). Some odorants dominate while others are masked, and factors such as concentration, temperature and humidity all play roles.

When sensed orthonasally, odors are perceived as coming from the environment, while when perceived retronasally, they are perceived as coming from food in the mouth (Small, 2005). Our two nostrils help us stereoscopically locate the source of the odor (Jacobs, 2019). The sinuses, a connected system of hollow cavities in the skull lined with mucosa tissue that has a thin layer of mucus, may help humidify air in the nasal cavity.

Human sensitivity to odorants ranges across several orders of magnitude (Amoore and Hautala, 1983). Around 1 part per trillion (ppt) appears to be a theoretical limit for sensitivity with many odorants are not perceived until above 1,000 ppm. The major components of air are not sensed at all, including nitrogen, oxygen and water vapor (Cain, 1988). Carbon dioxide is interesting because it is odorless at ambient concentrations yet, when it reaches 200-fold above background levels, selectively triggers only the trigeminal neurons (pain) and not the olfactory neurons (smell) (Amoore and Hautala, 1983).

Inter-individual variability in odor perception is high. Factors include age, sex, lifestyle, prior exposures, culture and health status (Ferdenzi et al., 2011; Doty and Cameron, 2009; Doty et al., 1985). Approximately 3% of Americans have minimal or no sense of smell (anosmia) (Hoffman et al., 2016). Prolonged or repeated exposure to an odor can lead to a decreased response (habituation), which has the benefit of allowing a baseline reset in preparation for a new stimulus (Wilson, 2009; Dalton, 2000). Habituation happens as quickly as 2.5 second and is accompanied by decreased transduction by the neurons after 4 seconds (Wang et al., 2002).

A growing field of research in public health is the microbiome, the microflora that contribute to gut, mouth and skin health. The nasal cavity, too, hosts microbes that contribute to normal functioning (Rawls and Ellis, 2019). Some microbes themselves emit odorants and can decrease the host's sensitivity (Koskinen et al., 2018).

Cognitive bias plays a role in odor responses (Government of Alberta, 2017). Odors trigger memories of previous experiences and are influenced by the power of suggestion. If given a prior warning (even if false) that an odor is harmful, increased irritation was reported. Fewer symptoms were reported if told the odor was healthful. Even when no odor was administered, suggestion that there was a harmful odor led to symptoms. Prior experience with an odor introduces bias, too. Emotional baseline is also a factor (Andersson et al., 2013).

Describing an odor in detail is often difficult, so most complainants start with saying "something smells bad" and then struggle to give further details. Unlike other senses with broad vocabularies, smell is anchored in the source of the odor and the person's history with

that source. In a way, our sense of smell is learned. Attributing words and meanings to odors occurs over a lifetime and even changes over time.

The food and beverage industry makes a science out of sensory description. Beer (Meilgaard et al., 1982), wine (Noble et al., 1987) and coffee are prime examples, and they conduct sophisticated sensory panels. Perfume formulation takes this to another level. To avoid complaints, the drinking water industry has developed taste-and-odor assessment protocols (Suffet et al., 2019). Odor notes and intensities are often assigned using the Flavor Profile Method (Method 2170, APHA et al., 2017), as described for drinking water (Lawless and Heymann, 2010) and beer (Clapperton, 1973).

1.1 Describing environmental odors

Environmental odors can be described and measured as presented in Table 1 (Burlingame, 2009). A key aid in odor description is the odor wheel (Figure 2 and Appendix A). Environmental odors are typically present as mixtures, which complicates their measurement. The exception is the release of a single chemical from a petroleum or chemical industry facility. The various odorants within a mixture trigger the olfactory sense in "concert" similar to the various notes in an orchestral piece of music. The interplay of odorants in a mixture can be complex, with both synergistic (amplification) and antagonistic (dampening) effects taking place. Further, dominant odorants can "mask" underlying odorants, and the latter are noticed only after sufficient dilution.

Table 1. Odor descriptors and measurement approaches

Odor Descriptor	Measurement Approaches
Odor – an individual odorant or mixture sensed by smell, usually with a negative hedonic tone	Odor panels are required. At present, unable to mimic the human sense of smell by instruments, although the electronic nose (multisensory array with machine learning) has this goal
Odorant – substance whose volatiles can be perceived by the olfactory organ	Single-gas sensors, gas chromatography often with mass spectrometry and sometimes with a sensory port
Odor note – identifiable, distinctive feature of an odor, such as "floral," "rotten egg," "tingling"	Standardized list or odor wheel (Appendix A) used by the public, air inspector or odor panels
Odor intensity – magnitude of the perceived strength of each odor note	Numerical scale or descriptive words ranging from odorless to extremely strong
Odor hedonic tone – perceived pleasantness or unpleasantness of an odor	Numerical scale or descriptive words ranging from extremely unpleasant to neutral to extremely pleasant
Odor frequency & duration – how often an odor is present and for how long	Single-gas sensors with data logging, odor diaries, or repeated field visits by and odor panel

Figure 2. An example of an odor wheel (Metro Vancouver, 2019)

1.2 Odor intensity

Odor intensity is often used as a surrogate for odor concentration. Its measurement has developed along two trajectories:
- Assigning words or numeric scores to intensity levels
- Determining the amount of dilution required until the intensity is no longer detectable

For a single odorant, intensity may be proportional to the odorant's concentration, although some odorants become odorless at sufficiently high concentration (e.g., hydrogen sulfide). In mixtures, such a link is tenuous or absent. Nonetheless, mathematical relationships are pursued using the Steven's Power Law or, more commonly, the Weber-Fechner Law:

$$\text{Steven's Power Law:} \quad Intensity = a\ (Concentration)^b$$

$$\text{Weber-Fechner Law:} \quad Intensity = k\ Log_{10}\ (Concentration/Initial\ Concentration)$$

Where a, b and k are odorant-specific constants. Plots of intensity versus concentration result in a straight line if, for Steven's Power Law, both intensity and concentration are logarithmically transformed. For the Weber-Fechner Law, the logarithm of only the concentration is taken to yield a straight line. Such lines are used to estimate the threshold below which an odorant is no longer detectable by 50% of a panel. This is known as the odor detection threshold concentration ($ODTC_{50}$). Such a value is useful for odor impact assessment, as described in Section 7.

The $ODTC_{50}$ can also be determined by dilution methods. The most common is the dynamic dilution olfactometer, which dilutes an odorous sample with various levels of dilution of odorless air until the threshold is reached. Alternatively, bags with various of levels of dilution can be presented to panelists, which is the approach used in Asia (see Table 2). Many regulations around the world focus on this value (termed "Odor Unit") for environmental odors, yet the continued number of odor complaints has proven this approach to be ineffective (personal communication from experts in Australia [Bydder, 2019; Najean, 2019] and Colorado [Wozniak, 2019; Brennan, 2019]). Although Odor Units are entrenched in Europe and other parts of the world, a gradual shift to community, population-based methods (e.g., odor panels) is replacing Odor Units. Switzerland prefers to rely on questionnaires and complaint tracking (Lebrero et al., 2011).

2. Background

Air quality throughout the United States has improved greatly over the past 50 years (USEPA, 2018), including in California (CARB, 2019). Nuisance odor complaints, however, continue to occupy a large portion of an air quality inspector's duties. Such complaints range from minor annoyance to more substantial impacts on health (e.g., headache, nausea), wellbeing (e.g., social, economic) and general quality of life. More than half of the complaints received by air pollution agencies worldwide concern malodors (Kaye and Jiang, 2000), which holds true as well for the United States (Leonardos, 1995) including California (South Coast AQMD, 2019).

Responding to odor complaints, however, is riddled with complexities. An odorous emission is typically a mixture of volatile chemicals rather than a single, easily identified compound. Even when present only at trace concentrations, most volatile emissions remain above their sensory thresholds and have the potential to adversely impact nearby communities (Sucker et al., 2008a). Further, the variability in odor perception and interpretation can be vexing to scientific approaches that seek to quantify and set limits (Gostelow et al., 2001). Analytical equipment often cannot achieve such low detection limits (Muñoz et al., 2010), which makes monitoring and enforcement difficult.

Unpleasant odors act as warnings to avoid the odor source, such as spoiled food. Continual signaling can lead to the public's concerns that the air is "unhealthy." Some people, however, have no sense of smell (anosmics), so they must rely on other senses. Residents also are concerned that environmental odors have a negative impact on property values (van Broeck et al., 2009).

Increased urbanization globally has led to residential encroachment and proximity to industrial facilities. The primary industries that tend to give rise to environmental odors include:
- Wastewater conveyance and wastewater treatment plants (WWTPs)
- Municipal solid waste landfills and trash transfer stations
- Composting facilities
- Animal agriculture and processing
- Rendering facilities and roadkill collection
- Chemical and petroleum industries
- Cannabis cultivation

Although these industries are varied, common approaches to odor management have been employed, as have common approaches to environmental odor investigations.

Muñoz et al. (2010) observed that "odor measurement is often approached from very independent and disconnected research fields." Both sensory and instrument measurements may be used that involve analytical chemistry, psychology, public health and hybrids of these. Approaches from around the world vary in complexity, focus and regulatory aims (Table 2) and enjoy varying degrees of success for identifying and mitigating odors (Brancher et al., 2017).

Table 2. Odor criteria for compliance monitoring by jurisdiction (Brancher et al., 2017)

Jurisdiction	Dilution Limit (EN 13725:2003, ASTM E679-04) for Compliance Monitoring	Comments Extracted from Brancher et al. (2017)
AMERICAS		
Brazil	-	Odor is a form of pollution; odor only mentioned for cellulose manufacturing activities
Canada	By province	Nuisance law
Canada – Alberta	-	Substantial set of odor guidance published by Clean Air Strategic Alliance in 2015 (CASA, 2015)
Canada – Quebec	Biogas & composting: 1X	Hydrogen sulfide standards in the 2011 Clean Air Regulation
Canada – Manitoba	< 1X desired	No national provision, just local
Canada – Ontario	1X	Odor-related pollutants have ambient limits
Chile	-	Sulfated pulp industry total reduced sulfur compound limits; swine facility odors led to a national strategy document
Colombia	-	30 working days to evaluate complaints; odor management plan may be required; daily limits: hydrogen sulfide 7 $\mu g/m^3$, total reduced sulfur 7 $\mu g/m^3$, ammonia 91 $\mu g/m^3$; hourly limits hydrogen sulfide 30 $\mu g/m^3$, total reduced sulfur 40 $\mu g/m^3$, ammonia 1,400 $\mu g/m^3$
Panama	Fenceline field monitoring: 15X for residential or commercial 30X for industrial or rural Receptor field monitoring: 7X for residential or commercial 15X for industrial or rural Confirmation, if needed, by panel: 3X low offensiveness industries 6X medium offensiveness industries 10X high offensiveness industries	At least 5 min during key periods; maximum values of hydrogen sulfide and ammonia for outlet stack emissions; regulation remains unofficial
United States	Various (field)	No federal provision, just local
EUROPE		
Austria	-	No legal limits on odors, just targets
Belgium - Flanders	Field inspection by sniffing method 0.5X very unpleasant industries 1.0X–1.5X unpleasant industries 2.0X neutral industries 2.5X–3.0X pleasant industries 3.5X–5.0X very pleasant industries	Additional criteria for specific industries
Denmark	-	No national provision, just local
France	-	No national provision, just local

Jurisdiction	Dilution Limit (EN 13725:2003, ASTM E679-04) for Compliance Monitoring	Comments Extracted from Brancher et al. (2017)
Germany	Odor-hour field measurement by VDI 3940 – Part 1:2006, which weights many short odor episodes more heavily than fewer long ones	2008 Guideline on Odour in Ambient Air
Ireland	-	No statutory odor standard, just guidance
Italy	-	No country-wide provision; addressed by regions
Netherlands	-	Long history regulating odors; regulated nationally since 1995; since 2016 nuisance law by local authorities
Spain	-	No national provision, just local
United Kingdom	-	No national provision, just local
OCEANIA		
Australia	-	All states adopt the Australian/New Zealand Standard 4323.3:2001 for odor measurement by dynamic olfactometry (AS/NZS, 2001)
Australia – New South Wales	Ground level concentration for individual odorants (lower of odor or health impacts)	
ASIA		
China	10X to 60,000X depending on stack height Ambient limits for 33 air pollutants Fenceline concentration limits for 8 odorants (ammonia, trimethylamine, hydrogen sulfide, methyl mercaptan, dimethyl sulfide, dimethyl disulfide, carbon disulfide and styrene)	No national odor standard; GB/T14675-93 follows the Japanese triangular odor bag method
Japan	Fenceline concentration limits for 22 offensive odorants	Developed independently since 1970s
South Korea	1,000X for industrial area stacks 500X for other stacks 20X for industrial fenceline 15X for other fenceline Source and ambient concentration limits for 22 odorants	2008 Malodor Prevention Law; follows the Japanese triangular odor bag method
Taiwan	By field method at fenceline: 50X in industrial and agricultural regions 10X in residential areas Ambient concentration limits for 4 odorants (ammonia, hydrogen sulfide, dimethyl sulfide, methyl mercaptan)	2008 Malodor Prevention Law follows the Japanese triangular odor bag method

As a basic principle, odors are caused by airborne chemicals. Merely identifying a subset of compounds in air, however, does not indicate which are contributing to the odor problem. The odor description (odor note), intensity, and frequency plus duration of its occurrence need to be understood to identify the odor source and take corrective actions. In other words, these factors (odor note, odor intensity, odor frequency and duration) provide an indication of which chemical(s) cause the odor, which in turn informs the optimal mitigation steps or technology. The level of odor offensiveness (hedonic tone) as well as odor note (e.g., sewage) and intensity (e.g., high or strong) can help prioritize nuisance odors by indicating the severity to the complainant or impacted population, and highly offensive odors may require immediate shutdown of the operation or source.

Regulating odors based on dilutions (i.e., the number of dilutions required for an odor to become imperceptible, often termed "Odor Units"), either predictive or in response to actual odor complaints, has been unsuccessful (personal communication from experts in Australia [Bydder, 2019; Najean, 2019] and Colorado [Wozniak, 2019; Brennan, 2019]). The evidence is that odor complaints persist despite the various Odor Unit approaches used around the world (Lebrero et al., 2011). For example, the Odor Unit limit may be set to 3 (i.e., 3 dilutions with odorless air), yet odor complaints continue. The main driver for setting Odor Unit limits is to treat an odor as a traditional air pollutant and use the same dispersion models (Brancher et al., 2017). The poor track record of this approach for odors demonstrates the need for another approach, such as the Odor Profile Method that is described in Section 6.1.

Risk assessment, the systematic evaluation of risks posed by exposures to chemicals and other stressors, has many of the same challenges as odor investigation. Both follow the source-release-pathway-receptor conceptual model and employ many of the same analytical techniques (e.g., gas chromatography with mass spectrometry). Both also suffer from large variability and uncertainties in their results, which can span an order of magnitude or more. Unlike the risk assessment of toxic chemicals, odor studies can include human sensory panels. To save resources, risk assessment conducts a screening-level assessment before a refined risk assessment is performed. Such an approach would apply well to odor investigations.

3. Complaint data management

South Coast AQMD receives the largest volume of odor complaints in California. Since 2010, the number has risen from around 3,400 to 7,500 per year, decreasing in 2017 to 6,000 (South Coast AQMD, 2019). Jurisdictions tend to use the same database software to manage odor complaints as they do for any air pollution concern. Development is typically through software vendors yet may be done in-hose if sufficient funds are available.

- SJVAQMD: Developed in-house, which was expensive; however, the system could serve as a model for other air districts. The database is on-line, smart phone friendly, interfaces with their app (ValleyAir) and can collect photos and videos. The system sends automated notifications to inspectors by text or e-mail. It also includes mapping features.
- SMAQMD: Transitioned from Microsoft Access to Microsoft Sharepoint, which sends automated e-mails and allows data logging from the field.
- PCAQMD: Moved to Accela software, which is also used by San Diego County. The data was previously in Structured Query Language (SQL) and Microsoft Access.
- Colorado: All complaints are tracked in CACTIS (Colorado Air Compliance Tracking & Inventory System) software, as is all inspection work.

Such data is valuable for tracking the trends in odor complaints. Software vendors also support facilities so they can track the complaints they receive directly and manage them in-house. Such systems are required in certain jurisdictions, such as Colorado.

All jurisdictions have phone and online ways to file odor complaints. Several websites from California air districts were reviewed (Table 3) and varied in the information gathered, including which fields were required.

Table 3. Complaints received online in California

Information Requested	San Joaquin Valley	South Coast	Bay Area	Sacramento	Placer County
Via app	X	*	**		
Via website	X	X	X	X	X
Complaint button on homepage			X	X	X
Warning that information may be released when required by law	X	X			
Warning that agricultural odors are exempt				X	
Complainant contact information (name, location, phone number, email)	R	R	O	O	R
Should an air inspector contact complainant?				O	
Would the complainant like to receive a report?	O				
Alleged source information (name, location)	O	R	O	O	
Odor description	O	R		R	
Date & time of observation	O	R		R	O
Continuous or intermittent?					O
Occurred before?					O
Wind conditions (strength and direction)					O
Is complainant impacted?					R
Is complainant willing to go to court?					R
Upload photo	O				O

* App has a button that calls the complaints phone line.
** App sends user to the website to fill out the complaint form.
Key: X = included, R = required, O = optional
Sources:
San Joaquin Valley AQMD https://www.valleyair.org/busind/comply/complaint.htm
South Coast AQMD https://www.aqmd.gov/home/air-quality/complaints/smoke-dust-odor
Bay Area AQMD http://www.baaqmd.gov/online-services/air-pollution-complaints
Sacramento Metropolitan AQMD http://www.airquality.org/Residents/Complaints
Placer County APCD https://www.placerair.org/1692/Complaints

More sophisticated evaluations than number of complaints are needed, however, to capture the actual impacts. The use of odor description using the odor wheels and intensity level of each odorants of each complaint into 3 intensity levels (weak, moderate and strong) by the complainant and inspector would clearly upgrade the systems.

Vancouver, Canada, has a complaint form that provides odor guidance in addition to collecting information from the complainant (http://www.metrovancouver.org/services/Permits-regulations-enforcement/air-quality/factors/odour/Pages/default.aspx):
- An introductory page listing common odorous air contaminants and their odor notes
- Tips on making an air quality complaint, which includes an odor wheel
- Information on what happens to an air quality complaint

- Online complaint form with several unique features: pick lists for "preferred method of contact (yes/no)" and "type of complaint (odor and 5 other options)"; a pop-up odor wheel; and whether the odor was observed in the last 15 minutes (yes/no)

This approach could serve as a template for other jurisdictions and serves as an upgrade to the California systems (Table 3) by capturing more detailed information and offering visually intuitive aids.

In addition to time trends, a complaints database can be analyzed statistically or visually. For drinking water, six utilities were included in a study of customer complaints (Gallagher and Dietrich, 2014). The data were evaluated using several statistical methods, and the same could be done for done for an odor complaint database. A combination of high frequency of complaints together with consistency of descriptors was indicative of episodic water quality problems. Another way of analyzing odor complaint data is through a "word cloud," as was done for a chemical spill in a river (Gallagher et al., 2015). See Figure 3 for an example where the size of the font indicates word frequency.
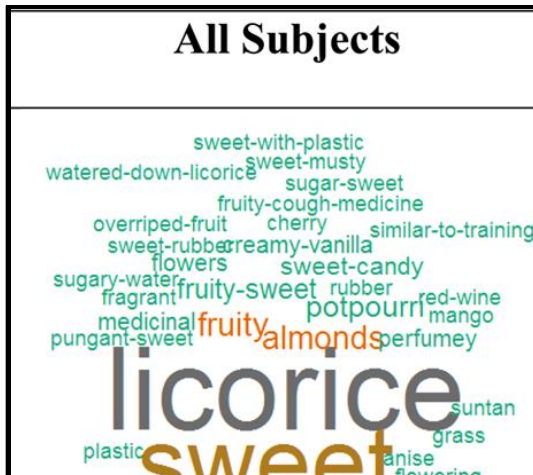

Figure 3. Example of an odor "word cloud" (Gallagher et al., 2015)

4. Initial screening-level approaches to investigating odor complaints

To obtain real-world, up-to-date information on the ways air inspectors conduct environmental odor investigations, phone interviews were conducted. Experts were contacted in Colorado and Australia, as well as in various air districts within California:

- California air quality management districts: South Coast (South Coast AQMD), San Joaquin Valley (SJVAQMD), Bay Area (BAAQMD), Sacramento Municipal (SMAQMD), Placer County (PCAQMD) and Feather River (FRAQMD)
- Colorado: State and Denver
- Australia: Sydney, Melbourne and Perth

Prior to each call, a list of questions was shared to initiate the conversation, which was otherwise unstructured and typically lasted 30 to 60 minutes. After each conversation, follow-up questions and documents were shared by e-mail.

Before summarizing the interviews, it's worth noting that California has a long history of addressing nuisance odor complaints. In the 1970s, CARB collected and analyzed health and odor annoyance information from residents near pulp mills (CARB, 1971). More recently, CARB acknowledged its lead role in addressing nuisance odor complaints from mobile sources and agreed on how complaints it happens to receive on odors from stationary sources would be coordinated with the air districts (CARB, 2002). CARB also trains the air district staff on visual smokestack opacity measurement (Method 9, USEPA, 1993; Rose, 1995). Training air inspectors regarding environmental odor evaluation could be developed as well.

Each air district in California has unique rules and history on how nuisance odor complaints are investigated. Table 4 compares California's methods with those of Colorado and Australia. Several common themes emerged during the conversations. In general, the initial odor investigation process is:

1. Gather sufficient information from the complainant to identify the source of the odor, if possible
2. Meet as soon as possible with the complainant to verify the odor (not necessarily needing to agree on the odor note or odor intensity) and walk (or drive) together toward the alleged source of the odor
3. Investigate upwind of the alleged source to rule out other sources
4. Collect sufficient information about the odor plume (GPS location, wind direction, temperature, humidity, date, time, etc.). If needed, the Kestrel 1000 wind meter, MesoWest meteorological data and HYSPLIT dispersion model have been used.
5. Meet with the alleged source to see if any recent upset or abnormal emissions occurred. Authority differs for facilities with air permits versus those exempt from odor regulations (e.g., agriculture).
6. Report back to the complainant on the findings and actions taken.
7. Enter case information into a database, which is typically the same as used for air permits. Odor Unit levels (number of dilutions) are not typically determined in California.

Depending on staffing and complaint volume, some air districts respond to every complaint while others set thresholds for an investigation to be triggered (e.g., more than 5 complaints about the same source within a 24-hour period). More rural air districts provide mostly an advisory role on odor complaint investigations because agricultural odors are exempt, and odors from composting are handled by solid waste agencies.

Table 4. Initial screening-level odor investigation approaches (California, Colorado and Australia)

Topic	Specific Approach	California	Colorado	Australia
Odor notes (odor wheels)	Trained and used previously but found unnecessary for initial investigations	X		
	Use presence/absence of odor instead	X	X	X
Odor intensity	Use absent/present	X		
	Use absent/faint/strong			X
	Use 10 levels, train inspectors, verify sense of smell		X	
Source identification	Walk with complainant toward odor source	X		
	Verify that the odor is not coming from another source upwind	X	X	X
Database	Use the same database for tracking odor complaints as for other air compliance work	X	X	X
	Mobile phone friendly	X (SJV)		
Complaints	Receive by phone, website or email	X	X	X
	Receive by app	X (SJV)	X (Denver)	

Key: SJV = San Joaquin Valley

For initial investigations of new complaints, air inspectors primarily trust the complainant's sense of smell and use their own as confirmation. Lists of standard odor names and odor intensity scales have not helped the initial investigation, although such training and pilot tests have been conducted in California in the past (Curren et al., 2016). When more complex situations, such as overlapping odors or unidentified sources, arise, then more sophisticated techniques are required. Asking the complainant to collect grab (bag) or integrated (SUMMA canister) air samples for analysis may allow detection by gas chromatography with mass spectrometry (GC-MS) or sensors (e.g., hydrogen sulfide, ammonia).

For the most part, experiences with odor panels and odor management plans have not been favorable. BAAQMD, although its regulations require such, stopped using odor panels around 5 years ago. Employees from BAAQMD were the panelists and worried about adverse effects from frequent exposures. Odor management plans are considered by some to be ineffective because they are written by consultants detached from the facility and a burden for inspectors to review. Some rules require odor management plans (e.g., South Coast AQMD Rule 410 for trash transfer stations), and Denver has found them effective in reducing odors from cannabis cultivation (personal communication with William Brennan at Denver Public Health

and Environment). The latter are typically a few pages in length, include a facility map, and signed by a certified industrial hygienist, which could be a model for more manageable and effective plans.

A joint project between BAAQMD and Envirosuite Inc. tried to use advanced backtracking technology, based on real-time fine-scale meteorological modelling, to instantly plot and visualize the trajectory of an odor complaint, thereby identifying its likely cause. The contract was not continued, however, due to the substantial requirements for meteorological data.

Sorting out valid complaints from those with other motives is challenging. Urban areas with infill housing can have odors used as a proxy for zoning disagreements, and cannabis cultivation odors can be targeted by those who opposed legalization. Due to the sharp spike in odor complaints after legalization, Denver formed a multi-stakeholder group that met 10 times to resolve issues. One result was the above-mentioned requirement for odor management plans in Denver.

On-the-job training is commonly used. Junior staff accompany senior staff to learn the techniques for odor investigations. Colorado is unique in providing annual training and certification of air inspectors. Both state and local air inspectors are tested on their sense of smell, with those too sensitive or insensitive excluded from odor investigations. The focus is on odor intensity, with detection (rather than clear odor recognition) as the concern, and an intensity scale of 0 to 10 is used. Distinguishing between midrange scores, such as 2 versus 4, can be tricky, however. Inspectors in Australia use "faint" and "strong" as simplified intensities. Odor notes (descriptors) are not used in Colorado investigations, which may have its origin in the dilution thresholds that have been codified in state regulations. Dilution thresholds (akin to Odor Units), however, have proven to be unpredictive and complaints continue. Denver sends two inspectors to investigate odor complaints to provide confirmation.

For drinking water odor complaints, the Flavor Profile Analysis is the gold standard. Both the odor note and intensity are determined by a panel. This leads, ideally, to the identity of the culprit chemical (odorant) and mitigation measures. Such an approach is successful for environmental odor investigation, too.

5. Refined investigations: community engagement

Participation of the local community in odor studies has proven to be a useful tool to qualitatively evaluate odor exposures (Gallego et al., 2008). Methods include:

- analyzing existing complaint databases
- administering surveys
- keeping odor diaries
- holding community meetings

Odor diaries are especially helpful and can be correlated with the activities of the potential source.

The methods to assess the impact of malodor on communities have been reviewed (Hayes et al., 2014). Although the methods still require refinement, investigations that integrate three tactics – hybrid analytical/sensory instrument measurements, odor panelist testing to name odor notes and intensities (e.g., via odor wheels), and comprehensive community surveys – have proven successful (de França Doria et al., 2009). Germany has several standards regarding community odor assessment (see Appendix B). One tip was to avoid using the word "odor" in surveys and, instead, ask about "things you don't like" to gather unbiased responses. Community members found the odor wheels (Appendix A) intuitive and helpful.

Involving the community is not only a rich source of information, it also can have a positive psychological effect. Biases against (or in favor of) the potential source of the odor, however, can override the usefulness of the data (Sironi et al., 2010).

6. Refined investigations: sensory and analytical methods

6.1 Odor profiling with confirmation by analytical chemistry

While chemical analyses can identify a subset of chemicals and their concentrations in ambient air, chemical analyses often do not directly relate to human sensory experiences (Gostelow et al., 2001). Odor samples usually contain multiple odorants (airborne chemicals) that can have synergistic and/or antagonistic effects on each other, altering the overall perception. Odor is not simply additive, unlike concentration. Further, the human nose is often more sensitive than analytical techniques. Therefore, the most accurate way to evaluate an odor it to judge its properties "as is" by a human panel. This direct approach is called "Odor Profiling" and can be performed at the location where the odor is observed (*in situ*) or by capturing a sample and transporting it to where a trained (or naïve) observer is located (Jiang et al., 2006).

A specific version of this approach, the Odor Profile Method (OPM; Burlingame 1999, 2009), has been developed based largely on flavor profiling for the food and drinking water industries, specifically Method 2710 "Flavor Profile Analysis" by the American Public Health Association, American Water Works Association and Water Environment Federation (APHA et al., 2017). This approach has been a mainstay of the drinking water industry to address taste-and-odor problems since the 1980s (Suffet et al., 1988; McGuire et al., 2005) and was recently reviewed and updated (Suffet et al., 2019). An approach similar to OPM is used in dentistry research for mouth odors (Greenman et al., 2004, 2005).

OPM includes three parts: (1) identify one or more odor notes in the air sampled, (2) determine the odor intensity for each odor note, and (3) note the frequency and duration of the odor at the site fenceline (Burlingame, 1999 and 2009). In more detail, OPM includes:
- Four or more panelists are screened for anosmia (lack of sense of smell) using a "scratch-n-sniff" test (Doty et al., 1984) and trained with mixtures of 2, 3, and 4 standard odorants. A health risk screen of all chemical exposures (Schweitzer and Suffet, 1999) and a human subjects review board approval are typically required. Such review is standard practice at universities and research institutions.
- Standardized odor note vocabulary is taught to panelists using "odor wheels" (Appendix A) that consist of three rings: an inner ring of general odor notes, a middle ring of more specific odor notes within each segment and an outer ring of known or potential odorants associated with each odor note.
- Panelists are calibrated to the odor intensity scale – threshold (1), slight (2), weak (4), medium (6), medium strong (8), strong (10), and very strong (12) – using sugar-in-water solutions tasted by mouth that represent weak (5% sugar = score 4), medium strong (10% sugar = score 8) and very strong (15% sugar = score 12).
- Group discussion is allowed yet panelists are instructed to act independently.

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- Overall panel results for "odor notes" require at least 50% agreement amongst panelists (else considered "another odor note"). Odor intensities for "odor notes" are calculated as the panel geometric mean (the standard deviation is reported, too).
- Frequency and duration are captured by multiple samples or visits by the panel to the site over, ideally, the course of 6 months or more to capture various seasons and weather patterns.

Note that only up to 2 odorants per mixture (up to 4 for experts) can be recognized by trained panelists (Poupon et al., 2018). OPM can be part of a diagnostic investigation or an ongoing monitoring program and conducted in the field ("odor patrol") or have samples collected and brought to panelists in an indoor, controlled setting. Hedonic tone was included early on in OPM (Burlingame, 2009) but not subsequently because it was considered too subjective and variable.

For confirmation of odorants indicated by the odor wheels, OPM requires gas chromatography with mass spectrometry (GC-MS) instrumental analysis that includes a parallel sensory port for the analyst to smell the eluting odorant (Khiari et al., 1992; Suffet et al., 2004). The calibrated intensity scores (sugar solutions) are in the range score 4 to 12, yet individual panelist scores for real samples – as well as the overall geometric mean of the scores – are often in the 1 to 3 range (+/- standard deviation). Both APHA et al. (2017) and the originator of OPM (Burlingame, 1999) warn against making intensity readings in this low range. Such intensity scores are below the score 4, which is designated the "odor recognition level" where 50% of a panel can identify an odorant correctly. Scores below 4 are, however, predictive of potential odor nuisance problems to consider and can indicate the disappearance of an odor nuisance. Their large standard deviations indicate the high level of uncertainty in this region.

OPM has been used to assess environmental odors for over 20 years. Key case studies are summarized in Table 5, which cover a range of odor sources. The case studies confirm that OPM, together with properly selected chemical analyses, can be a useful tool for identifying the specific processes within a facility that are responsible for an environmental odor. Further, OPM helps prioritize odorants for mitigation and monitoring.

Table 5. Summary of Odor Profile Method environmental odor case studies

Study	Culprit odorants identified by odor wheel and instrument?	Intensity results below calibration range? (i.e., intensity score <4)	Frequency and duration information used?
WWTP on-site & fenceline (Burlingame, 1999)	*Odor wheel:* not used *GC-MS-sensory:* not performed	~50%	3 years, correlate with operations and atmospheric stability
WWTP fenceline (Burlingame, 2009)	*Odor wheel:* used but not to identify odorants *GC-MS-sensory:* not performed	Data obscured by translating odor intensity and odor note into "odor annoyance"	7 months, 20 surveys
Landfill odors (Decottignies et al., 2009)	*Odor wheel:* used to identify odorants *GC-MS-sensory:* not performed	~10% on-site ~50% off-site	1-day study
Dried sludge odors (Decottignies et al., 2010)	*Odor wheel:* used to identify odorants *GC-MS-sensory:* not performed	100% during field test 1 out of 2 odor notes	1-day study
WWTP odor treatment by seashell biofilter (Abraham et al., 2015)	*Odor wheel:* identified 3 odorants *GC-MS-sensory:* identified 2 additional odorants	2/3 odor notes (day 1) 0/2 notes (day 2, a.m.) 2/3 odor (day 2, p.m.)	2 days, a year apart
Trash transfer station odors (Curren et al., 2016)	*Odor wheel:* identified 5 odorants and 1 chemical class *GC-MS-sensory:* identified 3 of the odorants	~50%	4 days/1 month
WWTP musty and masking odors (Zhou et al., 2016a, 2018; Vitko et al, 2017)	*Odor wheel:* identified 2 on-site fecal odorants, 3 on-site sulfurous odorants and 2 off-site musty odorants *GC-MS-sensory:* confirmed the above	~80%	15 days/1 month (April 2016) and unknown days in 2013
Landfill odors at nearby school (Bian, 2019)	*Odor wheel:* used to confirm absence rather than presence of typical landfill odors (e.g., rancid, sulfurous, decaying vegetation) *GC-MS-sensory:* not performed	~100%	100 days/6 months
WWTP biosolids odors (Fisher et al, 2018a, 2018b)	*Odor wheel:* used as basis for naming, and then adapted specifically for biosolids processing *GC-MS-sensory:* basis for new biosolids processing odor wheel	~100%	8 WWTPs, 2-8 weeks each

Study	Culprit odorants identified by odor wheel and instrument?	Intensity results below calibration range? (i.e., intensity score <4)	Frequency and duration information used?
WWTP processing odors (Hayes et al, 2017)	*Odor wheel:* used to identify primary odor categories for online odor observation database *GC-MS-sensory:* confirmed primary categories and showed variability between average and high sensitivity panelists	~100%	3 WWTPs, ~4 locations over 2 weeks (21 samples total)
Rubber processing odors (Kamarulzaman et al, 2019)	*Odour wheel:* prepared new odor wheel based on sensory and analytical measurements *GC-MS-sensory:* basis for new rubber processing odor wheel	~100%	4 sites over 2 years (96 samples total)

Another odor-intensity measurement system is used more widely than OPM. ASTM Standard E544 (2010) uses various vials (or bags) with dilutions of *n*-butanol in water (or air) to assign *n*-butanol-equivalent concentrations to the intensity of a given sample. The upper limit of this equivalency scale appears to be the saturation limit of *n*-butanol in water (or air) rather than a sensory upper limit. The intensity of the odor sample is expressed in mg/L (or ppm for air) of *n*-butanol, with a larger value of indicating a stronger odorant. The use of *n*-butanol as a reference odorant, however, is not well transferred to other odorants or odor mixtures and does not aid in the intended harmonization across odor panels according to an analysis of data from three odor laboratories (Feilberg et al., 2018).

An attempt to compare the *n*-butanol scale (headspace of water solutions) to the sugar-by-taste intensity scale used by OPM was conducted (Curren et al., 2014). A 512-fold increase from low concentration to high concentration of *n*-butanol compared well with a roughly 20-fold increase in sugar concentration. Note, however, that the *n*-butanol method advises against translating its results into perceived odor intensities (ASTM, 2010, note X2.3).

In Europe and Australia, field panels are central to the grid and plume methods (CEN, 2016a,b). Figure 4 shows how the grid method is applied, and Figure 5 shows how the plume method is applied. Both methods require trained panelists to decide whether they recognize (not detect) an odor note selected from a list (similar to an odor wheel). The grid method is applied over a sufficiently long period of time (e.g., half a year to one year) to provide a representative map of the exposure of the population to recognizable odors. Field panelists write down their observations every 10 seconds for 10 minutes (60 observations). If 6 of those observations are a recognized odor note, then the label "odor hour" is applied (although not a full hour of odor exposure occurred). The plume method is used to determine the area in which an odor plume can be perceived under specific meteorological conditions. The odor-plume

boundary is where the odor no longer is detectable, and panelists mark yes/no on a map as they walk through and out of the plume.
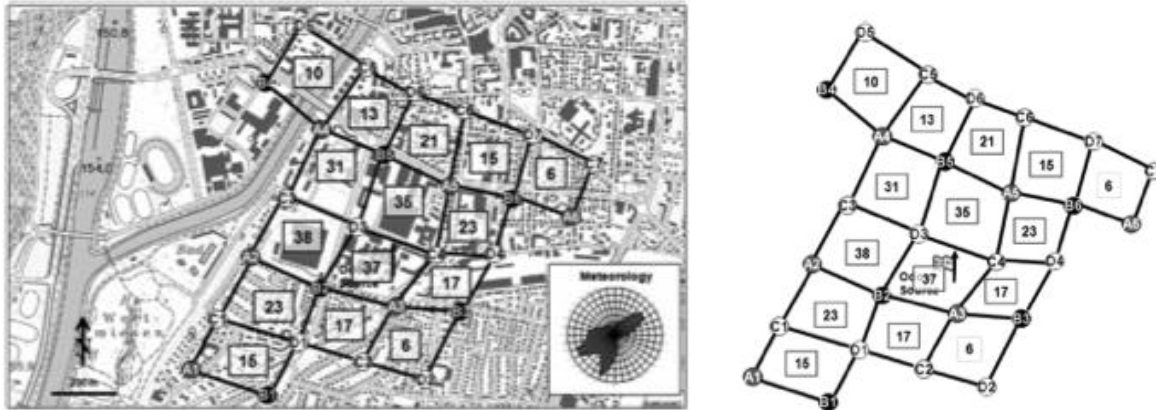
Figure 4. Grid assessment squares with measured odor values ("odor hour" frequency as %) (Guillot et al., 2012)
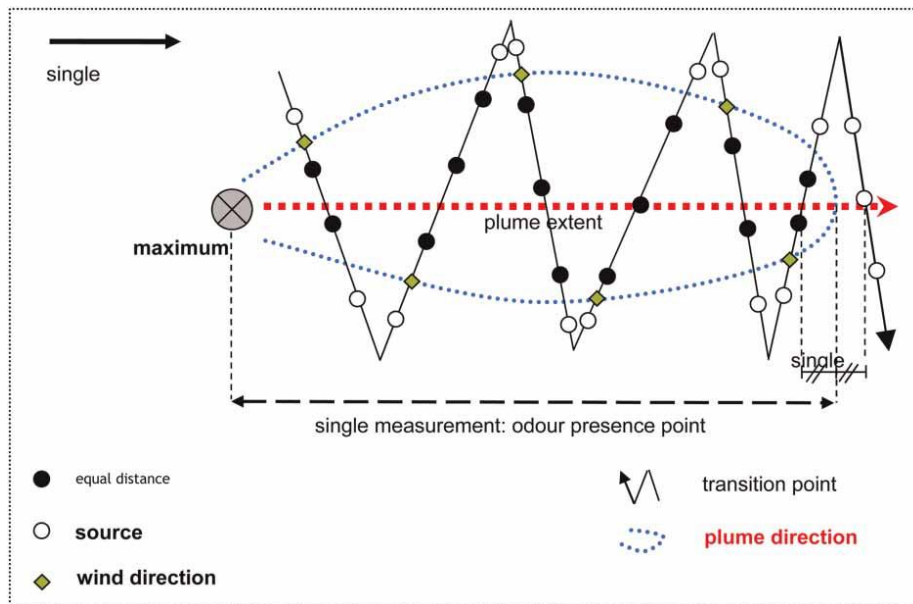

Figure 5. Plume assessment starting at the source and moving away (may be done in reverse) (Guillot et al., 2012)

6.2 Threshold testing by dilutions

Portable dilution instruments that mix odorless air with ambient air can be used by field investigators (or a field panel) to determine the level of dilution required to remove "total

odor." Specific odor characteristics are not defined. Such instruments include the Nasal Ranger® (St. Croix Sensory, 2008) and Scentroid SM100 (Scentroid, 2019), and their performance has been compared (Walgreaeve et al., 2015). Dynamic dilution instruments in the laboratory (olfactometers) can perform dilutions to air samples. Whether in the field or laboratory, dilution ratios or thresholds are considered ineffective odor investigation techniques (Lebrero et al., 2011; personal communication from experts in Australia [Bydder, 2019; Najean, 2019] and Colorado [Wozniak, 2019; Brennan, 2019]). They miss the odor "as is" and instead focus of the last remaining odorant after sufficient dilution, losing information along the way and failing to account for odorant behavior in mixtures (antagonism, synergism, etc.). Dilution is most applicable when mimicking the dispersion from odor source to fenceline (Zhou et al., 2016a) or determining single-odorant sensory thresholds, typically the $ODTC_{50}$ (ASTM, 2011).

6.3 Gas-specific sensors

Gas-specific sensors can target key odorants but not the total odor. They are often portable, relatively inexpensive, and continuously log data. The insufficient sensitivity of gas sensors, however, makes them impractical for most environmental odor monitoring. The two main exceptions are hydrogen sulfide and ammonia. These two odorants, however, do not usually account for the entire odor nuisance (or even the major portion) although they have been used as surrogates by many investigators. At WWTPs, hydrogen sulfide levels can be well controlled and monitored continuously, yet nuisance odor complaints often persist (Zhou et al., 2016a; Vitko, 2018).

Benzene, a carcinogen, is an odorant emitted from oil and gas production and refineries, gasoline stations, and the semiconductor industry. Benzene is especially challenging because health hazard limits are well below odor detection thresholds. Advanced benzene sensors using metal-oxide detectors have been developed that can work in various levels of humidity and interferants (Leidinger et al., 2017). They do not, however, reach the level of sensitivity required for community monitoring. As a best practice, benzene levels should be determined by gas chromatography to assure that OPM panelist are not exposed above hazardous levels.

6.4 Best practices for refined assessment of environmental odors

When a screening-level assessment fails to address an odor nuisance, more refined exposure assessment is necessary. OPM followed by GC-MS and GC-sensory conformation provides one of the strongest tools today. OPM combines the strength of human sensory panels to identify odor notes and the intensity of each odor note, associate those odor notes with key odorants using odor wheels, and target analytical chemistry methods accordingly. As the backbone of OPM, the various odor wheels included in Appendix A form a standard lexicon. OPM avoids the pitfalls of dilution-to-threshold methods, which for drinking water did not resolve underlying taste-and-odor problems and correlated poorly with customer complaints (Suffet et al., 2013).

When field air sampling is required, standard quality control techniques should be followed. These include blanks, spiked laboratory blanks, and spiked field samples. Some sample bag materials or canisters adsorb certain odorants, allow them to escape or even contribute compounds to the odorant load, thus biasing trace analysis of odorants (Boeker et al., 2014; Schuetzle et. al, 1975; Zhou et al., 2016b).

6.5 Ion mass spectrometry

A sophisticated instrument has been used for odor investigations called "selected ion flow tube mass spectrometry" (SIFT-MS) (Van Huffel et al., 2012; Fathi, 2014; Langford et al., 2018). It is transportable and can detect continuously the levels of 20 to 50 odorants, even if the levels are changing rapidly. The SIFT-MS instrument directly measures components of the air (without gas chromatography) by first using chemical ionizing agents on the sample followed by mass spectrometry (Hera et al., 2017). The chemical ionizing agents include cations (H_3O^+, NO^+ and O_2^+) and anions (O^-, OH^-, O_2^-, NO_2^- and NO_3^-). The ions are generated at the inlet by a microwave-powered ion source of moist air. The analyte concentration is found from the ratio of the product ion counts to the reagent ion counts, the flow rate, and instrument calibration. Low-part-per-billion (ppb) detection has been achieved, which is required for many odorants. As the price of this real-time instrument decreases, it will be used increasingly to monitor the frequency and duration of odors.

Another advanced instrument, proton-transfer-reaction mass spectrometry (PTR-MS), uses gas-phase hydronium ions (H_3O^+) as ion source reagents for online monitoring of volatile organic compounds in ambient air (Ellis and Mayhew, 2013). PTR-MS has an ion source that is directly connected to a drift tube (without a mass filter that is needed for SIFT-MS) and is passed on to a mass spectrometer for data evaluation. PTR-MS has response times of near 100 milliseconds and detection limits in par-per-billion concentrations. Hydronium ions only react with trace volatile organic compounds with a proton affinity higher than water, so modifications are being developed.

6.6 Electronic noses

Improved sensor technologies and advanced computational techniques have merged to produce non-specific gas-sensor arrays that try to mimic the human sense of smell. Often called an "electronic nose" or "e-nose," a bank of up to 30 sensors generates a complex electronic signal that is processed through computer algorithms (machine learning). The result is a reading – but not a true "fingerprint" (Boeker, 2014) – for a known odor that then can be compared to signals from future samples to see if they match. When properly calibrated, e-noses should continuously detect the presence of odors in ambient air, estimate concentrations of odors, and attribute the odor to a specific odor source (Dentoni et al., 2012).

The sensors in e-noses are typically a variety of metal oxides, conducting polymers and oscillating quartz crystals; however, new sensor materials are under development continually. As with all sensors, they are subject to the effects of temperature and humidity, degradation, poisoning and the need for frequent re-calibration to address drift.

It is difficult to find e-noses used outside of research laboratories (Boeker, 2014), which confirms the observation by Muñoz et al. (2010) that their initial promotion has been overly optimistic. Nonetheless, e-noses developed within laboratories, plus accompanying field tests, have led to numerous publications and several recent reviews of the emerging field. In 2000, an assessment by South Coast AQMD concluded that e-noses were primarily used for quality control of food and other products, and that a large effort would be required for field tests for environmental odor detection (South Coast AQMD, 2000). More recently, Australian researchers observed that an e-nose for chicken odor worked in-shed yet was unreliable beyond the shed (Atzeni et al., 2016). Today's e-noses function for the context for which they are designed (e.g., workplace safety, indoor air quality) but do not yet cover broad environmental odor monitoring (Schütze et al., 2017).

A workgroup in Europe was launched in 2015 to develop a standard for e-noses (Guillot, 2016). One area under development is stack monitoring, where the conditions are more predictable than ambient monitoring (yet harsh on the equipment). Producing minimum performance standards and other essential criteria will help guide the field.

Unlocking the molecular features that trigger our sense of smell may someday lead to improved e-noses. Keller et al. (2017) supplied chemoinformatic data (molecular geometry, atom types, functional groups, etc.) and sensory data on 407 molecules to teams so they could develop predictive algorithms. The algorithms were tested on 69 molecules, and the results were favorable for 8 odor notes ("garlic," "fish," "sweet," "fruit," "burnt," "spices," "flower," and "sour") out of 19 total. With successful reverse-engineering of the smell of a molecule and then combining that with appropriate sensors, a true e-nose that fully mimics the human nose may be achieved some day.

Other technologies have adopted the "e-nose" name, such as portable, fast gas chromatographs or mass spectrometers (Boeker, 2014). Even "electronic mucosa" is under development. In the nasal cavity, natural mucosa acts like the stationary phase of a gas chromatography column to differentially apportion odorants. "Electronic mucosa" consists of multiple sensor arrays, each separated by gas-chromatograph-like micro columns. The rich data set obtained could predict the presence of odorants at low concentrations (Deshmukh et al., 2015).

7. Human health risk assessment of environmental odors

Odorants are airborne chemicals and at sufficiently high concentrations trigger toxic effects in addition to sensory effects. The public fears that odors indicate "unhealthy" air and hopes that their absence indicates "healthy" air. Carbon monoxide, odorless yet deadly, disproves this belief system, but evolution taught us to avoid malodorous foods and environments. Advice from the expert in Melbourne, Australia, was that our sense of smell is 50% olfactory plus 50% memory (personal communication), which influences health impacts and can lead to psychological stress.

Human health risk assessment is a four-step process used to evaluate the health risks associated with chemical exposures (National Research Council, 1983). It can be applied to both sensory and conventional health endpoints. The four steps are presented in Figure 6 along with the ancillary pre (information gathering) and post (risk management) processes. At its core, risk assessment for non-cancer effects compares exposure concentrations and levels at which adverse effects are not expected to occur. In equation form, the comparison is:

Health: *Hazard Quotient = Concentration / RfC or REL*

Odor: *Odor Activity Value = Concentration / ODTC$_{50}$*

Where RfC (Reference Concentration) is determined by USEPA and REL (Reference Exposure Level) is determined by California EPA, both to protect against adverse effects from inhalation of airborne substances. The ODTC$_{50}$ (odor detection threshold for 50% of a panel) is determined by researchers, as discussed in Section 6.2. The overall goal is to keep exposures below these levels to avoid adverse health and sensory effects.
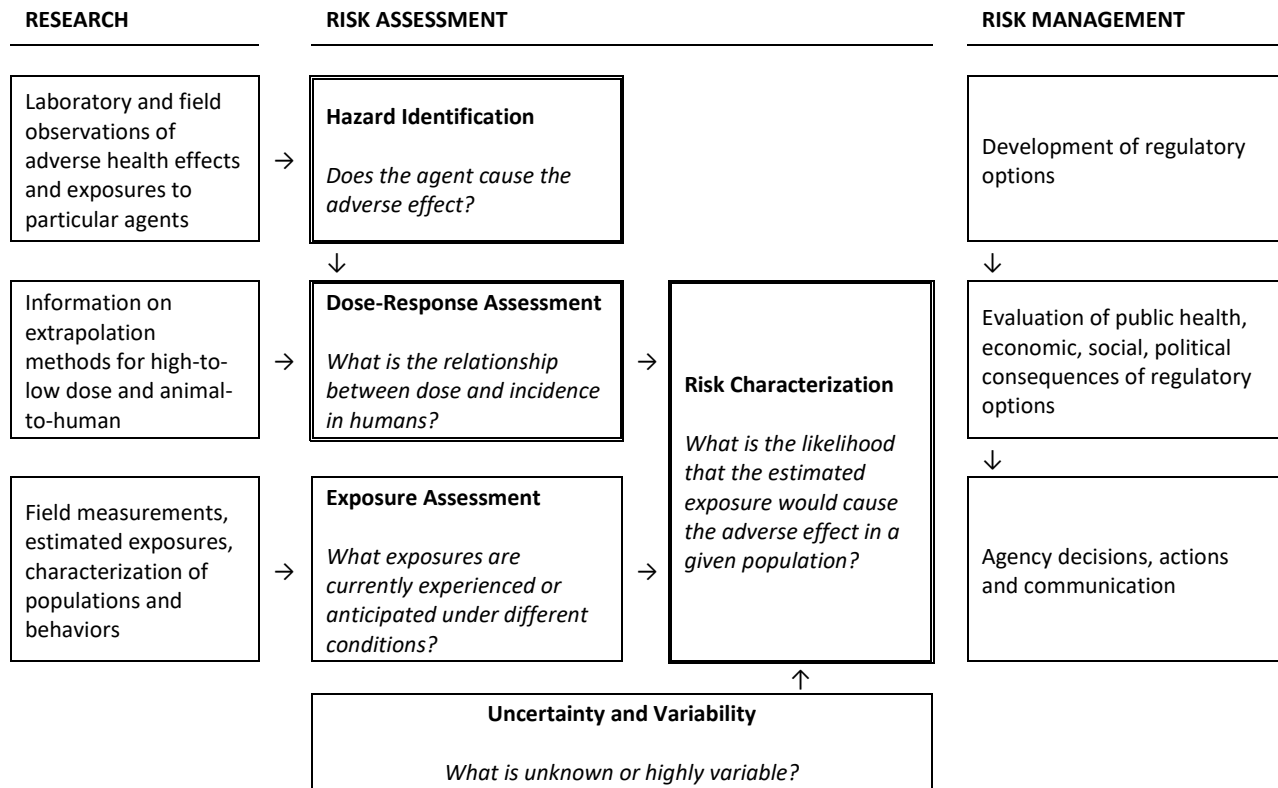
RESEARCH	RISK ASSESSMENT		RISK MANAGEMENT

Laboratory and field observations of adverse health effects and exposures to particular agents	→	**Hazard Identification** *Does the agent cause the adverse effect?*		Development of regulatory options
		↓		↓
Information on extrapolation methods for high-to-low dose and animal-to-human	→	**Dose-Response Assessment** *What is the relationship between dose and incidence in humans?*	→	**Risk Characterization** *What is the likelihood that the estimated exposure would cause the adverse effect in a given population?*	Evaluation of public health, economic, social, political consequences of regulatory options
				↓
Field measurements, estimated exposures, characterization of populations and behaviors	→	**Exposure Assessment** *What exposures are currently experienced or anticipated under different conditions?*	→		Agency decisions, actions and communication
		Uncertainty and Variability *What is unknown or highly variable?* ↑		

Figure 6. Elements of risk assessment and ancillary processes (National Research Council, 1983; Paustenbach, 2002a)

After an introduction to how olfaction works, the four steps of risk assessment are the framework for this section. The culmination is risk characterization, which is presented as case studies. A discussion of risk perception, wellbeing and environmental justice concludes the section.

7.1 Hazard identification

ATSDR listed the common symptoms (i.e., hazards or adverse effects) from exposure to environmental odors on its website (https://www.atsdr.cdc.gov/odors/index.html) and factsheet (ATSDR, 2017). The most common symptoms are headache and nausea. These two plus another 16 identified symptoms are included in Table 6, organized by the affected organ.

Table 6. Common symptoms from exposure to environmental odors

Organ	Symptom [a]	Effects from One Hour of Swine Odor [c]	Effects Noted in Epidemiology Studies [d]
Brain	Headache [b]	X	X
	Drowsiness	−	X
	Dizziness	−	X
Nose	Irritation	−	X
	Congestion	−	X
Eyes	Irritation, watery or dry	X	X
Throat	Irritation	−	X
	Hoarseness	−	X
	Sore throat	−	X
Lungs	Cough	−	X
	Chest tightness	−	X
	Shortness of breath	−	X
	Wheezing	−	X
	Sleep problems from irritation or cough	−	X
Heart	Palpitations	−	X
Stomach	Nausea [b]	X	X
Psychological, hormones	Depression	−	X
	Stress	−	X

Key: X = effect observed as elevated over controls, − = effect not observed as elevated over controls
[a] ATSDR (2017)
[b] Most common symptoms
[c] Schiffman et al. (2005)
[d] Alberta Health (Government of Alberta, 2017)

Only one experimental study of a typical, complex environmental odor (swine odor) and health effects was found (Government of Alberta, 2017), which included both physical effects and mood (Schiffman et al., 2005). Out of the dozens of parameters evaluated, only headaches, eye irritation and nausea symptoms were elevated among those exposed for one hour as compared to controls (Table 6).

The epidemiology evidence, however, indicated the full range of adverse effects from odor exposure (Table 6) (Government of Alberta, 2017). Such symptoms were self-reported, so potential bias is inherent. The distance from an odorous facility, an objective measure, contrarily did not predict the frequency of symptoms. The relationship between odor exposure and health symptoms appeared to be greatly influenced by odor hedonic tone, perhaps more so than odor intensity.

Contradicting studies occur frequently in the toxicological and epidemiological literature, especially regarding the health effects of odors (Government of Alberta, 2017). Exposure to malodor led to inability to focus on a task (Nordin et al., 2017). Other studies reviewed found, however, that odors have no effect on task performance, so the impact of

odors on task performance may be odorant-specific (Government of Alberta, 2017). Increased prevalence of gastrointestinal symptoms (nausea, vomiting and diarrhea) were observed as a function of proximity to a WWTP in Poland (Jaremków et al., 2017). The symptoms were correlated with both odors and microbiological pollutants (pathogenic α-haemolytic and mannitol-positive staphylococci) and could not be disentangled to single out odors as the primary agent. Similarly, the negative effects of traffic noise and odor on residents in Windsor, Ontario, Canada, had a strong covariance between these two parameters and could not be differentiated (Oiamio et al., 2015).

In California, one odorant (hydrogen sulfide) has a sensory-based limit (0.03 ppm; https://ww2.arb.ca.gov/resources/hydrogen-sulfide-and-health). Some other odorants and some co-pollutants within odors are considered hazardous air pollutants (or in California terminology, toxic air contaminants) because they cause other adverse effects beyond smell (e.g., cancer, noncancer toxicity). Detailed information on such adverse effects is found at https://oehha.ca.gov/air/toxic-air-contaminants. Odors also are known to contain odorless co-pollutants such as particulate matter and endotoxins (Schiffman and Williams, 2005).

There was a positive correlation between the presence of odors and the prevalence of self-reported health symptoms, such as headache and nausea, when communities near hazardous waste sites were compared (Shusterman et al., 1991). However, more serious health outcomes – cancers, mortality and birth defects – were not higher compared to the control sites.

7.2 Dose-response

Dose-response relationships aim to link the percentage of people experiencing adverse effects, such as odor annoyance and irritation, to the level of exposure. Adverse effects often increase as exposure increases; however, examples to the contrary are common. For example, hydrogen sulfide loses its characteristic "rotten egg" odor note as the concentration increases, leading to harmful levels going unnoticed (Amoore and Hautala, 1983).

Individual odorants and odorous mixtures tend to pass through various sensory thresholds as they increase in concentration. These include detection, recognition, annoyance and objection (rows 1-4 of Table 7). Concentration-dependent levels (and locations) of irritation may occur as well (rows 5-6 of Table 7). Other health effects, including those from acute and chronic exposure (rows 7-8 of Table 7), observe dose-dependent trends and have established health hazard benchmarks by more complex, non-sensory-based techniques often involving high-to-low dose extrapolation from animal studies. As an example, the sensory thresholds and health hazard benchmarks for hydrogen sulfide are included in Table 7.

Table 7. Odorant sensory thresholds and health hazard benchmarks, their descriptions and hydrogen sulfide as an example

Sensory Thresholds and Health Hazard Benchmarks	Description	Example: Hydrogen Sulfide
Chronic (long-term exposure) toxicity	Health effects from long-term exposure	0.0007 ppm (USEPA benchmark) 0.03 ppm (ATSDR benchmark)
Odor detection	Odor can barely be differentiated from odorless air	0.005 ppm (WHO benchmark, 30-min TWA, to avoid nuisance odor; $ODTC_{50}$ by Hoshika et al., 1993)
Odor recognition	Odor note can be characterized or described	0.03 ppm (California Ambient Air Quality Standard, decreased annoyance, 1-hr TWA) 0.13-30 ppm (rotten egg odor)
Perceived irritant	Irritation begins, usually in the respiratory tract	10-20 ppm (eye irritation)
Somatic irritant	Tissue damage begins	50-100 ppm (eye damage)
Acute (short-term exposure) toxicity	A single or short exposure rapidly leads to a toxic effect	0.07 ppm (ATSDR benchmark) 15 ppm (OSHA STEL, 15-min TWA) 10 ppm (OSHA PEL, 8-hr TWA) 100-250 ppm (loss of smell, throat stinging) 300 ppm (NIOSH IDLH) 250-500 ppm (headache, risk of death) 500-1,000 ppm (tremors, respiratory arrest) 1,000-2,000 ppm (collapse, death)
Odor annoyance	Annoyed, but no physical reaction or health symptoms	
Odor intolerance (objection)	Physical symptoms begin	

Source: Schiffman et al., 2000; Simonton and Spears, 2007; Collins and Lewis, 2000.

Sensory thresholds for odorants typically vary by several orders of magnitude, especially the $ODTC_{50}$ (Brancher et al., 2017). Further, reliable methods may not have been used, and results for odor detection and odor recognition are sometimes mixed up.

7.3 Residential exposure and risk characterization

Exposures to odorants (airborne concentrations) can be compared to the odor thresholds or hazard benchmarks from the dose-response assessment. This yields Odor Activity Values or Hazard Quotients. To demonstrate the process, case studies were selected that addressed odor (Case #1), health risks (Case #2) and both odor and health risk within the same study (Case #3). Although the most significant risks are often due to chemical exposures in the workplace (Pautenbach, 2002b), the focus of this paper is on residential (community) exposures to environmental odors, so worker exposure studies were excluded (e.g., Zhou et al., 2016 a; Wu et al., 2018; Byliński et al., 2019).

In **Case Study #1**, Odor Activity Values (OAV = C/ODTC$_{50}$) were calculated to prioritize odorants emitted from sewers in Australia (Sivret et al., 2016) and from cannabis (Rice and Koziel, 2015). Both efforts prioritized the subset of odorants monitored within the mixture to identify "high priority" odorants for further analysis. For the sewer study, the upper bound (95th percentile) concentrations were compared to the ODTC$_{50}$ values from Nagata and Takeuchi (2003). The ranking by OAV reduced the number of compounds from 31 to 8 "high-priority" odorants. Hydrogen sulfide and methyl mercaptan dominated across all sewer sites (OAVs above 15,000), and other volatile sulfur compounds (dimethyl sulfide and dimethyl disulfide) also ranked high for most sites. Diethyl sulfide, limonene, toluene and *m,p*-xylenes each ranked high for fewer sites.

The first study to report OAVs for odorants emitted from cannabis found 20 "high priority" substances, which were different than those traditionally associated with cannabis odor (Rice and Koziel, 2015). The most odorous compounds based on OAVs are listed in Table 8 and provide a starting point for future cannabis odor research. OAVs could only be calculated for those odorants that had existing ODTC$_{50}$ values in the literature, which is a common limitation of such rankings.

Table 8. High-odor-impact compounds from cannabis (Rice and Koziel, 2015)

Emitted from loose cannabis or through a zip-top bag	Emitted from fresh cannabis through a duffel bag
benzaldehyde	nonanal
myrcene	decanol
decanal	*o*-cymene
heptanal	isobutyraldehyde
methyl anthranilate	1-chloroacetophenome
octanal	nerol
hexanal	propylamine
methylisohexenyl ketone	*o*-guaiacol
linalool	linalyl acetate
β-caryophyllene	methyl anthranilate
α-humelene	benzaldehyde
acetic acid	limonene

Case Study #2 focused on conventional health risks. Intermittent "gas/sulfur/chemical" odors were experienced along the coastal area of Seal Beach, Huntington Beach, and Long Beach in Southern California. Air samples were collected and analyzed from March 2017 to October 2018. All of the results were posted, and a subset (35 samples from March to November 2017) were included in a risk assessment to address public health concerns (South Coast AQMD, 2018a). (No comparison against ODTC$_{50}$ values, however, was included.)

The results of the health risk assessment were:

- Acute exposures (around 1 hour)
  - Ethane, propane, isobutane, n-butane, n-hexane, benzene, toluene, ethylbenzene, xylenes, styrene and other hydrocarbons – all results were below acute RELs
  - Hydrogen sulfide – all results were below the California state standard of 30 ppb yet still may lead to temporary symptoms (headache, nausea)
- Chronic exposures (long-term or lifetime)
  - Cancer risk – continuous monitoring was not performed, so the results for carcinogens, such as benzene, could not be determined
  - Noncancer risk – same rationale

The authors acknowledged that some of the compounds detected did not have acute RELs and that multiple sources may be responsible for the odors. Applying OPM (odor panel, odor wheel, confirmation by GC-MS-sensory) as well as calculating OAVs would have been great additions to this study.

In **Case Study #3**, odorant exposures were compared to both health hazard benchmarks and odor thresholds. Over years, residents in North Denver have complained of intermittent, unpredictable "tar" and "asphalt" odors. The symptoms in Globeville, Colorado, included burning eyes and throat, headaches, skin irritation and sleep problems. A USEPA-funded environmental justice study was conducted there in 2012 (Morgan et al., 2015). Air samples were collected from locations near potential sources and within the community over a period of 7 months. Out of 23 analytes, the most prevalent were hexane, heptane, benzene, toluene, *m,p*-xylenes and naphthalene. The maximum concentrations, however, were below odor thresholds and health hazard benchmarks (Table 9), except for benzene and naphthalene, which were considered within normal ranges for urban air. The study authors were unable to determine which compounds led to the odors.

To see how the Odor Activity Values and Hazard Quotients might change if different odor thresholds and hazard benchmarks were selected, a comparison with the $ODTC_{50}$ ranges from AIHA (2013) and the RELs from California (OEHHA, 2016) was conducted (Table 9, last two columns).

Table 9. Comparison of odor thresholds and health hazard benchmarks in Morgan et al. (2015) to other sources

	Data from Morgan et al. (2015)			Comparison from Other Sources	
Odorant and Odor Note	**Maximum Concentration (ppb)**	**$ODTC_{50}$ (ppb)**	**Health Hazard Benchmarks (ppb)**	**$ODTC_{50}$ from AIHA (2013) (ppb)**	**California Health Hazard Benchmarks (ppb)**
hexane "gasoline"	2.6	65,000 130,000	50,000 TLV 600 chronic MRL	1,500 – 248,000	2,000 chronic REL
heptane "gasoline"	1.1	150,000	500,000 STEL 400,000 TLV	410 – 732,000	none
benzene "aromatic" "sweet" "solvent"	1.6	61,000	10,000 TLV 6 acute MRL 4 intermediate MRL 3 chronic MRL 0.04 cancer 10^{-6} risk	470 – 313,000	8.5 acute REL 0.9 8-hr REL 0.9 chronic REL
toluene "sour" "burnt" "benzene-like"	6.3	2,800 8,000	50,000 TLV 1,000 acute MRL 80 chronic MRL	21 – 157,000	9,800 acute REL 80 chronic REL
***m,p*-xylenes** "sweet"	2.9	50 730	150,000 STEL 100,000 TLV 2,000 acute MRL 600 intermediate MRL 50 chronic MRL	12 – 316,000	5,000 acute REL 160 chronic REL
naphthalene "tar" "creosote" "mothballs"	25	38 84	15,000 STEL 10,000 TLV 0.7 chronic MRL	19 – 1,020	1.7 chronic REL

The comparison did not change most of the Odor Activity Values and Hazard Quotients performed by Morgan et al. (2015). Only the maximum measurement of naphthalene (25 ppb) enters within the comparison range of $ODTC_{50}$ values (19 – 1,020 ppb), while the low ends of other comparison ranges for toluene and *m,p*-xylenes moved to within a factor of 3 to 4. The health risk characterization remains the same, with benzene and naphthalene exceeding the health hazard benchmarks. Urban levels of benzene are typically around 1.8 ppb (WHO, 2000), which are also above the cancer guidance value.

There are substantial uncertainties in the sensory and risk assessment of odorants, the greatest being how likely it is that the individual odorants monitored actually were the main contributors to the overall odor sensed. OPM can help identify key odorants that have been compiled into odor wheels (Appendix A). The exposure measurements (or estimates) tend to have less uncertainty than the odor thresholds and health hazard benchmarks against which they are evaluated. $ODTC_{50}$ values typically range over several orders of magnitude, and the health hazard benchmarks tend to incorporate one-to-three orders of magnitude of uncertainty factors in their extrapolation. The three case studies presented are considered screening-level, and any exceedance of a threshold or benchmark would require more refined assessment.

7.4 Risk perception, wellbeing and environmental justice

The health effects reported by residents living near odor sources may be due to odorless co-pollutants with odor serving as a marker of exposure (Government of Alberta, 2017). Few epidemiology studies, however, look at this possibility. Proximity to an odor source would be a determinant; however, residence distance to the source was often a poor predictor of odor-induced health complaints. The sole experimental study of odor (swine odor) (Schiffman et al., 2005) could not separate the effects of odors from those of co-pollutants in the mixture.

Risk perception plays a large role in how exposures to odors (and their presumed underlying toxic constituents) can lead to annoyance and outrage. Risk perception is how the exposed judge the severity of the risk and involves personal and cultural values and attitudes. Different perceptions of risk are applied to involuntary, imposed exposures, man-made sources and the unfamiliar. Odors often encompass all three of these factors. Key worries from odor exposures include ailments from long-term (chronic) exposures, such as asthma or lung cancer (Smethurst, 2011), ability to socialize at one's own property that is odor-impacted, and potential decrease in property value (Clean Air Strategic Alliance, 2015). These perceived risks are experienced disproportionately by disadvantaged communities.

The air monitoring of a disadvantaged community north of Denver was funded by USEPA as an environmental justice study (Morgan et al., 2015), and a community well-being study followed shortly thereafter (Eltarkawe and Miller, 2018). Participants took an online survey four times over a year. The results at the community level showed that odor-impacted communities had no difference in well-being as compared to control communities based on quality-of-life surveys. Individual results, however, showed that respondents who reported that the air was "very fresh" or "odor is highly acceptable" had higher levels of well-being. This finding supports other studies that indicate that unpleasant odors lead to annoyance, general psychological stress, and reduced quality of life.

Researchers in Australia studied environmental justice and odors around Melbourne (Gunn et al., 2017). They used a novel cluster approach to represent communities affected by odor and concluded that self-reported odor exposure correlated with indicators of socio-economic disadvantage in the community clusters affected by odor.

8. Conclusions: recommended best practices and summary of research needs

As mentioned, the goal of an odor investigation is to identify the source and culprit chemicals (odorants). The key descriptors – odor note, odor intensity, odor frequency and duration – indicate which chemical(s) cause the odor, which in turn informs the optimal mitigation steps or technology. Based on the information gathered in the previous sections, the current best practices are identified in this section. Areas for further research are then listed that would help fill gaps in current understanding or approaches to environmental odor investigation. Note that "next steps" can be found within both the best practices and research needs.

8.1 Complaint data management

Best practices

Data management is the first challenge for any odor investigation. To gather the required information and assess trends, the following is recommended:
- Follow the example of Vancouver and educate the user of on-line forms by providing an odor wheel and pick lists to describe the odor (odor note, odor intensity, odor frequency and duration, and wind direction during odor episodes).
- Train call-center operators on these same odor descriptors.
- Replicate the SJVAQMD database and field-enabled functionality in other air districts.
- Provide trend and complaint frequency data for the suspected odor source to air inspector prior to each new investigation.

Agreement among air districts as to which fields are required or optional, as well as a consistent disclaimer that information may be made public as required by law, would avoid confusion.

Research needs

A data management demonstration project is needed that includes both odor wheels and a model database. The goal is to develop a unified California approach that will be used statewide.

8.2 Initial screening

Best practices

For initial screening of a nuisance odor, two air inspectors, ideally, should respond to a complaint so they can corroborate the complainant's and each other's odor perception. If corroboration occurs, the source of the odor is usually identified by the complainant or the air inspectors' prior knowledge of the area. Standard practice is to move upwind of the likely

source to assess whether another source contributes. Recording wind direction, details of the complaint and any action taken document the investigation.

Research needs

A study of single versus two-inspector odor investigations would help show whether a second inspector is beneficial.

8.3 Training air quality inspectors

Best practices

Training air quality inspectors on how to better identify and consistently describe odors (odor note and odor intensity) would assist their work. For example, training on using an odor wheel (circular table of odor descriptions and potential culprit chemicals; see Figure 2 and Appendix A) and scratch-n-sniff booklets will standardize odor vocabulary. Maintaining a log of complaints identifies trends. For many air districts, a lower level of training for the ability to sense "something" in the air at the complainant's location is sufficient, and odor intensity only need be noted as "weak," "moderate" or "strong" to help prioritize the nuisance. Initial training of new inspectors is required and refresher training every 2 to 3 years is recommended. It is necessary for the air inspector's sense of smell to be verified periodically because an anosmic air inspector, obviously, would be unfit for odor investigations. This test can be done using "scratch-n-sniff" materials available for purchase online. CARB already offers stack opacity training and could offer odor training as well to provide consistency across air districts. Such training has assisted water districts to address taste-and-odor problems in drinking water.

For difficult-to-discern odors, returning to the location several times may be required. Involving a panel of air inspectors would help detect odors that are unusually low or sporadic. A local panel of residents, trained minimally, can help inspectors identify odors and their locations.

Research needs

Develop an air quality training system, initially with one air district followed by refinement and state-wide rollout. Mobile platforms with highly sensitive real-time methods (e.g., SIFT-MS or PTR-MS along with OPM) could be evaluated, especially where toxic emissions also are expected.

8.4 Multiple overlapping odors

Best practices

When multiple odors are present, identifying the cause of a nuisance odor is troublesome. No proven methods for apportioning overlapping odors were found.

Research needs

A current challenge in California is the overlapping odors found in Milpitas, which have resulted in thousands of complaints. To identify (fingerprint) which sources are contributing to the ongoing odors, new research methods such as using the Odor Profile Method with GC-sensory or GC-MS-sensory need to be developed. BAAQMD issued a request for proposals (BAAQMD, 2019). A community group that meets quarterly will conduct a parallel study. The odor-related health complaints due to the massive release of natural gas from Aliso Canyon, California, have received an initial health risk assessment (South Coast AQMD 2018b) and will undergo further assessment by a contractor ($1 million) and by the County of Los Angeles Department of Public Health ($25 million).

8.5 Refined odor assessment

Best practices

A wide range of instrument and sensory techniques are available, from sensors to questionnaires, for refining odor assessments. Unfortunately, no standard approach is followed today. For complex or unresolved odor exposures, sensory methods such as the Odor Profile Method have been used to identify culprit odorants using an odor wheel, panel assessment of the intensity of the odor to prioritize those odorants, and frequency plus duration information to identify the odor source. Confirmation of the targeted odorants is provided by analytical techniques, such as gas chromatography with a sensory port and parallel mass spectrometry with an OPM evaluation.

Research needs

First, develop a standard protocol (including a logic flow diagram) that includes OPM, GC-MS and GC-sensory approaches for California air inspectors. The focus should be on the components of odor rather than total odor or dilutions.

Currently, a standard approach has not been developed for involving an odor panel of local (community) residents. Such a panel would learn how to use the odor wheel, a simplified odor intensity scale (e.g., no odor, weak, strong) and an odor diary. Such information would supplement the odor inspector's evaluation and provide support.

More robust instrumentation is needed that can detect odors analytically (Lebrero et al., 2011; Muñoz et al., 2010). A compendium of odor sample collection materials (e.g., bag materials, cannister types) is needed, including which odorants adhere to which materials.

For intermittent odors, highly sensitive real-time methods (e.g., SIFT-MS or PTR-MS along with OPM) may be needed to capture their fleeting nature. The promise of e-noses that mimic the human sense of smell remains allusive, often failing to perform as well in the field as in the laboratory. Investigating and eventually being able to predict the synergistic, antagonistic, or masking interactions among odorants is a goal. Temperature and humidity effects also require more research.

One path forward for environmental odor exposure assessment includes population-based metrics of odor, such as odor diaries and plume monitoring by OPM human panels, confirmed by advanced analytical techniques. Better designed annoyance surveys of affected populations are needed, especially capturing the breadth of impacts and variability in receptors (Lebrero et al., 2011; Hayes et al., 2014). Development of odor-concentration-nuisance maps, similar to noise maps required by some jurisdictions, would allow improved odor regulation, response and urban planning. Mobile platforms could assist in such mapping and provide meteorology data (e.g., wind direction, wind speed, temperature, humidity).

An area for future research is metallic odors. A study of metallic odor complaints from drinking water (Omur-Ozbek and Dietrich, 2011) found that when metal particles contact the human mucosa, they can react to form odorants that are perceived retro-nasally. The complaints near metal industries in South Coast AQMD indicate that communities can be impacted, yet the literature search provided no relevant information. Further investigation is needed into metallic odors, including the ortho-nasal route.

8.6 Human health risk assessment

Best practices

Odors add a substantial layer of complexity to conventional human health risk assessment. Two entwined senses, irritation and olfaction, are involved and odor exposure and their triggering can lead to either transitory or more permanent health effects. In addition, odorless co-pollutants can contribute to adverse effects, and their contribution is difficult to separate from that from the odorants. The inter-individual variability in human responses to odors adds a large degree of uncertainty to any assessment. Nonetheless, several case studies demonstrate that odor thresholds and health hazard benchmarks can be applied to odorants to estimate sensory and health effects.

Research needs

How well this odorant-by-odorant approach addresses the health risks to communities, especially those suffering from environmental injustice, is an area in need of further research and objective methods.

More studies like the single experimental study of swine odor (Schiffman et al., 2005) are needed. Both physiological and psychological responses need to be measured simultaneously so correlations can be determined. Longitudinal "before-and-after" epidemiology studies are needed to determine the magnitude of impact of installing odor-emitting facilities near neighborhoods. For example, the large health-effects study in California after the natural gas leak in Aliso Canyon would benefit from pre-leak community health data. Research is needed into the objective measures of health symptoms from odor exposure, such as irritation (e.g., respiratory airflow changes, eye blink rate), stress hormones and brain activity imaging. To aid research into and prioritization of individual odorants, a robust, curated set of $ODTC_{50}$ values is required. A central repository for high-quality $ODTC_{50}$ values would be a service to the field.

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