The anatomy of odour wheels for odours of drinking water, wastewater, compost and the urban environment

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Abstract In the drinking water and air pollution fields, odour quality characterisation and intensity of each odour characteristic needs to be developed to evaluate the causes of the odours present. Drinking water quality characterisation has matured to the point where an “odour wheel” is described and the primary chemicals producing the odour are known and therefore a potential treatment can be defined from the odours reported. Sufficient understanding of the types of odorous compounds that can arise from wastewater and compost treatment processes and odours in the urban environment are starting to emerge. This article presents the anatomy of the odour wheels. It is hoped that the foundation of odour wheels will evolve as odour quality data are reported and linked with chemical cauisation. The compost and urban odour wheels are presented in print for the first time.

Keywords Compost odours; drinking water odours; odour wheel; urban odours; wastewater odours

Introduction

Odour wheels are based upon sensory panel testing to develop odour character and related odour intensity. The hypothesis for an odour wheel is that:

1. Each odour type comes from a compound(s) of similar odour.
2. Each chemical odorant has a unique individual odour signature defined by its odour quality, odour threshold concentration and chemical concentration.
3. Each odour signature is related to solubility in air and water by Henry’s Law under the correct thermodynamic conditions.
4. There is a hedonistic impact of odour on people.

The first step in developing an odour wheel is to define the relevant odour qualities notes. Figure 1 shows the evolved drinking water odour wheel, “2000” (Suffet et al., 1999) and the wastewater wheel (Burlingame et al., 2004), respectively. The inner circle of the wheels indicate the primary odour categories, similar to primary colours of the rainbow. The outer circle, indicates the variation within each primary odour category, i.e. the primary odour – grassy/woody has variations or sub-groups of grassy, woody, cardboard and hay on the drinking water wheel. The outer list of specific chemicals associated with each sub-group represents these sub-categories. The chemicals that have been confirmed as the cause of taste and odour events in drinking water are noted by an asterisk (*) outside the circles. The chemicals that are listed outside the circles without an asterisk have been used by sensory panels as “representative” of the odour defined by a particular odour characteristic in the outer circle. The taste and odour wheel has been described in detail by Suffet et al. (2004a,b) and the representative compounds are shown in the Standard Methods of Water and Wastewater, 2170 (APHA et al., 2000).
Figure 1 (a) The drinking water taste and odour wheel (Suffet et al., 1999) and (b) the wastewater odour wheel for evaluating wastewater treatment odours (Burlingame et al., 2004)
The objective of this paper is to define how to develop an odour wheel to describe any odour problem from drinking water to animal production odours. Odour wheels are dynamic, they evolve with understanding of the causes of particular odours. However, their basic structure is the same as they are based upon natural processes occurring in the environment or caused by man’s industrial activities. The goal of an odour wheel is to identify odour problems and the chemicals causing those problems, conducting odour quality control monitoring, and developing a dialogue about odour problems with the public.

**Flavour profile analysis and the odour profile method**

The flavour profile method was developed by Cairncross and Sjostrom (1950) of Arthur D. Little, Inc. The flavor profile analysis (FPA) sensory panel defines the odour characteristic listed in the sub-groups of an odour wheel. The intensity or strength of each odour character is reported on a seven-point scale as per Figure 2. Figure 2 shows the odour intensity relationship to chemical concentration of an odorant as described by Thiemer (1982). Standard Methods of Water and Wastewater, 2170 (APHA et al., 2000) describes the FPA method and shows the list of specific chemicals that are surrounding the rings as standards. Burlingame et al. (2004) used the concept of FPA for the ambient “odour profiling method” (OPM) for odour from sewage treatment plants.

**Odour wheels**

Odour wheels are a simple method of classification of the odour character (i.e. quality, note, type, group or category) and intensity of each characteristic. Odour wheels are based upon FPA sensory panel testing to develop odour characterisation and related odour intensities. It can be used similarly for wine tasting as described by Noble et al. (1987). A wine with a weak/moderate fruity character of apple (weak/moderate = 6) and pear (very weak = 2) and a woody (weak = 4), with a threshold taste of astringency (threshold = 1) is an example of an FPA analysis of wine.

In a drinking water wheel (Figure 1a), characteristics might include a musty odour (weak intensity = 4), a grassy odour (very weak intensity = 2) and a chlorinous odour (very weak intensity = 2). The odour wheel is the development of a common language, a “periodic table” of odour response. Odour wheels enable expert odour panels to characterise the details of each odour characteristic and their intensities, as well as to express the response in similar terms to their particular community. “Here we have a wine with a fine fruity aroma of apple and pear and wood character from the proper aging in barrels with only a perceptible astringency” or “The water has a musty, slightly grassy character from an algae growth in the reservoir. The water is safe to drink with a slight chlorinous odour indicating proper disinfection”.

![Odourant concentration versus odour intensity for flavour profile method](image)

**Intensity Scale**

- No odour = 0
- Threshold = 0 or 1
- Very weak = 2
- Weak = 4
- Weak-moderate = 6
- Moderate = 8
- Moderate-strong = 10
- Strong = 12

Figure 2 Odourant concentration versus odour intensity for flavour profile method
Present laws for the control of odour problems in air and water environments do not consider odour character or intensity of each odour characteristic. The present state of odour regulations in air or water is based upon the number of dilutions it takes to reach an odour threshold level. In drinking water in the US and Europe, it is expressed as the threshold odour number (TON) usually at 2 or 3 (EPA, 1991; AFNOR, 1997). Is the TON acceptable to the consumers? That is debatable. For example, will US or European people accept chlorine in their water? The answer appears to be “yes” in the US (EPA, 1991) and “no” in Europe (Piriou et al., 2006).

In the air pollution control field, odour concentration and intensity and hedonic rating have reached the point of standardisation (Mahin, 2001). Three aspects of evaluation have been described well by Gostelow et al. (2001):

1. The evaluation of odour strength on a dilution scale. All odours are the same and only detection of total threshold is evaluated.
2. The evaluation of odour intensity using a relative intensity scale above threshold comparative to a butanol odour scale.
3. The rating of hedonic tone using a scale of pleasantness.

Both (2001) has used these approaches for studies of ambient air. However, there is no standardisation of odour quality characterisation and the intensity of each odour quality. The FPA or OPM methods have no dilution; specifies and quantifies each odour and changes of odour, e.g. earthy (intensity = 4), chlorinous (intensity = 2). In the food-beverage and drinking water fields, the use of odour wheels for odour quality characterisation and intensity rating of each odour quality has proved essential information when the goal is identifying odour problems and causes, conducting odour quality control monitoring, and developing good public relations when positive outcomes of solution to problems occur. In fact, the use of odour quality characterisation is now being studied for earthy/musty odours in water for setting drinking water odour goals for water supplies (Booth, 2005) and eventually, the setting of drinking water standards may be developed as described by Suffet et al. (2004a, b). The development of these aspects of the wastewater odour wheel was completed by Burlingame et al. (2004). A compost odour wheel and an urban odour wheel are presented here to describe odour characteristics for each odour problem for the first time.

Evolution of an odour wheel

Mallevialle and Suffet (1987) describe the evolution of the drinking water odour wheel from major water utility surveys since the 1950s. The Off-Flavours Committee of the International Association on Water Pollution and Research and Control (now known as International Water Association) discussions in the 1980s led by Persson (1992), and a survey of US water utilities in 1993, published in 1996 (Suffet et al., 1996) helped finally define the odour wheel. The first complete drinking water taste and odour wheel was presented in 1995 (Suffet et al., 1995) and upgraded as shown in Figure 1 in 1999 (Suffet et al., 1999). The development of the drinking water wheel as well as the wastewater wheel presented in 2004 by Burlingame et al. (2004), asked the question: How do we define categories of odour problems in terms of the odour signature of chemicals, i.e. odour quality, odour threshold concentration and chemical concentration based upon flavour profile panel testing. What are the key types of odours that water treatment personnel describe as their removal problems? The final driver for the development of odour wheels has always been in trying to answer the general public’s complaints about an odour problem. Odour wheels help the utilities attempt to define odour problems and how to treat them. The choice of odour categories evolved by a carefully detailed evaluation of the technical literature of taste and odour problems and treatment chemistry in the
drinking water and wastewater fields (see Suffet et al., 1995, 1999, 2004a, b and Burlingame et al., 2004). For example, a detailed description of the grassy/woody (grassy/hay/straw/woody, etc.) area in the drinking water and wastewater wheel will be described.

The drinking water wheel is more developed as more chemicals have been identified as the cause of the odour than with the wastewater wheel, e.g. “hay/woody” has been identified as being caused by B-cyclocitral in drinking water (Young et al., 1999). However, it is only suspected to cause the odour in wastewater. On the other hand, the wastewater wheel defines “cardboard” as an odour characteristic based upon the work of Dravnieks (1985) as a significant odour and the drinking water wheel does not. Two grassy compounds have been confirmed in drinking water supplies: cis-hexene-1-ol (grassy-green/sharp) and cis-3-hexenyl acetate (grassy-fresh, sweet) (Khiari et al., 1995). When grass was allowed to decay in water, the first compound to be released in the water was the acetate which can biologically or chemically hydrolyse at pHs below 6.1 to the corresponding alcohol. Cis-3-hexenyl acetate exhibits an OTC of 1–2 μg/L, only 2–4% of the OTC of the cis-hexene-1-ol (Khiari et al., 1999). Burlingame et al. (2004) did not judge that the cis-3-hexenyl acetate (grassy-fresh, sweet) would be present in wastewater due to more intense biological activity and it is not included in the wastewater wheel. Thus, the odour wheels are based upon the best available knowledge at the time and so evolve with scientific advancement. In that spirit, the wastewater wheel has been slightly modified for better presentation (Figure 1b).

Table 1 describes the drinking water odour wheel by source of odorant and mechanism of environmental or water treatment reactions with chemicals entering the water treatment process. The three odour types that are natural products are the raw materials from nature, on earth and in natural water. Only the rancid odour is from natural breakdown products and could be placed in the aerobic and/or anaerobic categories. The three odour characteristics that are of industrial origin are products of human need. Two natural biodegradation processes produce the odours represented by aerobic and anaerobic biodegradation (Juttner, 2006).

The choices of primary odour categories on the drinking water wheel: eight odours

The goal of drinking water suppliers is to produce water that does not have any taste or odour problems. However, natural products of grass/hay/wood/fish/vegetable/fragrant/fruity and flowery are present in the water resources of lakes, streams and groundwater and produce the background dissolved organic matter and suspended solids of these water bodies. Groundwater usually is least impacted by these natural sources of odour. Table 2 shows that the first two groups of industrial chemicals are produced for industrial purposes, i.e.

<table>
<thead>
<tr>
<th>Table 1 The sources of odour problems in drinking water</th>
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<tbody>
<tr>
<td>1 Natural products</td>
</tr>
<tr>
<td>Grass/hay/straw/woody odours</td>
</tr>
<tr>
<td>Fishy/rancid odours</td>
</tr>
<tr>
<td>Fragrant/vegetable/fruity/flowery odours</td>
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<tr>
<td>2 Industrial products</td>
</tr>
<tr>
<td>Chemical/hydrocarbon/miscellaneous odours</td>
</tr>
<tr>
<td>Medicinal/phenolic odours</td>
</tr>
<tr>
<td>Chlorinous odours</td>
</tr>
<tr>
<td>3 Aerobic oxidation products</td>
</tr>
<tr>
<td>Earthy/musty/moldy odours (carotenoids via carotene oxygenase to geosmin and 2-methylisoborneol)</td>
</tr>
<tr>
<td>4 Anaerobic degradation products</td>
</tr>
<tr>
<td>Marshy/swampy/septic/sulphurous odours</td>
</tr>
<tr>
<td>(proteins to sulphides and amines for swampy odours)</td>
</tr>
<tr>
<td>(fats via lipoxygenase to fatty acids for rancid odours)</td>
</tr>
<tr>
<td>(carbohydrates to aldehydes, ketones, fatty acids and alcohols)</td>
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</tbody>
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chemical/hydrocarbon/ miscellaneous/medicinal and phenolic, but do find their way into natural waters. Some of these chemicals react with disinfectants to cause off-flavours, e.g. phenols are chlorinated in the presence of bromide to bromophenol (medicinal off-flavours) (Piriou et al., 2006). The disinfectants chlorine and ozone are used in water treatment to protect human health. Chlorine in its many forms is the most prominent taste and odour in the US (Suffet et al., 1996). The production of disinfection by-products of health concern, e.g. chloroform, versus health concern from microbes versus taste and odour considerations from free or combined chlorine must be balanced by drinking water purveyors. This is accomplished in most cases except for taste and odour events which must be minimised. Aerobic and anaerobic biodegradation of natural products and wastes from human use produce the last two categories on the drinking water wheel. Jutttner (2005) has described the “carotenoid system” production of the second most prevalent taste and odour problem, the earthy/musty (geosmin/methylisoborneol) problem from algae metabolites in eutrophic lakes, reservoirs and streams. Fats are also oxidised by aerobic organisms lipoxygenases to fatty acids. Fatty acids are also a product of anaerobic microbial degradation as well as from carbohydrates. Proteins produce sulphide and amine odours by anaerobic oxidation. Aerobic and anaerobic microbial biodegradable industrial products produce similar odours by the same biochemical processes. It is only the industrial chemical/hydrocarbon and miscellaneous odours produced by non-degradable or strictly chemical processes that produce odours of “kerosene”, for example from the fuel additive methyl tertiary butyl ether (MTBE) (Stocking et al., 2001). Thus, the odour production of

<table>
<thead>
<tr>
<th>Drinking water wheel (8 classes)</th>
<th>Wastewater wheel (11)</th>
<th>Compost odour wheel (11)</th>
<th>Urban odour wheel (12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Fishy/Rancid</td>
<td>2. AmmoniaFishy</td>
<td>2. Fishy/Ammonia</td>
<td></td>
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<tr>
<td>3. Fragrant/ Vegetable/ Fruity/ Flowery</td>
<td>3. Fragrant/ Fruity</td>
<td>2. Fragrant/ Fruity</td>
<td></td>
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<tr>
<td>4. Terpene/Pine/Lemon</td>
<td>4. Terpene/Pine/ Lemon</td>
<td>3. (Parks)Terpenes/ Pine/Lemon/Grassy</td>
<td></td>
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<tr>
<td>Industrial products</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Aerobic oxidation</td>
<td>8. Earthy/Musty/Mouldy</td>
<td>6. Earthy/Musty/ Mouldy</td>
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<tr>
<td>7. Earthy/Musty/Mouldy</td>
<td>7. Earthy/Musty/ Mouldy</td>
<td>7. Earthy/Musty/ Mouldy</td>
<td></td>
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<tr>
<td>8. Rancid/Putrid</td>
<td>7. Rancid/Putrid/Dead</td>
<td>8. Rancid/Putrid/Dead</td>
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Carotenoids via carotene oxygenase → gt; geosmin and MIB
Protein to sulphides and amines (swampy); Fats via lipoxygenase → fatty acids (rancid); Carbohydrates to aldehydes, ketones, fatty acids and alcohols
Sweet – should it be added to the drinking water list?
Ammonia from anaerobic digestion
Anaerobically converted starches and cellulose to fatty acids
drinking water odours really is a description of odour source or biological and chemical reactions that produce them. However, within the last 30 years of identifying and treating particular odorants, it has not been discussed. Tables 1 and 2 also describe the aerobic and anaerobic production of aldehydes which can cause sweet odours. Perhaps “sweet” should be added to the drinking water wheel odour list as a ninth category?

Much research has been performed into the science of aesthetic water quality, but utilities have had difficulty incorporating this science into their practices. A decision tree was developed by McGuire et al. (2005) which provides a resource that drinking water utility professionals can now use to describe an off-flavour, determine the origin, quickly learn how to proceed with an investigation of the off-flavour event and identify potential solutions. Utility personnel can quickly learn how to be detectives for their systems without the training necessary to be experts. If the decision tree does not lead to resolution of the taste and odour problem then the utility professional, who was not previously knowledgeable in off-flavours, can have a productive discussion with an expert regarding tastes and odours. Communicating the lessons learned by the scientists of aesthetic water quality to the utility professionals in a quick and easy manner will lead to more resolved taste and odour events and better drinking water quality. The basis of the decision tree is the drinking water wheel and the use of odour panels to define the odour characteristics and the intensity of each characteristic. The prediction of problems in water quality through monitoring programmes may assist in identifying some changing conditions, but may not accurately diagnose all taste and odour problems as they occur. Consequently, the best treatment steps may not be prescribed. For this reason, the final step in dealing with taste and odour problems is always a public education program to inform the public about their drinking water.

The choices of primary odour categories on the waste water wheel: 11 odours

Basically, the wastewater odour wheel as described by Burlingame et al. (2004) contains 11 odour characteristic types. The wastewater odour wheel contains the eight characteristics from the drinking water wheel with “ammonia” added to “fishy”. Three new characteristic are added: aerobic oxidation of fatty acids to rancid and putrid odors, the human source of anaerobic digestion of faecal/sewery and natural odours of the final products as “terpenes”, “pine” and “lemon” (see Figure 1b). Table 2 shows the relationship of odour characteristics of the wastewater wheel to the other wheels. New applications are presented in articles within these journal pages.

The evolution of the compost odour wheel: 11 odours

Figure 3a shows the compost odour wheel presented by Rosenfeld et al. (2004a). The wheel is designed to understand compost odour problems. Table 2 shows the relationship of odour characteristics of the compost wheel to the other wheels. The compost odour wheel contains the six characteristics from the drinking water wheel with “medicinal” and “chlorinous/ozonous” removed and “grassy” moved to natural products such as “pine”. As compared with the wastewater odour wheel, the compost odour wheel shows that “ammonia” was added to “fishy” and aerobic oxidation of fatty acids to the “rancid” category. The human source of anaerobic digestion “faecal/sewery” and the category of natural product production “terpene/pine/lemon” and industrial sources, “solventy/hydrocarbon”, are also included from the wastewater wheel. A manure odour is added to the “faecal/sewery” category as a sub-group. A new type of odour that is “putrid/dead animal” forms a separate category. An 11th odour category is added: a desired products of composting – “sweet”. This last characteristic is apparently the final step of aerobic digestion of leafy material. The identification of the compost odour characteristics and their relationship to complex waste treatment odours is another challenge. It is hoped that
Figure 3 (a) The compost odour wheel and (b) the urban odour wheel. This paper hopefully will initiate other odour wheels to help define other waste treatment issues such as wastewater sludge drying and urban odour problems.
the compost wheel will eventually help define the control of the composting process in a
manner as McGuire et al. (2005) has done for the drinking water field.

**The evolution of the urban odour wheel: 12 odours**

Figure 3b shows the urban odour wheel presented by Rosenfeld et al. (2004b). The wheel
was designed to understand the odours of the city environment. The urban odour wheel
contains five characteristics from the drinking water wheel. Table 2 shows the relationship
of odour characteristics of the urban odour wheel to the other wheels. The urban
odour wheel builds upon the compost odour wheel as the sources and natural processes
of composting happen in the urban environment but slower and more diffuse. Two more
set of odour characteristic are added. These are the categories “bakery” and “restaurant”.
The “solventy/hydrocarbon” is named “fuel/gas station/solvent”. The “terpene/pine/
lemon/grassy” is named “park”. The identity of the urban odour characteristics and their
relationship to complex air odours is another research challenge.

**Discussion**

The odour wheels or classification schemes are beginning to form the foundation for the
evolution of odour quality data with a link to chemical causation. There are three to four
odour categories that are natural products or the raw materials from nature on earth and
in natural waters. Only the rancid odour that occurs from natural breakdown products is
included in the drinking water wheel, although this category also falls within the aerobic
and/or anaerobic microbial reaction categories for the other wheels. Two natural biodegrada-
tion processes produce the odours represented by aerobic and anaerobic biodegrada-
tion whether within the environment or a treatment process. Other odour characteristics
are of industrial origin. This evaluation indicates that wheels for such odour problems as
sludge odours from waste treatment or farm odours from animal husbandry can be classi-
fied and evaluated and hopefully this will lead to odour minimisation.

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