# The use of an odour wheel classification for the evaluation of human health risk criteria for compost facilities

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**Abstract** Odorants are released during the decomposition of organic waste at compost treatment plants. Composting releases volatile organic chemicals (VOCs), including alcohols, aldehydes, volatile fatty acids, ammonia and other nitrogen compounds, xenobiotic solvents, and various sulphur compounds into the environment as categorised by a compost odor wheel. Each odorant possesses a characteristic odour signature – quality and threshold as well as a toxicity value. This paper presents data relating the human odour detection limit to human health threshold criteria developed by the National Institute for Occupational Safety and Health, Occupational Safety and Health Administration, the United States Environmental Protection Agency Region 9 and the World Health Organisation. This comparison indicates that: (1) the human odour threshold concentrations (OTC) for most compost odorants are far lower than their respective human health risk (regulatory) threshold values, (2) several compost odorants have OTC that are below some of their respective regulatory thresholds and above others (i.e. dimethyl amine, formic acid acetone, ethyl benzene and toluene) and (3) only the VOCs probably present as contaminants in the raw composting material have OTC greater than all of its regulatory thresholds (i.e. benzene). Benzene is the most hazardous VOC associated with composting and should be monitored.

**Keywords** Compost odour; compost odour wheel; compost risk assessment; odour risk analysis

## Introduction

Odour control at the fence line of composting facilities is a common goal. When odour plumes cross the fence line of facilities, neighbours and community members become alarmed and have human health concerns. This paper evaluates the human detection limits of common compost odorants to their respective human health threshold criteria developed by the National Institute for Occupational Safety and Heath (NIOSH), Occupational Safety and Health Administration (OSHA), United States Environmental Protection Agency Region 9 (EPA) and the World Health Organisation (WHO). This paper will also evaluate odour threshold concentrations (OTCs) and odour characteristics from compost treatment processes. A conservative compost odour wheel is presented to sum up the consensus odour evaluation (Rosenfeld *et al.*, 2004; Suffet and Rosenfeld, 2006). The odour wheel takes into account sulphur, nitrogen and oxygen odorous compounds which are the basis for most of the nuisance odours. Ten of the odorants categories are from the raw material or produced during the composting process. The last odour wheel category includes a set of xenobiotic compounds present probably in the raw material, such as the substituted benzenes (Komilis *et al.*, 2004).

The odorants released from a compost treatment plant vary depending on the raw compost entering the plant and the operation of the treatment processes. The odorants released from compost plants are typically from organic waste which are microbially

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degraded in sequential order where the sugars are consumed first, followed by cellulose, proteins, lignins, oils and finally, waxes (Killham, 1994). The oxidation state of the odorous nitrogen and sulphur compounds depends on how the compost treatment facility is operating under aerobic or anaerobic conditions. Also, anaerobic conditions are responsible for production of odorous volatile fatty acids.

Human health risk evaluation criteria include: OTC meaning the minimum concentration that humans can sense in the presence of an odorous gas, recommended exposure limits (REL), short-term exposure limits (STEL), preliminary remediation goals (PRG) and permissible exposure limits (PEL). Each exposure limit is established for a particular compound over a particular time period, resulting in an effective dose for an individual. The REL is usually based upon exposure to the compound over an 8–10 hour time period. The STEL is based upon a 15 minute exposure limit. The PEL is based upon a concentration over an average eight hour workday or 40 hour work week to which most workers can be exposed without experiencing adverse effects. Substances at or above PRG concentrations are subject to remediation (OSHA, 1993, 1997; WHO, 2000; EPA, 2004; NIOSH, 2004).

The odour wheel describes the sensory and chemical links between odour descriptors (Figure 1) (Rosenfeld *et al.*, 2004; Suffet and Rosenfeld, 2006). For the compost odour wheel, the odour descriptors have been linked to known compost chemicals as well as potential compost chemicals that have a particular odour but have not been associated

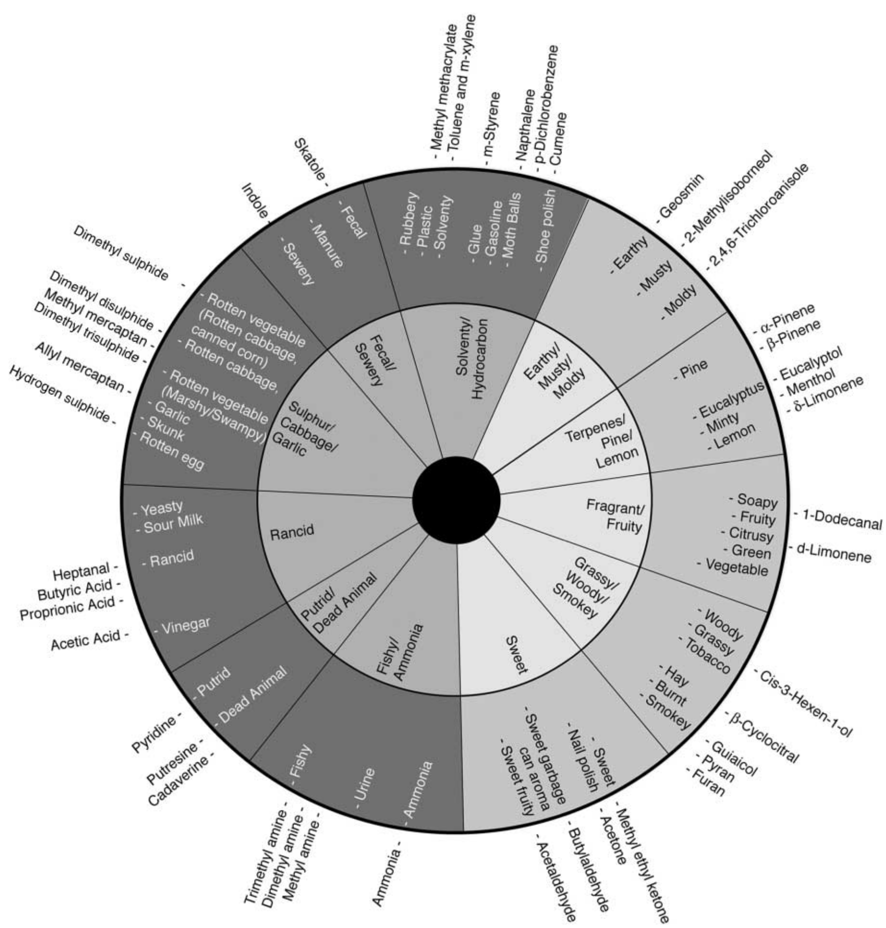


**Figure 1** Compost odour wheel

with a particular compost odour source. When compost air odour control methods and sources are linked to specific chemical causes and their odour quality identified, air odour problems will be more easily solved. With this in mind, a compost odour classification wheel was developed as shown in Figure 1 (Rosenfeld *et al.*, 2004; Suffet and Rosenfeld, 2006). The classification scheme serves as a basis for sensory testing and odour control. The 11 categories of odour descriptors are listed and potential chemical causes are reported based upon Table 1A and B. The intensity of each odour quality was not determined and remains the work of an odour panel to refine the evaluations in the future. In this investigation, the "warning" property of odour is evaluated. "Warnings" would be given when a compound's OTC was less than regulatory levels. In this case, there are five possibilities: (1) there is an OTC, but no regulatory limit; (2) the OTC is less than the regulatory limit; (3) the OTC is equal to the regulatory limit; (4) the OTC is greater than the regulatory limit; (5) there is no OTC known.



## Method

Chemical characteristics, OTCs and health risk evaluation criteria for odourous gasses associated with compost are compiled in Table 1A and B. Odorous gasses resulting from composting can include sulphur compounds, nitrogen compounds, volatile fatty acids and other volatile organic compounds. The toxicity threshold values or regulatory limits published by NIOSH, OSHA, EPA and WHO are presented to allow for comparison to the OTC. Investigators do not always give the same name to the odour characteristics, but the consensus descriptions are within a specific type. OTCs are sometimes reported with order of magnitude differences. VOCs such as substituted benzenes that have been shown to be present in compost emissions (Komilis *et al.*, 2004), but probably not associated with odorants produced by the composting process are studied to assess any source of problems.

## Results and discussion

### Sulphur compounds: sulphur/cabbage/garlic

Anoxic conditions at compost treatment plants produce sulphur-type odours (Banwart and Bremner, 1975). Table 1A and B indicate the present knowledge of sulphur compounds and other compounds thought to be present in compost treatment plants that could be part of the compost plant's odour quality. However, the relationship between the OTC of the chemicals present, their relative concentrations and the type of odour has not yet clearly been defined (Rosenfeld and Suffet, 2004).

The OTCs for sulphur compounds are below their respective regulatory limits, effectively giving a warning to exposed individuals. Sulphur compounds' OTCs (Table 1A and B) are generally lower than most other compounds (Ruth, 1986). Hydrogen sulphide has an OTC of 0.70 $\mu g/m^3$ (Ruth, 1986). The REL and PEL for hydrogen sulphide are 15,000 $\mu g/m^3$ ceiling (10 min) and $2.77 \times 10^7$ $\mu g/m^3$ ceiling, respectively (OSHA, 1993; NIOSH, 2004). Ceiling concentration limits are the highest concentrations allowable for human exposure. In the case of hydrogen sulphide, the REL and PEL are almost eight orders of magnitudes higher than the OTC. The EPA Region 9 ambient air PRG for hydrogen sulphide is 1 $\mu g/m^3$ (EPA, 2004).

Similar to hydrogen sulphide, the REL and PEL for carbon disulphide are between three to six orders of magnitudes higher than its OTC. Carbon disulphide has an OTC of 24.3 $\mu g/m^3$ (Ruth, 1986). Carbon disulphide's REL and PEL are 3,000 $\mu g/m^3$ and $6.23 \times 10^7$ $\mu g/m^3$, respectively (OSHA, 1997; NIOSH, 2004). For this compound, the EPA Region 9 ambient air PRG is 730 $\mu g/m^3$. Aside from being sulphur compounds, the

**Table 1A** Human detection limits and regulatory limits of odorous gases associated with wastewater treatment and compost

| Compounds | Formula | Odour | OTC | | Ref. | B.P. (°C) | M.W. | Ref. | NIOSH REL (based on 8-hr TWA) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | µg/m³ | ppb | | | | | µg/m³ | ppb |
| Sulphur compounds – compost wheel; sulphur/cabbage/garlic | | | | | | | | | | |
| Hydrogen sulphide | $H_2S$ | Rotten eggs | 0.7 | 0.502 | 3 | −60.3 | 34.1 | 9 | – | – |
| Methyl mercaptan | $(CH_3)SH$ | Sulphidy | 0.04 | 0.02 | 3 | 5.9 | 48.1 | 9 | – | – |
| Carbon oxysulphide | $COS$ | Pungent | – | – | – | −50.2 | 60.1 | 9 | – | – |
| Dimethyl sulphide | $CH_3SCH_3$ | Decayed cabbage | 2.5 | 0.984 | 3 | 37.3 | 62.1 | 9 | – | – |
| Ethyl mercaptan | $CH_3CH_2SH$ | Garlic | 0.03 | 0.013 | 3 | 35 | 62.1 | 9 | – | – |
| Sulphur dioxide | $SO_2$ | Irritating | 1,175 | 448 | 3 | −10.1 | 64.1 | 9 | 5,000 | 2,000 |
| Allyl mercaptan | $CH_2=CHCH_2\text{-}SH$ | Garlic-like | 0.2 | 0.066 | 3 | 67.5 | 74.2 | 9 | – | – |
| Carbon disulphide | $CS_2$ | Disagree, sweet | 24.3 | 7.7 | 3 | 46.2 | 76.1 | 9 | 3,000 | 10,000 |
| Propyl mercaptan | $CH_3CH_2CH_2SH$ | Unpleasant | 0.2 | 0.064 | 3 | 67 | 76.2 | 9 | – | – |
| Crotyl mercaptan | $CH_3CH=CHCH_2SH$ | Skunk-like | 0.37 | 0.1 | 3 | – | 90.2 | 3 | – | – |
| Dimethyl disulphide | $(CH_3)_2S_2$ | Rotten cabbage | 0.1 | 0.026 | 3 | 109.7 | 94.2 | 9 | – | – |
| Thiophenol | $C_6H_5SH$ | Putrid, garlic | 1.2 | 0.266 | 3 | 169 | 110.2 | 9 | – | – |
| Benzyl mercaptan | $C_6H_5CH_2SH$ | Unpleasant | 13.2 | 2.6 | 3 | 195 | 124.2 | 9 | – | – |
| Dimethyl trisulphide | $(CH_3)_2S_3$ | Rotten cabbage | 6.2 | 1.2 | 3 | – | 126.2 | 9 | – | – |
| Nitrogen compounds – compost wheel: fishy/ammonia | | | | | | | | | | |
| Ammonia | $NH_3$ | Pungent, irritating | 26.6 | 38.3 | 3 | −33.4 | 17.0 | 9 | 18,000 | 25,000 |
| Methylamine | $CH_3NH_2$ | Fish, ammonia-like | 25 | 20 | 3 | −6.0 | 31.1 | 9 | 12,000 | 10,000 |
| Dimethylamine | $(CH_3)_2NH$ | Fishy, ammonical | 37.8 | 20.5 | 3 | 6.9 | 45.1 | 9 | 18,000 | 10,000 |
| Trimethylamine | $(CH_3)_3N$ | Fishy, pungent | 0.80 | 0.332 | 3 | 2.9 | 59.1 | 9 | 24,000 | 10,000 |
| Volatile fatty acids – compost wheel: rancid | | | | | | | | | | |
| Formic acid | $HCOOH$ | Pungent, penetrating | 45 | 24 | 3 | 100.7 | 46.0 | 9 | 9,000 | 5,000 |
| Acetic acid | $CH_3COOH$ | Sour, vinegar-like | 2,500 | 1,017 | 3 | 117.9 | 60.1 | 9 | 25,000 | 10,000 |
| Propionic acid | $CH_3CH_2COOH$ | Sour | 84 | 28 | 3 | 140.7 | 74.1 | 9 | 30,000 | 10,000 |
| Butyric acid | $CH_3(CH_2)_2COOH$ | Sour, perspiration | 1.00 | 0.278 | 3 | 163.5 | 88.1 | 9 | – | – |
| Valeric acid | $CH_3(CH_2)_3COOH$ | Unpleasant | 2.60 | 0.624 | 3 | 186.0 | 102.1 | 9 | – | – |
| Caprinic acid | $CH_3(CH_2)_8COOH$ | Rancid, sour | 11,951 | 1,696 | 3 | 269.0 | 172.3 | 9 | – | – |
| Aldehydes/ketones – compost wheel: fragrant/fruity and sweet | | | | | | | | | | |
| Acetaldehyde | $CH_3CHO$ | Green sweet, fruity | 0.2 | 0.111 | 3 | 20.1 | 44.1 | 9 | 180,000 | 100,000 |
| Formaldehyde | $CH_2O$ | Unpleasant | 1,470 | 1198 | 3 | −19.5 | 30.0 | 9 | – | 16 |

**Table 1A** (*continued*)

| Compounds | Formula | Odour | OTC | | Ref. | B.P. (°C) | M.W. | Ref. | NIOSH REL (based on 8-hr TWA) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | µg/m³ | ppb | | | | | µg/m³ | ppb |
| Acrolein | $CH_2CHCHO$ | Burnt, sweet | 52 | 22.6 | 3 | 52.7 | 56.1 | 9 | 250 | 100 |
| Propionaldehyde | $CH_3CH_2CHO$ | Sweet, ester | 22 | 9.3 | 3 | 49 | 58.1 | 9 | – | – |
| Acetone | $CH_3COCH_3$ | Sweet, minty | 47,466 | 20,016 | 3 | 56.2 | 58.1 | 9 | 590,000 | 250,000 |
| Crotonaldehyde | $CH_3CHCHCHO$ | Pungent, suffocating | 105 | 36.7 | 3 | 102 | 70.1 | 9 | 6,000 | 2,000 |
| Butanaldehyde | $CH_3CH_2CH_2CHO$ | Sweet | 28,000 | 9495 | 3 | 76 | 72.1 | 9 | – | – |
| Butanone | $CH_3COCH_2CH_3$ | Sweet, minty | 738 | 251 | 3 | 79.6 | 72.1 | 9 | 590,000 | 200,000 |
| Valeraldehyde | $CH_3(CH_2)_3CHO$ | Pungent | 98 | 27.8 | 3 | 103 | 86.1 | 9 | 175,000 | 50,000 |
| 2-Pentanone | $CH_3COCH_2CH_2CH_3$ | Sweet | 28,000 | 7,967 | 2 | 105 | 86.1 | 9 | 530,000 | 150,000 |
| 2,4-Heptadienal | $CH_3CH_2(CH)_5O$ | – | – | – | – | 84 | 110.0 | 9 | – | – |
| 2,4-Decadienal | $CH_3(CH_2)_4(CH)_5O$ | – | – | – | – | – | 152.0 | 9 | – | – |
| 1-Dodecanal | $CH_3(CH_2)_{10}CHO$ | Clean, fresh | 15.2 | 2.02 | 3 | 185 | 184.3 | 9 | – | – |
| Substituted benzenes – compost wheel: solventy/hydrocarbon | | | | | | | | | | |
| Benzene | $C_6H_6$ | Sweet, solventy | 4,500 | 1,409 | 3 | 80 | 78.1 | 9 | 319 | 100 |
| Toluene | $C_6H_5CH_3$ | Rubbery, mothballs | 8,025.00 | 2,130.40 | 3 | 111.1 | 92.1 | 9 | 375,000 | 100,000 |
| Methyl methacrylate | $CH_2 = C(CH_3)COOHCH_3$ | Arid, fruity, sulphidy | 205 | 50 | 3 | 101.1 | 100.1 | 9 | 410,000 | 100,000 |
| Styrene | $C_6H_5CH = CH_2$ | Solventy, rubbery | 202.1 | 47.4 | 3 | 145 | 104.2 | 9 | 215,000 | 50,000 |
| Ethyl benzene | $CH_3CH_2C_6H_5$ | Aromatic | 8,700.00 | 2,003.00 | 3 | 136.2 | 106.2 | 9 | 435,000 | 100,000 |
| m Xylene | $C_6H_4(CH_3)_2$ | Sweet | 348 | 80.12 | 3 | 138.9 | 106.2 | 9 | 435,000 | 100,000 |
| p Xylene | $C_6H_4(CH_3)_2$ | Sweet | 348 | 80.12 | 3 | 138.3 | 106.2 | 9 | 435,000 | 100,000 |
| 1,2,4-trimethylbenzene | $C_6H_3(CH_3)_3$ | Distinctive aromatic | – | – | – | 169.4 | 120.2 | 9 | 125,000 | 25,000 |
| 1,3,5-trimethylbenzene | $C_6H_3(CH_3)_3$ | Distinctive aromatic | – | – | – | 165 | 120.2 | 9 | 125,000 | 25,000 |
| *n*-Propyl benzene | $C_6H_5CH_2CH_2CH_3$ | – | – | – | – | 159 | 120.2 | 9 | – | – |
| Cumene (isopropylbenzene) | $C_6H_5CH(CH_3)_2$ | Sharp, aromatic | 39.2 | 8 | 3 | 152.2 | 120.2 | 9 | 245,000 | 50,000 |
| Naphthalene | $C_{10}H_8$ | Mothball, tar-like | 1,500 | 286 | 3 | 217.8 | 128.2 | 9 | 50,000 | 10,000 |
| *n*-Butyl benzene | $C_6H_5CH_2CH_2CH_2CH_3$ | – | – | – | – | 183 | 134.2 | 9 | – | – |
| *p*-Isopropyl toluene | $C_6H_4CH_3(CH(CH_3)_2)$ | Fresh, citrus | – | – | – | 176 | 134.2 | 9 | – | – |
| 1,4-Dichlorobenzene | $C_6H_4Cl_2$ | Mothballs | 90,000 | 14,969 | 3 | 173.9 | 147.0 | 9 | 450,000 | 75,000 |
| Complex N compounds I – compost wheel: Faecal/sewery | | | | | | | | | | |
| Indole | $C_8H_7N$ | Strong, moth ball | – | – | – | 253 | 117.2 | 9 | – | – |
| Skatole | $C_6H_5C(CH_3)CHNH$ | Perfume | $4.0 \times 10^{-4}$ | $7.48 \times 10^{-5}$ | 3 | 265 | 131.1 | 9 | – | – |

**Table 1A** (*continued*)

| Compounds | Formula | Odour | OTC | | Ref. | B.P. (°C) | M.W. | Ref. | NIOSH REL (based on 8-hr TWA) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | µg/m$^3$ | ppb | | | | | µg/m$^3$ | ppb |
| Complex N compounds II – compost wheel: putrid/dead animal | | | | | | | | | | |
| Pyridine | $C_5H_5N$ | Burnt, sickening | 9 | 2.8 | 3 | 115.6 | 79.1 | 9 | 15,000 | 5,000 |
| Putrescine | $NH_2(CH_2)_4NH_2$ | Putrid, rotting flesh | – | – | – | 158 | 88.2 | 9 | – | – |
| Cadaverine | $NH_2(CH_2)_5NH_2$ | – | – | – | | 179 | 102.2 | 9 | – | – |
| Complex alcohols – compost wheel: earthy/musty/mouldy | | | | | | | | | | |
| 2-Methylisoborneol | $C_{11}H_{20}O$ | – | – | – | – | – | 168.2 | 9 | – | – |
| Geosmin | $C_{12}H_{22}O$ | Earthy | – | – | – | – | 182.3 | 9 | – | – |
| 2,4,6 Trichloranisole | $C_6H_2(Cl)_3OCH_3$ | – | – | – | – | 265.1 | 211.5 | 9 | – | – |
| Complex fragrances – compost wheel: terpenes/pine/lemon | | | | | | | | | | |
| Alpha-Pinene | $C_{10}H_{16}$ | Sweet, pine | – | – | – | 155 | 136.2 | 9 | – | – |
| Beta-Pinene | $C_{10}H_{16}$ | – | – | – | – | | 136.2 | 9 | – | – |
| D-Limonene | $C_6H_7CH_3CCCH_3$ | Lemon, sweet | – | – | – | 176 | 136.2 | 9 | – | – |
| Eucalyptol | $C_{10}H_{18}O$ | – | – | – | – | 176 | 154.3 | 9 | – | – |
| Menthol | $C_6H_9CH(CH_3)_2CH_3OH$ | Pungent | – | – | – | 212 | 156.3 | 9 | – | – |
| Vanillin | $C_6H_3OH(OCH_3)CHO$ | Perfume | $2.0 \times 10^{-4}$ | $3.2 \times 10^{-5}$ | 3 | 285 | 152.1 | 9 | – | – |
| Other compounds – compost wheel: grassy/woody/smoky | | | | | | | | | | |
| *Cis*-3-Hexen-1-ol | $CH_3CH_2CHCHCH_2$ $CH_2OH$ | Sweet, alcohol | – | – | – | 156 | 100.2 | 9 | – | – |
| *Cis*-3-Hexyl acetate | $CH_3CH_2CHCHCH_2$ COOCH3 | Unpleasant | 12.00 | 2.030 | 3 | 168 | 144.2 | 9 | 300,000 | 50,000 |
| Other compounds – not on compost odour wheel | | | | | | | | | | |
| Phenol | $C_6H_5OH$ | Medicinal, sweet | 178.6 | 46.501 | 3 | 181.7 | 94.1 | 9 | – | – |
| Heptanol | $CH_3(CH_2)_6OH$ | – | 14 | 2.95 | 1 | 175.8 | 116.2 | 9 | – | – |
| Benzothiazole | $C_6H_4SCHN$ | Penetrating | 442 | 80 | 3 | 231 | 135.1 | 9 | – | – |

**Table 1B** Regulatory limits of odorous gasses associated with wastewater treatment and compost

| Compounds | NIOSH STEL (based on 15-min TWA) | | Ref. | OSHA PEL (based on 8-hour TWA) | | Ref. | Region 9 PRG | Ref. | WHO | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | µg/m³ | ppb | | µg/m³ | ppb | | µg/m³ | | µg/m³ | |
| Sulphur compounds – compost wheel: sulphur/cabbage/garlic | | | | | | | | | | |
| Hydrogen sulphide | 15,000 ceiling | 10,000 ceiling | 7 | $2.77 \times 10^7$ ceiling | 20,000 ceiling | 6 | 1 | 4 | 150 | 10 |
| Methyl mercaptan | 1000 | 500 ceiling | 7 | 20,000 ceiling | 10,000 ceiling | 5 | 2.1 | 4 | – | – |
| Carbon oxysulphide | – | – | – | – | – | – | – | – | – | – |
| Dimethyl sulphide | – | – | – | – | – | – | – | – | – | – |
| Ethyl mercaptan | 1,300 | 500 ceiling | 7 | 25,000 ceiling | 10,000 ceiling | 5 | – | – | – | – |
| Sulphur dioxide | 13,000 | 5,000 | 7 | 13,000 | 5,000 | 5 | – | – | 125 | 10 |
| Allyl mercaptan | – | – | – | – | – | – | – | – | – | – |
| Carbon disulphide | 30,000 | 10,000 | 7 | $6.23 \times 10^7$ ceiling | 20,000 (30,000 ceiling) | 6 | 730 | 4 | 100 | 10 |
| Propyl mercaptan | 1,600 | 500 | 7 | – | – | – | – | – | – | – |
| Crotyl mercaptan | – | – | – | – | – | – | – | – | – | – |
| Dimethyl disulphide | – | – | – | – | – | – | – | – | – | – |
| Thiophenol | 500 | 100 ceiling | 7 | – | – | – | – | – | – | – |
| Benzyl mercaptan | – | – | – | – | – | – | – | – | – | – |
| Dimethyl trisulphide | – | – | – | – | – | – | – | – | – | – |
| Nitrogen compounds – compost wheel: fishy/ammonia | | | | | | | | | | |
| Ammonia | 27,000 | 35,000 | 7 | 35,000 | 50,000 | 5 | 100 | 4 | – | – |
| Methylamine | – | – | 7 | 12,000 | 10,000 | 5 | – | – | – | – |
| Dimethylamine | – | – | 7 | 18,000 | 10,000 | 5 | 0.021 | 4 | – | – |
| Trimethylamine | 36,000 | 15,000 | 7 | – | – | – | – | – | – | – |
| Volatile fatty acids – compost wheel: rancid | | | | | | | | | | |
| Formic acid | – | – | 7 | 9,000 | 5,000 | 5 | 3.1 | 4 | – | – |
| Acetic acid | 37,000 | 15,000 | 7 | 25,000 | 10,000 | 5 | – | – | – | – |
| Propionic acid | 45,000 | 15,000 | 7 | – | – | – | – | – | – | – |
| Butyric acid | – | – | – | – | – | – | – | – | – | – |
| Valeric acid | – | – | – | – | – | – | – | – | – | – |
| Caprinic acid | – | – | – | – | – | – | – | – | – | – |
| Aldehydes/ketones – compost wheel: fragrant/fruity and sweet | | | | | | | | | | |
| Acetaldehyde | 270,000 | 150,000 | 7 | 360,000 | 200,000 | 5 | 0.87 | 4 | – | – |
| Formaldehyde | – | 100 | 7 | – | – | – | 0.15 | 4 | 100 | 10 |
| Acrolein | – | – | 7 | – | – | – | 0.021 | 4 | – | – |

**Table 1B** (*continued*)

| Compounds | NIOSH STEL (based on 15-min TWA) | | Ref. | OSHA PEL (based on 8-hour TWA) | | Ref. | Region 9 PRG | Ref. | WHO | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | µg/m³ | ppb | | µg/m³ | ppb | | µg/m³ | | µg/m³ | |
| Propionaldehyde | – | – | – | – | – | – | – | – | – | – |
| Acetone | – | – | 7 | 2,400,000 | 1,000,000 | 5 | 3,300 | 4 | – | – |
| Crotonaldehyde | – | – | 7 | – | – | – | 0.0035 | 4 | – | – |
| Butanaldehyde | – | – | – | – | – | – | – | – | – | – |
| Butanone | 885,000 | 300,000 | 7 | 590,000 | 200,000 | 5 | – | – | – | – |
| Valeraldehyde | – | – | 7 | – | – | – | – | – | – | – |
| 2-Pentanone | – | – | 7 | 700,000 | 200,000 | 5 | – | – | – | – |
| 2,4-Heptadienal | – | – | – | – | – | – | – | – | – | – |
| 2,4-Decadienal | – | – | – | – | – | – | – | – | – | – |
| 1-Dodecanal | – | – | – | – | – | – | – | – | – | – |
| Substituted benzenes – compost wheel: solventy/hydrocarbon | | | | | | | | | | |
| Benzene | 3,190 | 1,000 | 7 | 3,190 | 1,000 | 6 | 0.25 | 4 | – | – |
| Toluene | 560,000 | 150,000 | 7 | 753,600 | 200,000 | 6 | 400 | 4 | 0.26 | 10 |
| Methyl methacrylate | – | – | 7 | 410,000 | 100,000 | 5 | – | – | – | – |
| Styrene | 425,000 | 100,000 | 7 | 426,000 | 100,000 | 6 | 1,100 | 4 | 0.26 | 10 |
| Ethyl benzene | 545,000 | 125,000 | 7 | 435,000 | 100,000 | 5 | 1,100 | 4 | – | – |
| *m*-Xylene | 655,000 | 150,000 | 7 | 435,000 | 100,000 | 5 | 110 | 4 | – | – |
| *p*-Xylene | 655,000 | 150,000 | 7 | 435,000 | 100,000 | 5 | 110 | 4 | – | – |
| 1,2,4-Trimethylbenzene | – | – | – | – | – | – | 6.2 | 4 | – | – |
| 1,3,5-Trimethylbenzene | – | – | – | – | – | – | 6.2 | 4 | – | – |
| *n*-Propyl benzene | – | – | – | – | – | – | – | – | – | – |
| Cumene (isopropylbenzene) | – | – | 7 | 245,000 | 50,000 | 5 | 400 | 4 | – | – |
| Naphthalene | 75,000 | 15,000 | 8 | 50,000 | 10,000 | 5 | – | – | – | – |
| *n*-Butyl benzene | – | – | – | – | – | – | | | – | – |
| *p*-Isopropyl toluene | – | – | – | – | – | – | – | – | – | – |
| 1,4-Dichlorobenzene | – | – | 7 | 450,000 | 75,000 | 5 | – | – | – | – |
| Complex N compounds I – compost wheel – faecal/sewery | | | | | | | | | | |
| Indole | – | – | – | – | – | – | – | – | – | – |
| Skatole | – | – | – | – | – | – | – | – | – | – |
| Complex N compounds II – compost wheel – putrid/dead animal | | | | | | | | | | |
| Pyridine | – | – | 7 | 15,000 | 5,000 | 5 | 3.7 | 4 | – | – |

**Table 1B** (*continued*)

| Compounds | NIOSH STEL (based on 15-min TWA) | | Ref. | OSHA PEL (based on 8-hour TWA) | | Ref. | Region 9 PRG | Ref. | WHO | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | µg/m³ | ppb | | µg/m³ | ppb | | µg/m³ | | µg/m³ | |
| Putrescine | – | – | – | – | – | – | – | – | – | – |
| Cadaverine | – | – | – | – | – | – | – | – | – | – |
| Complex alcohols – compost wheel: earthy/musty/mouldy | | | | | | | | | | |
| 2-Methylisoborneol | – | – | – | – | – | – | – | – | – | – |
| Geosmin | – | – | – | – | – | – | – | – | – | – |
| 2,4,6-Trichloranisol | – | – | – | – | – | – | – | – | – | – |
| Complex fragrances – compost wheel: terpenes/pine/lemon | | | | | | | | | | |
| Alpha-Pinene | – | – | – | – | – | – | – | – | – | – |
| Beta-Pinene | – | – | – | – | – | – | – | – | – | – |
| D-Limonene | – | – | – | – | – | – | – | – | – | – |
| Eucalyptol | – | – | – | – | – | – | – | – | – | – |
| Menthol | – | – | – | – | – | – | – | – | – | – |
| Vanillin | – | – | – | – | – | – | – | – | – | – |
| Other compounds – compost wheel: grassy/woody/smoky | | | | | | | | | | |
| *Cis*-3-Hexen-1-ol | – | – | – | – | – | – | – | – | – | – |
| *Cis*-3-Hexyl acetate | – | – | 7 | 300,000 | 50,000 | 5 | – | – | – | – |
| Other compounds – not on compost odour wheel | | | | | | | | | | |
| Phenol | 19,000 | 5,000 | 7 | 19,000 | 5,000 | 5 | 1,100 | 4 | – | – |
| Heptanol | – | – | – | – | – | – | – | – | – | – |
| Benzothiazole | – | – | – | – | – | – | – | – | – | – |

[1] Nagy, 1991. 50% odour detection limit
[2] Miller, 1993. Low human detection limit
[3] Ruth, 1986. Low odour detection limit
[4] EPA Region 9 PRG Table, October 2004
[5] OSHA, *Table Z-1 Limits for Air Contaminants*, 1993
[6] OSHA, *Table Z-2 Limits for Air Contaminants*, 1997
[7] NIOSH, *Pocket Guide to Chemical Hazards*, 2004
[8] NIOSH, *Pocket Guide to Chemical Hazards*, Appendix G, 1989 Air Contaminants Project, Exposure Limits Not in Effect
[9] The Merck Index, 13th edition, 2001
[10] World Health Organization, *Air Quality Guidelines*, 2nd Edition, 2000

characteristic that links these two compounds together is that they have OTCs below their REL, PEL and PRG concentrations.

Unlike hydrogen sulphide and carbon disulphide, sulphur dioxide becomes hazardous at concentrations closer to or below its OTC. The REL and PEL of sulphur dioxide, which has no strong pungent smell attached to its presence, are only one order of magnitude greater than its OTC (Table 1A and B). The OTC of sulphur dioxide is 1,175 $\mu g/m^3$ (Ruth, 1986) while the REL and PEL are 5,000 $\mu g/m^3$ and 13,000 $\mu g/m^3$, respectively (OSHA, 1993; NIOSH, 2004). According to WHO, hazardous concentrations begin at 125 $\mu g/m^3$ (WHO, 2000). Sulphur dioxide is one of several criteria pollutants in our air today. National Ambient Air Quality Standards (NAAQS) require sulphur dioxide concentrations not to exceed an annual concentration of 80 $\mu g/m^3$. Clearly, before sulphur dioxide can be humanly detected, it could already pose a health hazard. This is in contrast to carbon disulphide and hydrogen sulphide, which have strong odours detectable at very low concentrations with RELs and PELs between six and seven magnitudes greater than their OTCs.



#### Nitrogen compounds: fishy/ammonia

Table 1A and B also indicate the present knowledge regarding nitrogen (N) compounds that could be part of the compost plant's odour quality. As with sulphur compounds, the relationship between the many N-type chemicals present, their relative concentrations and the type of odours has not yet clearly been defined. Ammonia and trimethylamine comprise most of the odorous N emissions from wastewater, composting and organic biomass decay. Ammonia produces a pungent medicinal odour, while trimethylamine produces a fishy odour with a human detection limit 100 times lower than ammonia (Rosenfeld and Henry, 2001; Rosenfeld *et al.*, 2002).

Table 1B illustrates that compounds producing a fishy/ammonia-like odour have OTCs well below their REL. For instance, ammonia has an OTC of 26.6 $\mu g/m^3$ while its REL is 18,000 $\mu g/m^3$. Dimethylamine has an OTC which is below the REL and PEL but above the PRG. This indicates a possibility of hazardous conditions before the OTC is reached. Dimethylamine has an OTC of 37.80 $\mu g/m^3$ (Ruth, 1986). Both the REL and PEL for dimethylamine are 18,000 $\mu g/m^3$ while the Region 9 EPA ambient air PRG is 0.021 $\mu g/m^3$. The PRG is three orders of magnitudes lower than the OTC (EPA, 2004).

#### Volatile fatty acid: rancid

Compounds such as volatile fatty acids are thought to be present in most compost treatment plants that could be part of the compost plant's odour quality. The relationship between these compounds, their relative concentrations and the type of odours has also not been defined. Aerobic secondary treatment produces oxygenated compounds, such as aldehydes, alcohols, ketones and volatile fatty acids (Mosier *et al.*, 1977). Anaerobic digestion processes during compost treatment result in the formation of volatile fatty acids (Killham, 1994). Volatile fatty acids have a rancid, vinegar and body odour-like smell (see Table 1A and B) (Rosenfeld and Suffet, 2004). The volatile fatty acids listed in Table 1B also have OTCs which are below their REL. However, formic acid has an OTC which is below the PEL and REL but above the PRG. The OTC of formic acid is 45.00 $\mu g/m^3$ (Ruth, 1986), while its REL and PEL are two magnitudes higher at 9,000 $\mu g/m^3$ (OSHA, 1993; NIOSH, 2004). The Region 9 USEPA ambient air PRG for formic acid is 3.1 $\mu g/m^3$, much lower than the compound's REL and PEL (EPA, 2004).

#### Aldehydes and ketones: fragrant/fruity and sweet

Aldehydes and ketones generally have sweet pungent odours that result from incomplete decomposition of organic matter during biosolids production. While the sweet solvent-like odours of ketones and aldehydes may not be perceived as unpleasant, mixed with other odorants they contribute to a generally unpleasant odour (Rosenfeld and Suffet, 2004; Rosenfeld *et al.*, 2004).

Acetaldeyde is similar to hydrogen sulphide and carbon disulphide, in that it gives exposed individuals a warning because the OTC is far below the REL, PEL and PRG concentrations. Acetaldehyde has a REL and PEL five orders of magnitudes higher than its OTC at 0.20 $\mu g/m^3$ (Ruth, 1986; OSHA, 1993; NIOSH, 2004). The EPA Region 9 ambient air PRG for acetaldehyde is 0.87 $\mu g/m^3$ (EPA, 2004). Acetone may potentially present hazardous conditions before the OTC is reached. The OTC of acetone is below the PEL and REL, but above the EPA Region 9 PRG values. Acetone has an OTC of 47,466 $\mu g/m^3$ (Ruth, 1986). Acetone's REL and PEL, 590,000 $\mu g/m^3$ and $2.4 \times 10^6$ $\mu g/m^3$, respectively, are both between one and two orders of magnitude greater than their OTCs (OSHA, 1993; NIOSH, 2004). However, EPA Region 9 ambient air PRG for acetone is 3,300 $\mu g/m^3$, which is one order of magnitude lower than the OTC (EPA, 2004), indicating the potential for hazardous conditions before humans detect the compounds' odour.

#### Complex N-compounds: faecal/ sewery and putrid/dead animal

Composting can also generate complex nitrogen compounds which produce a faecal and sewery odour or with a putrid and dead animal-like odour. More research needs to be conducted in this area of odour to determine the OTCs for these compounds. Pyridine, however, produces a burnt, sickening odour which is associated with a dead animal. For this compound, the OTC of 9 $\mu g/m^3$ is well below the REL of 15,000 $\mu g/m^3$.

#### Complex alcohols and fragrances: earthy/musty/mouldy and terpenes/pine/lemon

Complex alcohols and fragrances are often noted at composting facilities. These produce an earthy, musty odour or a pine and lemon odour. However, more research needs to be conducted in this specific odour area to establish OTCs, RELs and PELs.

#### Other compounds: grassy/woody/smoky

A grassy, woody, smoky odour is also often detected near compost facilities. The unpleasant, grassy odour of *cis*-3-hexyl acetate is noticed well below its REL. The OTC of this compound is 12 $\mu g/m^3$ while its REL is 300,000 $\mu g/m^3$. Essentially, there is no definitive relationship between strong, pungent smells and hazardous concentrations. Instead, these comparisons demonstrate that compounds with high OTCs can pose a greater risk than compounds that have low OTCs.

#### Substituted benzenes: solventy/hydrocarbon

Komilis *et al.* (2004) identified various xenobiotic VOCs in the gaseous emissions of organic municipal solid waste components. The VOCs appear to be embedded in the solid matrix and are released upon wetting and heating during the initiation of the composting process. The results demonstrated that municipal solid waste composting can be a source of hazardous VOC emissions.

Several substituted benzenes have OTCs which are below the REL and PEL but above the PRG. Ethyl benzene has an OTC of 8,700 $\mu g/m^3$. The RELs and PELs for ethyl benzene is at least two orders of magnitude higher than its OTC. The EPA Region 9 ambient air PRG for ethyl benzene is 1,100 $\mu g/m^3$, once again much lower than its OTC (EPA, 2004). In addition, toluene has a PRG of 400 $\mu g/m^3$ (EPA, 2004), much lower than its OTC at 8,025 μg/m$^3$ (Ruth, 1986). Cumene (isopropylbenzene) gives a warning to an exposed individual by having an OTC that is below its REL and PEL, but cumene does not have a PRG value. Cumene's OTC is 39.20 μg/m$^3$ and both the REL and the PEL are 245,000 μg/m$^3$ (Ruth, 1986; OSHA, 1993; NIOSH, 2004).

Benzene is a case in which the REL PEL and PRG are lower than the OTC. Therefore, there is no warning smell associated with hazardous benzene exposure. Benzene is a known carcinogen and has an OTC of 4,500 μg/m$^3$. The REL and PEL for benzene are 319 μg/m$^3$ and 3,190 μg/m$^3$, which are below the OTC (OSHA, 1993; NIOSH, 2004). The EPA Region 9 ambient air PRG of benzene is 0.25 μg/m$^3$, which is four orders of magnitude lower then the OTC (EPA, 2004). Benzene is the most hazardous VOC associated with composting and should be monitored.



## Conclusion

Each odorant possesses a characteristic odour signature-odour quality and odour threshold as well as a toxicity value. Odorants are released into air during the decomposition of organic waste at the compost treatment plant. Composting releases volatile organic chemicals, including alcohols, aldehydes, volatile fatty acids, ammonia and other nitrogen compounds, xenobiotic solvents and various sulphur compounds into the environment. This paper begins to develop an understanding of how the VOCs present in the raw compost (including xenobiotic solvents) are related to human health threshold criteria developed by NIOSH, OSHA, USEPA and WHO. This comparison indicates that: (1) the human OTC for most compost odorants are far lower than their respective human health risk (regulatory) threshold values; (2) several compost odorants have OTC that are below some of their respective regulatory thresholds and above others (i.e. dimethyl amine, formic acid, acetone, ethyl benzene and toluene); (3) only the VOCs probably present as contaminants in the raw composting material have OTC greater than all of its regulatory thresholds (i.e. benzene). Benzene is the most hazardous VOC associated with composting and should be monitored.

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