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Including an Odor Impact Potential in Life Cycle Assessment of waste treatment plants

Including odors in Life Cycle Assessment

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Abstract

Odors occupy a leading position among air quality issues of growing concern. Odors can be emitted from different economic sectors, from industrial to agricultural, including waste treatment activities. Although there are different techniques to determine odor emissions, a standardized indicator has not still been defined to include odor impact into methodological tools such as Life Cycle Assessment. In this sense, some proposals can be found in current literature. Considering these approaches, the present work proposes the Odor Impact Potential, an indicator to be used in Life Cycle Assessment or in waste treatment technologies benchmarking. A simple method is reported to calculate the Odor Impact Potential value from different types of data: chemical analysis of odorants or olfactometric determinations. Data obtained in a previous work for an industrial scale anaerobic digestion plant have been used to present an example of application. Additional Odor Impact Potential calculations from other published data (thermal waste treatment plant and wastewater treatment plant) are also included. The aim of Odor Impact Potential is not to replace parameters such as odor emission rates, odor concentration or odor emission factors but to use those values to calculate the odor derived impact in Life Cycle Assessment studies.

Keywords: Anaerobic digestion; environmental impact; odor emissions; olfactometry; organic waste; volatile organic compounds.

1. Introduction

The European standard EN 13725 (CEN, 2003) defines odor as an organoleptic attribute perceptible by the olfactory organ on sniffing certain volatile substances. This perception depends on concentration and intensity, quality (identity) and hedonic tone (pleasant/unpleasant) of the odor. Being considered as atmospheric pollutants, odors are the major cause of citizens' complaints to local authorities (Capelli et al., 2013).

Odors can be emitted from many activities comprising different economic sectors. In fact, odor sources include agricultural, municipal (i.e. water and solid waste treatment or landfills) and industrial activities (e.g. chemical industry, food industry, among others). Focusing on municipal solid waste treatment installations, odor emissions are the main contributor to their negative image and reputation (Gostelow et al., 2001). Landfills, composting and anaerobic digestion plants are good examples of this situation. Composting and anaerobic digestion have a significant potential to biostabilize organic wastes decreasing their odorous potential (Haug, 1993). Anaerobic digestion can be considered as a renewal energy source by the use of biogas produced during biological degradation of organic materials in absence of oxygen (Adani et al., 2001). In addition to odor nuisance, composting and anaerobic digestion also present other environmental impacts that should be considered, such as energy and water consumption or greenhouse gases emissions (Colón et al., 2012). Gaseous emissions released as volatile organic compounds (VOC) have been associated to odor nuisance, although other compounds, such as ammonia or hydrogen sulphide, also contribute to odor level (Font et al., 2011; Komilis et al., 2004).

The main sources of odors in waste treatment installations are the volatile substances produced by the uncontrolled fermentation of organic wastes during storage and pre-treatment (Sironi et

al., 2007). Several works reported that N-compounds, S-compounds, volatile fatty acids, ketones, esters, terpenes and hydrocarbons were the most common compounds present in vegetables, fruit and garden waste and municipal solid waste, and are emitted in treatment plants causing odor nuisance (Alfonsín et al., 2013; Tsai et al., 2008; Mao et al., 2006; Eitzer, 1995). Particularly, Limonene, alpha-Pinene and dimethyl disulphide were found in concentrations over their odor threshold during raw and anaerobically digested sludge composting (Maulini-Duran et al., 2013). In anaerobic digestion facilities, the establishment of the anaerobic metabolism produces a set of odorous compounds, including inorganic molecules (ammonia and hydrogen sulphide) and organic molecules such as volatile fatty acids, terpenes, alcohols and sulphur compounds (Rosenfeld and Suffet, 2004). Even though anaerobic digestion is performed in enclosed reactors (digesters), the substances generated during the anaerobic digestion process, can be emitted from the post-stabilization and maturation stages of the digested waste and are also responsible of malodors (Tepe et al., 2008). Diffuse emissions of biogas that can occur in valves, pipes and connectors should also not be disregarded as odor sources (European IPPC Bureau, 2006).

Given that odor is a perception, the best way to measure it should be employing humans (olfactometry). In fact, dynamic olfactometry, using trained human panelists, is the internationally accepted method for the determination of odor concentration, which is expressed as OU m⁻³ (European odor units per cubic meter, CEN, 2003). One of the main drawbacks of olfactometry is that it must be conducted in a controlled laboratory set with enough panelists available to conduct the analysis. Samples should be collected at the emission point, stored and analyzed in a short period (CEN, 2003).

Odor dispersion models can be applied further to calculate the odor concentration that will be

perceived by citizens based on olfactometric determinations (Capelli et al., 2013). In addition, field olfactometric measurements have been performed involving scentometers (field olfactometers) to be compared to values obtained from the above-mentioned dispersion models (Bokowa, 2012). Community modeling, i.e. the use of selected individuals (monitors) to detect and determine odors intensity has also been proposed and results compared to dispersion calculations using estimate emissions from a landfill site (Sarkar et al., 2003).

Electronic noses (EN) and chemical analysis are also used to quantify the odorants emitted (Hobbs et al., 1995). An EN is an instrument that comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern recognition system capable of recognizing simple or complex odors. The sensor array produces an olfactory pattern that can be classified based on a reference database acquired by the instrument after a previous training phase (Capelli et al., 2013). Electronic noses presented some problems of application on odor impact assessment due to variable atmospheric conditions, sensor drift over time and high sensitivity requirements. However, the technology used in EN is in continuous improvement and in recent years different studies have been published reporting interesting results. Sironi et al. (2007) found a good correspondence between EN and odor level in waste treatment plants after a previous training of this measuring equipment with real samples of known odor concentration. Nicolas et al. (2012) used an EN in the study of odor nuisance near a composting facility, concluding that the instrument was efficient enough to assess odor annoyance. Brattoli et al. (2011) report different successful applications of EN in environmental analysis, mainly in situ measurements using portable devices. These authors also point as a new trend the use of nanotechnologies and nanomaterials to improve EN detection capacity (nanoelectronics noses). When compared to olfactometric determinations, EN present lower analysis costs also allowing continuous monitoring in the field near sources and receptors (Laor et al., 2014).

Finally, gas chromatography coupled with mass spectrometry (GC/MS) is frequently used to identify and quantify odorous compounds (Defoer et al., 2002). However, GC/MS results cannot always be directly correlated to odor level. When a mixture of chemical compounds is responsible of odor, it should be kept in mind that each compound has a different odor threshold value and that compounds concentrations are not additive in terms of odor. Additionally, if synergic effects appear, odor estimation from chemical determinations is strongly imprecise.

Notwithstanding the existence of different techniques to evaluate odor emissions and regulations in force in different countries (Bokowa, 2010), there is not a standardized indicator for odor impact, to be incorporated into methodologies for assessing the potential environmental impacts, such as Life Cycle Assessment (LCA). LCA is a methodological tool of wide application to study the environmental aspects and potential impacts through the entire life of a product or service, from the extraction of raw materials to the final disposal of waste, including production and use. That means: developing an inventory of relevant inputs and outputs of the studied system (inventory analysis), assessing their potential impacts (impacts assessment) and interpreting the results in relation to the proposed targets (interpretation) (International Organisation for Standardisation, 2006). LCA methodology relates system outputs to global impacts such as Global Warming Potential, Acidification Potential and Human Toxicity Potential, among others (Pennington et al., 2004). However, there is a growing interest to incorporate social and local impacts to LCA, giving the opportunity for odors to be represented in this widespread methodological tool (Dreyer et al., 2006).

In this regard, Heijungs et al. (1992) classified emissions of odorous substances by means of an indicator called “malodorous air”. This indicator, following an approach similar to critical

volumes, is based on Odor Threshold Values (OTV) and is defined as the sum of the amount of each malodorous compound emitted ($m_{i,air}$, in kg) divided by its respective OTV ($OTV_{i,air}$, in $kg \cdot m^{-3}$), as reflected in Equation 1.

$$\text{Malodorous air} = \sum_i \frac{m_{i,air}}{OTV_{i,air}} \quad (\text{Equation 1})$$

The OTV is the concentration of a given substance, under defined standard conditions, at which 50% of a representative sample of the population can just detect the difference between a sample of air mixed with that substance and a sample of clean air. Thus, the Malodorous air suggested by Heijungs et al. (1992) is expressed in m^3 and represents the quantity of air contaminated to the OTV. Similarly, the same author proposed the Malodorous water parameter.

Marchand et al. (2013) also proposed an approach for an odor indicator that fits into LCA methodology. In their study, the concentration of individual chemical compounds that can be responsible for odors is determined and compared to different reference compounds depending on odor character and considering their OTV. This approach generates a list of equivalent concentration values for the different reference compounds. Recently, Peters et al. (2014) defined an “odor footprint” to be included in LCA for odor assessment. In this case, the persistence of the odorants is considered as are their consequences and relationships with other environmental indicators. Persistence is determined by means of the diffusion rate and degradation kinetics of odor responsible compounds in the atmosphere.

In this context, and based on Heijungs et al. (1992) “malodorous air” proposal, the present is an attempt to include odors in LCA studies of waste treatment installations, considering the possibility of using olfactometry, as well as gas chromatography/mass spectrometry as analytical

methods to determine inventory emissions, always combined with the Odor Threshold Values. The main purpose of this work is to present an impact potential easy to calculate and applicable to different types of activities or processes and odor emissions data. Data from a full-scale anaerobic digestion plant previously published in Orzi et al. (2010) has been used to present an example of application. Other sets of data from different published works have also been used for better discussion. The aim of this indicator is not to replace parameters such as odor emission rates, odor concentration or odor emission factors, but to use their values, calculated from different data sets, to include odor derived impact in LCA studies, as well as in treatment technologies and plant management benchmarking.

2. Materials and Methods

In brief, the proposed indicator, named Odor Impact Potential (OIP), will express the amount of clean air necessary to dilute the odorous emission to a concentration non-detectable by human nose. This definition also corresponds to that for odor concentration (in olfactometric measurements). However, in LCA studies, the amount of clean air should be referred to a functional unit previously selected.

As stated before, odors can be directly (by olfactometry) or indirectly (by GC/MS) measured. Following, the two approximations are discussed. In both cases, the amount of clean air to obtain an odor concentration not detectable by human nose is used.

2.1 OIP determination from individual odorants concentration data

In this approach, the chemical concentration (ppmv, ppbv, ppm or ppb) of individual odor-causing compounds in gaseous emissions should have been determined by GC/MS. Then,

odorants concentration values should be compared to OTV determining clean air needs (m^3) to dilute the emission and reach OTV by calculating the ratio between compound concentration and compound OTV. High compounds concentration and/or the low OTV will derive in high clean air needs. However, the volume of clean air obtained following these calculations will correspond to the dilution of 1 m^3 of gaseous emission. To reach a representative value of plant operation, the concentration of the different compounds emitted should be converted to volumetric ($\text{m}^3 \text{ compound s}^{-1}$) or mass flow ($\text{kg compound s}^{-1}$) of each compound by means of the total volumetric flow of the emission ($\text{m}^3 \text{ s}^{-1}$). In fact, to reach the desired value, the equation proposed by Heijungs et al. (1992) can be applied for a single compound (not calculating the sum), substituting the compound total mass emitted by the compound mass flow.

When different gaseous samples and/or different compounds concentration from a single treatment plant are available, the clean air needs will be determined by the highest value obtained from calculations regarding all sampling days or locations within the plant and/or all the studied compounds. Dilution of gaseous emissions needed according to this highest value will also avoid odor disturbances that can originate the rest of pollutants detected.

In addition, and as stated above, in a LCA context, the needs for clean air should be compared with a functional unit. This ratio will also allow comparison within treatment plants. A functional unit commonly used in waste treatment plant studies corresponds to the treatment of 1 Mg of feedstock. Other possibilities are a fixed amount of compost, digestate or biogas produced (depending on the type of treatment plant and the final product obtained).

Thus, differences among OIP (expressed as m^3 of clean air Mg^{-1} feedstock) and Heijungs et al. (1992) “malodorous air” proposal (expressed in m^3 of clean air) rely firstly on the calculation in

OIP case of clean air needs based on a single compound emission (the one requiring the highest amount), instead of the sum of clean air needs for each of the contaminants analyzed; and secondly, on the use of a functional unit to which diluting air needs are referred.

2.2 OIP determination from olfactometric data

The data on odorous emissions from a treatment plant can also be available in form of odor concentration determined by olfactometry (OU m⁻³). In this case, odor units or odor concentration itself express the number of sample dilutions with clean air to obtain an odor concentration not detectable by human nose and thus, the volume of clean air necessary to dilute the sample under its odor threshold. Again, in the LCA context, results should be referred to a functional unit.

2.3 Some aspects of concern on OIP

OIP does not consider the dispersion of odors in the atmosphere. Depending on the factors affecting dispersion (atmospheric and climatic conditions, distance from inhabited areas, existence of other odor focus, characteristics of the receptors, etc.), the same facility located in different areas could emit the same odor but cause different nuisance. However, to define a general and easy to use indicator, even though odor is a local impact, OIP should only include the odor emission and not its dispersion. In this sense, OIP will be also valuable to compare technologies, regardless of their location.

OIP obtained from olfactometric data will be directly related with the nuisance that can be caused to the neighbors. Consequently, although OIP can be obtained from different data, if this impact potential should be included in LCA studies, the olfactometric methodology is recommended when available. In general, the OIP will be expressed as OU Functional Unit⁻¹.

3. Results and Discussion

As an example of application to numerically operate the proposed indicator (OIP), data presented in Orzi et al. (2010) has been used. These data reflect VOC and ammonia emissions from a full-scale anaerobic digestion waste treatment plant treating 30000 Mg of feedstock mix per year consisting in organic fraction of municipal solid waste (OFMSW) coming from a source-selection collection system and farm wastes. The surface of the post-digester tank (storage tank), completely open to the atmosphere, was identified as the main gaseous emissions source (3000 m²). Field data were collected during three sampling campaigns. Also, olfactometric measurements are provided.

Table 1 presents emissions of total VOC and ammonia measured in three different days (named A, B and C). Total VOC concentration was determined by gas chromatography and ammonia concentration was measured using a specific sensor. Odor measures (obtained by olfactometry) are also reported in Table 1, both as odor concentration (OU m⁻³) and odor units emitted per unit area and time (OU m⁻² s⁻¹) (Orzi et al., 2010). Variability of emissions comparing different days can be observed for all parameters presented. No relationship was observed within the concentration of total VOC or ammonia and the variation in odor emissions detected. However, it is difficult to observe a direct relationship between these two parameters, as the odor level will be caused by the individual VOC present in the samples and their odor threshold. As stated in the Introduction, the relationship between chemical (GC-MS measurements) and odor concentration (olfactometry) is specific for each type of odorant and cannot be generalized.

Main VOC present in gaseous samples that can be responsible of odors were also identified in Orzi et al. (2010) by GC/MS. Their concentration has been summarized in columns 1, 2 and 3 of Table 2, corresponding to the three different sampling days, while column 4 presents mean values and standard deviation. The predominance of p-Cymene and 2-Butanone is clear in A and B samples, while in C sample D-Limonene presents a concentration higher than 2-Butanone. These predominant compounds show concentrations one order of magnitude higher than the rest of compounds identified.

3.2 OIP determination

Table 2 summarizes the values obtained for OIP from individual odorants concentration data. OTV values are also presented for the different compounds found in gaseous samples (Column 5). OIP calculated from VOC concentration depends on OTV used. Table 3 summarizes OTV for VOC considered in Orzi et al. (2010) reported by different authors. As can be seen in Table 3, there are differences of several orders of magnitude among OTV reported for the same compound in most cases depending on the laboratories and methods used (Capelli et al., 2013). Thus, simulating the worst case scenario, OIP has been calculated using the lowest OTV for each compound (Column 5 in Table 2). These values have been marked in bold in Table 3. The lowest OTV corresponds to p-Cymene, the VOC with the highest concentration in all the samples analyzed. Clearly, the OTV is exceeded by all the compounds in all the samples analyzed.

Concentration values for the different compounds were obtained by Orzi et al. (2010) from post-digestion tank material samples emissions using an air sampling chamber (sample-air contact area: 0.196 m^2 ; applied airflow: $0.35 \text{ m}^3 \text{ h}^{-1}$). Thus, to calculate OIP, firstly, concentration values

in Columns 1, 2 and 3 in Table 2 have been multiplied by the airflow applied to the gaseous sampling chamber ($0.35 \text{ m}^3 \text{ h}^{-1}$) and by the relationship between real emitting area at the treatment plant (3000 m^2 , post-digestion tank) and sample-air contact area in the sampling chamber (0.196 m^2). Secondly, values obtained have been divided by OTV values in column 5 to obtain columns 6, 7 and 8. In this case, the functional unit chosen was the treatment of 1 Mg of feedstock. Values of clean air needs per Mg of feedstock are presented in Table 2 (column 9), calculated considering maximum clean air needs for each compound among the three sampling days. The values used are presented in bold in columns 6, 7 and 8. In the present case study, the maximum value of clean air needs per Mg of feedstock treated corresponds to p-Cymene. Thus, the result for OIP in the studied plant is $8.47 \cdot 10^8 \text{ m}^3 \text{ Mg}^{-1}$ feedstock (Table 2, column 9, value in bold and underlined), the maximum clean air needs value.

To calculate OIP based on olfactometric data, values of OU m^{-3} and OU Mg^{-1} feedstock reported in Table 1 have been directly used. In this case, OIP value is $3.54 \cdot 10^7 \text{ OU Mg}^{-1}$ feedstock (equivalent to m^3 clean air per Mg feedstock), the maximum odor emission factor obtained corresponding to sampling day B (in bold and underlined in Table 1).

3.3 Comparison of OIP values

OIP obtained from compounds concentration data is 24-fold the OIP value calculated from olfactometric data. Also, OIP olfactometric is fixed by sampling day B data, while OIP from compounds concentration corresponds to sampling day C corroborating the fact mentioned above that there is not always a direct relationship within odor concentration and chemical concentration of odorants. OIP obtained from compounds concentration data is strongly dependent on the OTV used for the calculation, considering in the present example the worst-case scenario. On the other hand, olfactometric measurements are performed following a

standard methodology also covering interactions among odorants or other compounds present in gaseous samples, being difficult to overestimate odor level during these measurements. Thus, OIP calculation from olfactometric data is recommended. In case of comparison between waste treatment installations, this recommendation can be overcome fixing a common set of OTV values.

The variability detected in gaseous emissions (Tables 1 and 2) should be considered when studying odors associated to a waste treatment plant. Thus, different sampling campaigns are recommended to adequately reflect this variability. The number of campaigns will depend on the type of plant and its operational characteristics. This recommendation affects both odor determination methodologies, the analysis of the chemical compounds and the olfactometric determinations. This statement will affect the economic cost of the studies and may be a barrier to reach reliable data. The determination of a gaseous emissions inventory was not the scope of the present paper but to present OIP and an example of OIP calculation of from real data.

3.4 OIP calculation from other published data

It is not straightforward to find sets of data in published works (odorous compounds emissions expressed as individual odorants concentration and mass flow and olfactometric data) like those provided by Orzi et al. (2010) and used as example for OIP calculation. However, to extend the practical application of OIP, data presented in Schauberger et al. (2011) on odor and odorous compounds emission from a waste thermal treatment plant have been used.

Schauberger et al. (2011) calculated plant VOC emissions (mass flow, mg s^{-1}) and odor emissions (ou s^{-1}) using an inverse dispersion technique. OTV for the different VOC evaluated are also listed in their paper. These authors also pointed out the diversity in OTV available in the

literature. They summarize OTV considering the minimum and mean VOC odor threshold concentration. Waste treatment capacity of the plant is 90000 Mg/y. Calculations of OIP have been done based on maximum values reported for VOC mass flow and odor emissions. In the case of OIP from odorants concentration data, minimum (worst case scenario, as done above using Orzi et al. (2010) data) and mean OTV have been considered. Results are summarized in Table 4. The pollutant that will determine OIP value in this case will be butyl acetate (OIP value in bold in Table 4). As can be observed, comparing Tables 2 and 4, none of the pollutants considered by Orzi et al. (2010) were considered by Schaubberger et al. (2011) since both processes are completely different. OIP values (from odorants and odor concentration are clearly higher in the case of the anaerobic digestion plant (Tables 1 and 2). However, the ratio between OIP calculated using individual odorants data ($67755.7 \text{ m}^3 \text{ clean air Mg}^{-1} \text{ feedstock}$) and OIP from olfactometric data ($2608.7 \text{ OU Mg}^{-1} \text{ feedstock}$) for the waste thermal treatment plant is 26 (worst case scenario). This value is close to that obtained in the case of the anaerobic digestion plant (equal to 24). The dependence of OIP from individual odorants on OTV is also reflected in these results. Using mean OTV values (column 3 in table 4) in OIP calculation, the value of this impact potential will be reduced to $4106 \text{ m}^3 \text{ clean air Mg}^{-1} \text{ feedstock}$ and the relationship between OIP concentration and odor will be lower than 2. Above recommendation of OIP calculation from olfactometric measurements is thus reinforced.

In another published work, Lehtinen and Veijanen (2011) presented VOC concentrations ($\mu\text{g m}^{-3}$) measured at different points in a wastewater treatment plant, as well as odor concentration in OU m^{-3} . Sludge thickening, sludge dewatering and biofilter outlet are the emission sources in this installation. Also, an OTV list of some of the VOC emitted is provided. In this case, the treatment capacity of the plant is given, but not the total emission flow. In this sense, a proper OIP value cannot be determined based on the data presented. However, a similar value

expressed as m^3 of clean air per m^3 of gaseous emission can be calculated based on VOC concentration reported and compared with odor emission in OU m^{-3} . The values obtained, considering VOC maximum concentration values listed in Lehtinen and Veijanen (2011), are presented in Table 5. As can be seen in Table 5, Sulphur compounds (DMS and DMDS) are the VOC determining the maximum clean air needed to dilute emissions to OTV in the three emission points. Highest clean air requirement corresponds to sludge thickening (1620 m^3 of clean air per m^3 of gaseous emission due to DMDS concentration). In the case of odor concentration (in OU m^{-3} , also listed in Table 5), biofilter outflow will require the maximum clean air amount. If the concentration values obtained are compared to the respective odor concentration, in this case clean air needs are higher based on olfactometric values, with ratios ranging from 5 (in the case of sludge thickening) to 22 (in the case of sludge dewatering).

Dincer and Muezzinoglu (2006) presented similar data than Lehtinen and Veijanen (2011), but corresponding to a rendering plant, a sanitary landfill and large petroleum and petrochemical industries. Although in this case OTV are not reported, calculations made in the case of the wastewater treatment plant (Lehtinen and Veijanen, 2011) could be reproduced based on OTV provided by other authors, thus extending OIP (or derived/similar indicators) to different industrial installations.

4. Conclusions

The Odor Impact Potential (OIP) is proposed to include odor impact in LCA studies or in waste treatment technologies and in plant management benchmarking. Through the OIP calculation, it is possible to assess the potential impact of an installation by odorous emissions, an area not widely explored in LCA studies. This impact potential can be calculated from chemical analysis of odorants, as well as from olfactometric determinations. The last option is highly

recommended. It should be considered that, even if olfactometry may appear as an expensive and difficult to apply technique, its acceptance has been growing worldwide since a standard methodology exists (EN 13725), being present in odor regulations of many countries.

OIP indicates the number of sample dilutions with clean air needed to obtain an odor concentration not detectable by human nose and thus, the volume of clean air necessary to dilute the sample under its odor threshold value related to the functional unit selected.

However, when a waste treatment plant is analyzed, enough sampling and measuring must be performed to overcome variability in gaseous emissions and reduce uncertainty in OIP results. This recommendation can be extended to other types of odor sources.

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References

- 3M Occupational Health and Environmental Safety Division (2010) Respirator Selection Guide. <http://www2.lbl.gov/ehs/chsp/html/OdorThresholds-3MRespiratorSelectionGuide.pdf>. Accessed 15 December 2015
- Adani F, Calcaterra E, Malagutti L (2001) Preparation of a test for estimating biogas production from pretreated urban waste. In: Christensen TH, Cossu R, Stegman R (eds.) The Sustainable Landfill, Eighth International Waste Management and Landfill Symposium, S. Margherita Di

Pula, Cagliari, Italy. CISA, Cagliari, pp 571–577

Alfonsín C, Hernández J, Omil F, Prado OJ, Gabriel D, Feijoo G, Moreira MT (2013) Environmental assessment of different biofilters for the treatment of gaseous streams. *J Environ Manage* 129: 463-470

Bokowa AH (2010) Review of odor legislation. *Chemical Engineering Transactions* 23: 31-36

Bokowa AH (2012) Ambient odour assessment similarities and differences between different techniques. *Chemical Engineering Transactions* 30: 313-318

Brattoli M, de Gennaro G, de Pinto V, Demarinis Loiotile A, Lovascio S, Penza M (2011) Odour Detection Methods: Olfactometry and Chemical Sensors. *Sensors-Basel* 11: 5290-5322

CEN Standard 13725 (2003) Air quality—determination of odor concentration by dynamic olfactometry. European Committee for Standardization, Brussels, Belgium

Capelli L, Sironi S, Del Rosso R, Guillot JM (2013) Measuring odours in the environment vs. dispersion modelling: A review. *Atmos Environ* 79: 731-743

Clayton GD, Clayton FE (eds) (1981). *Patty's Industrial Hygiene and Toxicology: Volume 2A, 2B, 2C: Toxicology*. 3rd ed. John Wiley & Sons, New York

Colón J, Cadena E, Pognani M, Barrena R, Sánchez A, Font X, Artola A (2012) Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. *Energ Environ Sci* 5: 5731-5741

Curren J (2012) Characterization of odor nuisance. PhD dissertation. University of California Los Angeles. <http://www.wcsawma.org/wp-content/uploads/2012/11/JMC-dissertation.pdf>. Accessed 15 December 2015

Defoer N, De Bo I, Van Langenhove H, Dewulf J, Van Elst T (2002) Gas chromatography–mass spectrometry as a tool for estimating odor concentrations of biofilter effluents at aerobic composting and rendering plants. *J Chromatograph A* 970: 259–273

Devos M, Patte F, Rouault J, Laffort P, van Gemert LJ (1990) Standardized Human Olfactory

Thresholds, IRL Press, Oxford

Dincer F, Muezzinoglu A (2006) Chemical characterization of odors due to some industrial and urban facilities in Izmir, Turkey. *Atmos Environ* 40: 4210–4219

Dreyer L, Hauschild M, Schierbeck J (2006) A framework for social life cycle impact assessment. *Int J Life Cycle Ass* 11: 88–97

Eitzer B (1995) Emissions of volatile organic chemicals from municipal solid waste composting facilities. *Environ Sci Technol* 29: 896–902

European IPPC Bureau (2006) Reference Document on Best Available Techniques for the Waste Treatments Industries. http://eippcb.jrc.ec.europa.eu/reference/BREF/wt_bref_0806.pdf.

Accessed 15 December 2015

Fazzalari FA 1978 Compilation of odor and taste threshold values data. American Society for Testing and Materials, Philadelphia

Feilberg A, Bildsoe P, Nyord T (2015) Application of PTR-MS for measuring Odorant Emissions from Soil Application of Manure Slurry. *Sensors-Basel* 15: 1148-1167

Font X, Artola A, Sánchez A (2011) Detection, Composition and Treatment of Volatile Organic Compounds from Waste Treatment Plants. *Sensors-Basel* 11: 4043-4059

Gostelow P, Parsons S, Stuetz R (2001) Odor measurements for sewage treatment works. *Water Res* 35: 579–97

Haug R (1993). *The Practical Handbook of Composting Engineering*. Lewis Publishers, Boca Raton, Florida

Heijungs R, Guinée J, Huppes G, Lankreijer R, Udo de Haes H, Wegener Sleeswijk A, Ansems A, Eggels P, Van Duin R, De Goede H (1992) *Environmental life cycle assessment of products. Guide and backgrounds*, CML, Leiden, Holland

Hobbs P, Misselbrook T, Pain B (1995) Assessment of odors from livestock wastes by a photoionization detector, an electronic nose, olfactometry and gas chromatography–mass

spectrometry. *Journal of Agricultural Engineering Research*, 60: 137–144

International Organisation for Standardisation. ISO 14040 (2006) Environmental management. Life cycle assessment—principles and framework. Geneva

Komilis D, Ham R, Park J (2004) Emission of volatile organic compounds during composting of municipal solid wastes. *Water Res* 38: 1707–1714

Laor Y, Parker D, Page T (2014) Measurement, prediction, and monitoring of odors in the environment: a critical review. *Rev Chem Eng* 30: 139-166

Lehtinen J, Veijanen A (2011) Odour Monitoring by Combined TD–GC–MS–Sniff Technique and Dynamic Olfactometry at the Wastewater Treatment Plant of Low H₂S Concentration. *Water Air Soil Pollut* 218: 185–196

Mao IF, Tsai CJ, Shen SH, Lin TF, Chen WK, Chen ML (2006) Critical components of odors in evaluating the performance of food waste composting plants. *Sci Total Environ* 370: 323–329

Marchand M, Aissani L, Mallard P, Béline F, Réveret JP (2013) Odor and Life Cycle Assessment (LCA) in Waste Management: A Local Assessment Proposal. *Waste Biomass Valori* 4 : 607–617

Maulini-Duran C, Artola A, Font X, Sánchez A (2013) A systematic study of the gaseous emissions from biosolids composting: Raw sludge versus anaerobically digested sludge. *Biores Technol* 147: 43-51

Nagata Y (2003) Measurement of odor threshold by triangle odor bag method. In *Odor measurement review*. Office of Odor, Noise and Vibration, Environmental Management Bureau, Ministry of environment. http://orea.or.jp/en/PDF/Odor_Measurement_Review,.pdf. Accessed 15 December 2015

Nicolas J, Cerisier C, Delva J, Romain AC (2012) Potential of a network of electronic noses to assess the odour annoyance in the environment of a compost facility. *Chemical Engineering Transactions* 30: 133-138

Orzi V, Cadena E, D'Imporzano G, Artola A, Crivelli M, Davoli E, Adani F (2010) Potential odor emissions measurement in organic waste during anaerobic digestion: Relationship with process and biological stability parameters. *Biores Technol* 101: 7330–7337

Pennington DW, Potting J, Finnveden G, Lindeijer EW, Jolliet O, Rydberg T, Rebitzer G (2004) Life cycle assessment (Part 2): Current impact assessment practise. *Environ Int* 30: 721–739

Peters GM, Murphy KR, Adamsen APS, Bruun S, Svanström M, ten Hoeve M (2014) Improving odour assessment in LCA-the odour footprint. *Int J Life Cycle Ass* 19: 1891-1900

Rappert S, Müller R (2005) Odor compounds in waste gas emissions from agricultural operations and food industries. *Waste Manage* 25: 887-907

Rosenfeld PE, Suffet IH (2004) Understanding odorants associated with compost, biomass facilities, and the land application of biosolids. *Water Sci Technol* 49: 193-199

Sarkar U, Longhurst PJ, Hobbs SE (2003) Community modelling: a tool for correlating estimates of exposure with perception of odor from municipal solid waste (MSW) landfills. *J Environ Manage* 68: 133-140

Scaglia B, Orzi V, Artola A, Font X, Davoli E, Sanchez A, Adani F (2011) Odours and volatile organic compounds emitted from municipal solid waste at different stage of decomposition and relationship with biological stability. *Biores Technol* 102: 4638-4645

Séverine G, Cécile H, Vincent P (2005) The elimination of odours resulting from a process of treatment of sewage sludge by biofiltration. In *Biotechniques for air pollution control: proceedings of the international congress Biotechniques for Air Pollution Control*. A Coruña, Spain.

Schauberger G, Piringer M, Knauder W, Petz E (2011) Odour emissions from a waste treatment plant using an inverse dispersion technique. *Atmos Environ* 45: 1639-1647

Sironi S, Capelli L, Céntola P, Del Rosso R (2007) Development of a system for the continuous monitoring of odors from a composting plant: Focus on training, data processing and results

- validation, methods. *Sensors Actuat B-Chem* 124: 336-346
- Tepe N, Yurtsever D, Mehta R J, Bruno C, Punzi VL, Duran M (2008) Odor control during post-digestion processing of biosolids through bioaugmentation of anaerobic digestion. *Water Sci Technol* 57: 589-594
- Tsai C, Chen M, Ye A, Chou M, Shen S, Mao I (2008) The relationship of odor concentration and the critical components emitted from food waste composting plants. *Atmos Environ* 42: 8246–8251
- Van Gemert LJ (2003) *Compilations of Odour Threshold Values in Air, Water and Other Media*. Boelens Aroma Chemical Information Service. Huizen, The Netherlands
- Woodfield M, Hall D (eds.) (1994) *Odour measurement and control—an update*. AEA/CS/REMA-38, AEA Technology—National Environmental Technology Centre, Oxfordshire
- Wu C, Liu J, Yan L, Chen H, Shao H, Meng T (2015) Assessment of odor activity value coefficient and odor contribution based on binary interaction effects in waste disposal plant. *Atmos Environ* 103: 231-237