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A Unique Approach of Using the Odor Profile Method and Persistency Curves to Evaluate Odor Nuisance

A dissertation submitted in partial satisfaction of the requirements

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in

Environmental Health Science

by

Yuge Bian

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ABSTRACT OF THE DISSERTATION

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Yuge Bian

Doctor of Philosophy in Environmental Health Science

University of California, Los Angeles, 2021

Professor Irwin Suffet, Chair

Odor complaints have become the majority of all air quality complaints in recent years. Evaluating an odor nuisance requires sensory analyses to determine the cause of the problem; and chemical analyses to control the problem since chemicals cause odors. The best choice of sensory methods is the Odor Profile Method (OPM), using an Odor Wheel to identify the odor(s). The best choice of chemical analysis is based upon the chemicals that caused the perceived odors and were identified by the odor wheel.

The OPM can determine odor character, intensity, frequency, and duration for each odor within an odorous mixture at a specific time and location. The OPM is based upon the Weber-Fechner law that states:

Odor Intensity = k Log (concentration of the chemical(s) causing the odor) + b

Persistency curves can determine odor persistence upon dilution. Persistency curves include two types, the Weber-Fechner Curve and the Odor Dilution Curve. Weber-Fechner curve indicates the persistence of each odorous compound and the Odor Dilution Curve indicates the persistence of each odor type that are perceived in an odor mixture.

An odor panel using the OPM has successfully evaluated if the closure of a Landfill from 6-9 AM has minimized the odor complaints related to this Landfill. The OPM results have shown the odor characters of the possible odors produced by the Landfill to be rancid, rancid-sweet, rotten vegetable, and sewery/fecal. The intensities of these odor characters were between 1 - 4. Only 1.3% of the samples produced an odor related to the Landfill, and the duration of odor events was all less than 40 minutes.

Reproduction of the Weber-Fechner curves of the selected six odorants was done by four panelists. The determined Weber-Fechner curves were similar to the previous study, but the regression lines were not identical. The determined Weber-Fechner curves were used as the reference for the same panelist to understand odor persistency at the Energy Development Facility. The Odor Dilution Curve at the EDF biofilter confirmed the information provided by the Weber-Fechner curves. The musty odor (caused by IPMP, MIB etc.) dissipates slower than the fecal odor (caused by skatole, indole, etc.) and the sulfur odor (caused by dimethyl sulfide, dimethyl disulfide, etc.). The masking effect that the musty odor was covered by sulfur odor and fecal odor also can be explained by the cross-over of Weber-Fechner curves. The slope, k of the Weber-Fechner curves upon dilution of each odor type using the OPM method can provide an insight into the persistency of each specific odorant. This information was used to evaluate the performance of an odor masking agent. Lower k value, higher application concentration or application at a further distance of the masking agent might solve the poor performance of the odor masking agent.

An odor attribution study was conducted to evaluate three facilities: an Energy Development Facility, a Resource Recovery Park and a Wastewater Treatment Plant. Results of the OPM data only shown one out of three facilities has consistency between the air sample from the inside locations of the facility with the air sample from the downwind location. The Odor Dilution Curve results showed that with higher dilution ratios, most of the odor characteristics disappeared. However, in some locations, the Odor Dilution Curve showed the unmasking effect of musty odor. The musty odor was not detected at the OPM level or at the lower dilutions but started to appear after the higher intensities of fecal, rancid or rotten vegetable odor have disappeared. The Odor Dilution Curves successfully predict odor types that were not shown buy the OPM. The comparison of the Odor Activity Value data and the OPM data proved that OPM as a sensory method works well on telling odor characters and intensities. However, not all the data correlate with each other due to the unknown synergistic or antagonistic effect for odor mixtures.

Above all, it has been proved that using only chemical analysis or only odor sensory data is not enough. The combination of the two should be performed for any type of odor attribution study. The OPM have provided predictions on odor nuisances from the source level, the Weber-Fechner curves have provided predictions on the persistence of an odorant and gave valuable suggestion on masking agent selection. Odor Dilution Curves have provided odor predictions at the level of the receptors. This thesis, for the first time, have used the OPM, the Persistency Curves and the combination of the two to evaluate odor nuisance.

The dissertation of Yuge Bian is approved.

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University of California, Los Angeles

2021

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List of Acronyms.

D/T	Dilution TO Threshold
DMDS	Dimethyl Disulfide
DMS	Dimethyl Sulfide
EDF	Energy Development Facility
FPA	Flavor Profile Analysis
GC/MS	Gas chromatography/mass spectrometry
IPMP	2-Isopropyl-3-methoxypyrazine
LG	Landfill Gas
MIB	2-Methylisoborneol
OAV	Odor Activity Value
OCSD	Orange County Sanitation District
OPM	Odor Profile Method
OTC	Odor Threshold Concentration
RRP	Resource Recovery Park
SCAQMD	South Coast Air Quality Management District
TR	Trash Odor
WWTP	Waste Water Treatment Plant

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CONFERENCE PRESENTATIONS

Yuge Bian, Fuqiang Liu, Irwin Suffet. Characteristics of Nuisance Odor Emissions from the Sludge Drying Process. WEF Residual and Biosolid conference, 2018, Phenix, AZ, USA

Yuge Bian, Haoning Gong, Irwin Suffet. Monitoring of Landfill Nuisance Odors at an Off-Site, Odor-Impacted Location using an "Odor Patrol" Panel. IWA Odor & VOC air emission conference, 2019, Hangzhou, China

Chapter 1

Introduction and Objectives

1.1 Introduction

From 2000 to 2018, odor complaints have become the majority of the total air quality complaints, as exemplified in **Figure 1.1** for the South Coast Air Quality Management District (SCAQMD), (SCAQMD, 2019). Understanding the odor description, odor intensity, odor frequency, odor duration, and odor persistency is a significant challenge for evaluating odor complaints. Understanding odor measurements has been complicated because the research and application have occurred in independent and disconnected research fields (Muñoz et al., 2010). There are various approaches worldwide, and each approach produces a different level of success (Brancher et al., 2017).

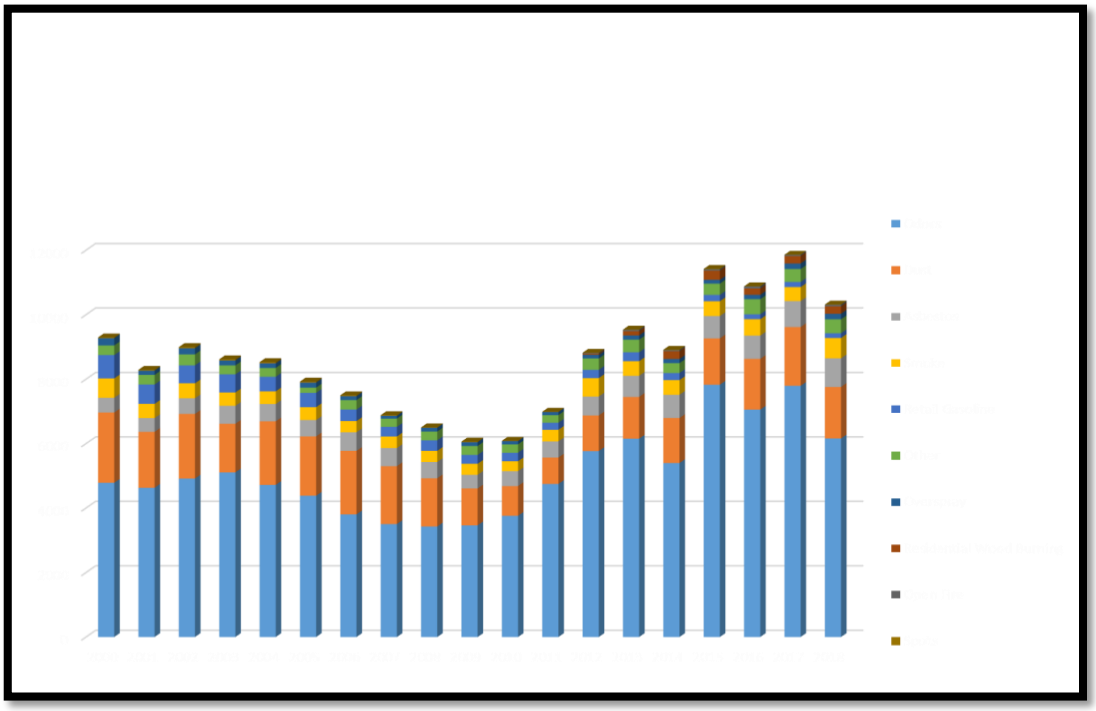

Figure 1.1. Air quality complaints received by the South Coast Air Quality Management District (SCAQMD), 2000 – 2018 (SCAQMD, 2019)

One method for odor description is odor hedonic tone, also known as the acceptability of the odor, and is a highly subjective approach. A scoring system by Dravnieks (1984) simply describes pleasant odor with a higher number and unpleasant odor with a lower number. The hedonic tone value does not provide information on each odor's description or intensity. When an odor nuisance occurs, it is confirmed chiefly as an unpleasant odor even without the use of a hedonic tone.

A new technology that has developed and is often referred to as electronic nose (E-nose) (Br, 2019) The E-nose relies on a set of non-specific gas-sensor adsorption arrays that are sensitive to different odors or a mixture of odors to try to mimic the human sense of smell. However, studies have shown that the prediction ability of E-nose is not perfect. For example, a study used E-nose to sense the odor produced during the raising of chickens. The array of sensors did well in a chicken shed; however, outside the chicken shed, the results were not satisfactory (Atzeni et al., 2016). Thus, the E-nose appears to works only where it is used for a constant odor mixture but cannot be used over a wide range of different environmental odors (Schueze et al., 2017).

The current approach for analyzing odor problems is the Dilution to threshold (D/T) method (ASTM E679, 2011; EN13725, 2003; ASTM E544, 2010). An Olfactometer is used to evaluate the total odor. Olfactometry describes the dilution ratio needed for the total odor to disappear and is reported in odor units (OU). The D/T value does not indicate odor characters or each distinct odor's intensity and only serves as an estimate of the severity of the total odor. Various studies have shown the ineffectiveness of dilution to threshold method. The panelist perceived some environmental odors but could not be measured by dynamic dilution olfactometry (Guillot et al., 2012). Some countries, such as Switzerland, prefer not to use the D/T method but using the questionnaires and complaints (Lebrero et al., 2011). For the drinking water industry, dilution-to-threshold limits did not resolve underlying taste-and-odor problems and correlated poorly with customer complaints (Suffet et al., 2013).

If a single odorant is responsible for an odor, chemical analysis can be the most appropriate method to use. However, in an environment of mixed odorants, Schiffman et al. (2001) found that the concentration of a mixture of detected odorants at a pig farm was low, but the odor nuisance was high. Thus, chemical identification of the compounds alone in an air mixture can neither indicate odor nuisance levels nor indicate which odorants contribute the most to the odor nuisance.

Recently, researchers have started to use both sensory and analytical measurements to support their study of the odor problems. One approach is the Odor Activity Value (OAV) (Feilberg et al., 2010), which uses the measured concentration of one odorant divided by the odor threshold concentration of that odorant. OAV can determine the odorant(s) that have the most significant potential of generating the highest intensity of the odor nuisance from an odor mixture but does not indicate the specific odor perceived.

The Odor Profile Method was developed based on the Flavor Profile Analysis from the food and fragrant industry (Caul, 1956). This method has been successfully used since 1992 in the drinking water industry as Standard Method 2170 (APHA, AWWA and WPCF, 1992). The OPM began to be used for air analysis studies by Burlingame (1999), Burlingame al. (2003), Burlingame (2009) and Curren et al. (2014). The OPM includes (1) identifying one or more odor notes in the air sampled using an appropriate odor wheel of probable odor notes and (2) determining the odor intensity for each odor note. The OPM helps determine what odors are present in that total odor and which one to select for treatment. The intensity of an odor obtained by the OPM is proportional to the logarithm (base 10) of the concentration of the odorant, based on Weber- Fechner law (Fechner, 1859). The OTC is defined as the concentration when intensity is 1 (I=1) on the Weber-Fechner curve (**Figure 1.2**) (Suffet et al., 1995).

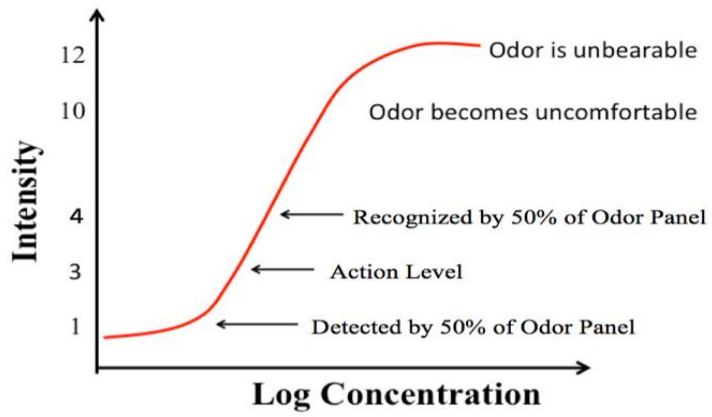

Figure 1.2. Intensity Scale for Each Odor by Weber-Fechner Curve

Previous studies have determined the odor gap between OTC and Method Reporting Limit (MRL) (**Figure 1.3**). An odorant can still cause an odor nuisance when it has a concentration less than its MRL. The odor gap can cause the situation where chemical analysis does not work when determining odor-causing compounds. It may not be possible to evaluate odor through chemical analysis if the impacted area is far from the emission source as the concentration of the odorants decreased with distance or air dilution. In these situations, using an odor panel following the OPM practice is the most applicable approach.

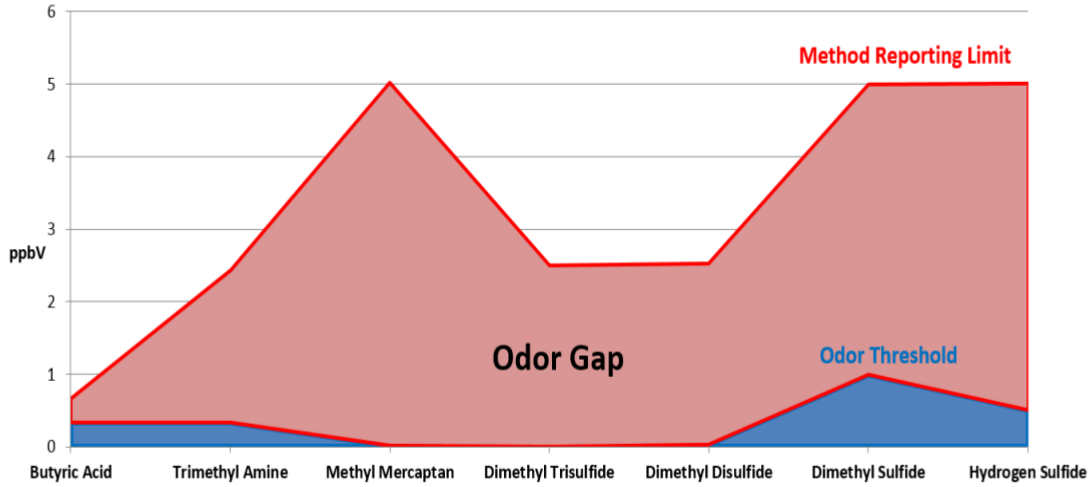

Figure 1.3 MRL vs. OTC for Seven Odorants (Zhou et al., 2017)

Various studies have evaluated the performance of odor masking agents. The masking performance is evaluated by chemical detection of the change of concentration of reduced sulfur compounds (Choi et al., 2012). However, analyzing reduced sulfur compounds is not equivalent to odor evaluation. Thus, the relationship between the Weber-Fechner curves of odor masking agents and odorous compounds should be examined to illustrate this problem. However, since the sensitivity of odor varies from person to person, results from previous studies should not be directly used. Thus, OTCs for six common detected odorants from OCSD WWTPs (Zhou et al., 2017) were re-evaluated. The OPM aims to detect odor character only at a specific location. Persistency curves for an odor mixture can provide supporting information on odor persistency at a further distance. The persistency curve can also show if there is a masking/unmasking effect that is typical for an odor mixture due to odor synergistic or antagonistic effects.

If the analysis is for pharmaceuticals, pesticides of different types or disinfection byproducts, you select the problematic chemicals to measure. Otherwise, one should not measure everything and get confused about what you want to find out. Therefore, for an odor study, one should select the odorants to measure. In order to save time and money, an odor wheel should be used in advice to determine potential compounds that may cause the odor problem (e.g., Wastewater odor wheel, landfill odor wheel, compost odor wheel etc.). Then measure the important ones using chemical analysis. These procedures have been done in the drinking water industries of identifying the odor-causing agents (Suffet et al., 2019). Thus, the best choice of sensory methods is the Odor Profile Method using an Odor Wheel to identify the odor(s). The best choice of chemical analysis is based upon the chemicals that have been identified by the odor wheel that might cause the perceived odor(s).

1.2 Objectives

This dissertation aimed to establish a unique approach to evaluate odor nuisance problems from different situations and odor sources. The detailed objectives of this study were to:

- Evaluate if an odor panel using the OPM can determine odor character, odor intensity, odor frequency and duration of odor nuisance; and support the odor complaint data.
- Evaluate the Weber-Fechner curves to understand odorant's persistence and its value on odor mixture persistency explanation and odor masking agent selection when solving an odor nuisance problem.
- Determine the use of odor mixture persistency curves to observe odor masking and the unmasking effect caused by dilution of an odor mixture is as it moves from the source.

- Compare the OAV with OPM to determine the relationships between these two methods and provide guidance on proper methods for odor nuisance evaluation.

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Chapter 2

The Use of the Odor Profile Method with an "Odor Patrol" Panel to Evaluate an Odor Impacted Site Near a Landfill

2.1 Abstract

A third-party-trained "Odor Patrol" program was conducted at a school that is about a one-mile distance from a landfill to clarify the odor nuisance problems from the landfill. Every 20 min from 6 to 9 a.m. on school days, the "Odor Profile Method" (OPM) was used with the landfill odor wheel to identify the odor type and intensity of each odor type. This study showed that an Odor Patrol using the OPM can accurately define odor nuisance changes over time and can be used as a method to confirm changes of odor nuisances in a field study. The Odor Patrol only found 13 data inputs of the 1000 data inputs (1.3%) for the 100-day odor monitoring with a landfill odor or trash odor that could cause odor complaints. The Odor Patrol data and the Odor Complaint data compared well. The OPM by an "Odor Patrol" could determine the contribution of the nuisance odors from 6 to 9 a.m. at the school site, about one mile away from the landfill. The study demonstrated a novel approach for odor monitoring by using the Odor Profile Method with an Odor Patrol. The OPM not only confirmed the mitigation of a landfill odor problem, but it also determined odor character, odor intensity, odor frequency and odor duration during this study period. "Landfill gas" was determined to be primarily a rotten vegetable odor with a secondary sewery/fecal odor of lower intensity, and "trash odors" were primarily a rancid and sweet odor with a secondary sewery/fecal and/or rotten vegetable odor of lower intensities generated from trash reaching the landfill. The order of intensity observed from high to low was: Trash odor (Rancid–Sweet) > Rotten vegetable > Sewery/Fecal > Rancid. Thus, trash odor is the prominent problematic odor from the landfill site. Quality assurance methods were used to remove local odors from the evaluation.

2.2 Introduction

Since 2009, California's South Coast Air Quality Management District (SCAQMD) has seen a dramatic increase in the number of complaints related to nuisance odors from a landfill. This landfill processes one-third of the daily waste from Los Angeles County per day. This is about 8,300 tons of waste daily or more than 2.3 million tons annually. The landfill primarily accepts trash that has been separated from other waste streams, such as green wastes, metals and plastics.

The current approach for analyzing odor problems is the Dilution to threshold (D/T) method (ASTM E679, 2011; EN13725, 2003; ASTM E544, 2010). The D/T value does not indicate odor characters or each distinct odor's intensity and only serves as an estimate of the severity of the total odor. Various studies have shown the ineffectiveness of dilution to threshold method. The panelist perceived some environmental odors but could not be measured by dynamic dilution olfactometry (Guillot et al., 2012). For the drinking water industry, dilution-to-threshold limits did not resolve underlying taste-and-odor problems and correlated poorly with customer complaints (Suffet et al., 2013). Some countries, such as Switzerland, prefer not to use the D/T method but using the questionnaires and complaints (Lebrero et al., 2011). The SCAQMD method for odor detection relies on counting consumer complaints and sending an odor inspector to investigate the odor problem at the complaint location. When the consumer complaints reach an excessive number, and the odor inspectors verify these, SCAQMD considers it an odor nuisance problem.

Figure 2.1 shows the Odor Complaint history between 6 and 9 a.m. in an area about a mile away from the landfill between 2008 and 2018 (Tseng et al. 2018). **Figure 2.1** shows that thousands of complaints were most frequently received between 6 and 9 a.m. on weekdays.

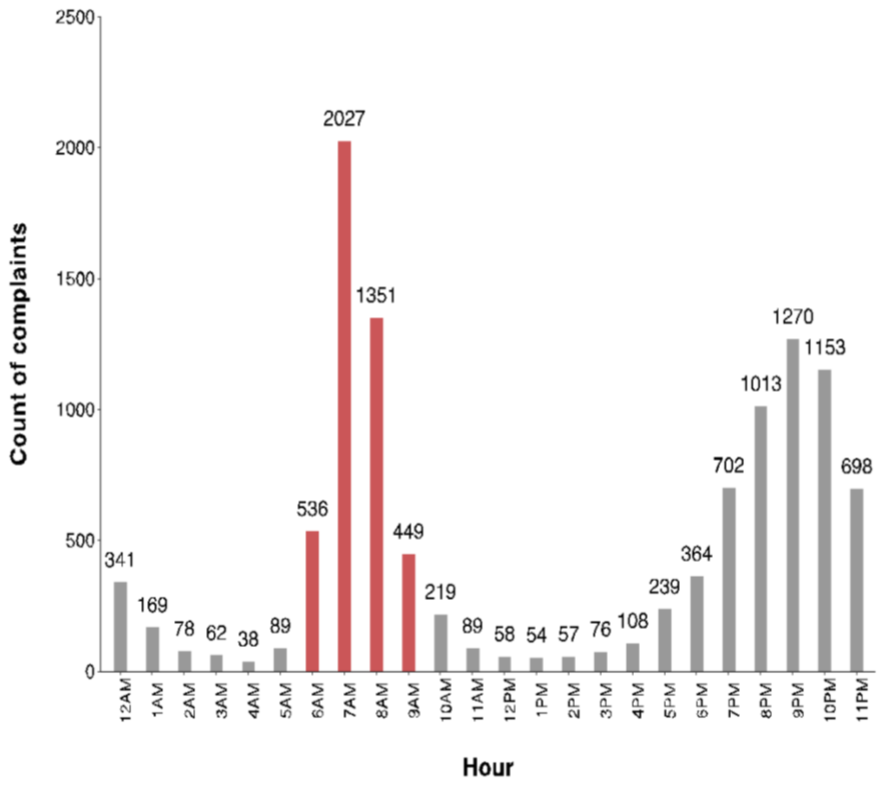

Figure 2.1. Odor complaints from January 2008 to April 2018 near the school site (Tseng et al., 2018).

There were some concerns related to the complaint data. The general population has not been trained with professional knowledge about identifying odors. Thus, they might be mistaking other environmental odors from the surrounding area with the odors from the landfill. The population may make false odor reports because of ongoing odor concerns. The inspectors developed a general knowledge of the source of odors characteristics as landfill gas and trash odor. However, they were not professionally trained to characterize multiple odor characteristics such as rancid and sweet at a site, unlike the food and drinking water professional panelists, who use a standard method: Flavor Profile Analysis (FPA) (Lawless et al., 2010; Ricet et al., 2017). The inspectors did not have an odor intensity scale to rate the intensity of each odor characteristic. Additionally, another primary concern was the duration of an odor event. The residents might not be observing an odor simultaneously as when an inspector arrives at the complaint site.

SCAQMD required the landfill not to accept waste between 6 and 9 a.m. on weekdays due to many complaints. SCAQMD decided that a Third-Party Odor-Monitoring Program should be conducted at the school site from 30 October 2017 to 2 May 2018 (100-week days) to evaluate the effects of closing the landfill between 6 and 9 a.m. weekdays. The Odor Monitoring Program selected a human panel called an "Odor Patrol" that used the unique "Odor Profile Method" (OPM) (Burlingame, 1999, 2003, 2009; Curet et al., 2014) for air analysis based upon the well-documented Flavor Profile Analysis (Lawet et al. 2010; Rice et al., 2017) that uses trained odor professionals.

The objectives of the study were:

1. Determine if the "Odor Profile Method" by an "Odor Patrol" can evaluate the odor nuisance caused by a particular odor source: i.e., determine the odor character, odor intensity of each odorant and determine the frequency and duration of the odor problem.
2. Can the "Odor Profile Method" by an "Odor Patrol" be used to determine if the landfill's closure between 6 and 9 a.m. can minimize odor complaints at an impacted site about one mile away?

The novelty of this study is the use of OPM to describe the odors and the intensity of each odor that can be defined as being from a landfill.

2.3 Methods

2.3.1 Odor Profile Method

The Odor Profile Method was based upon the FPA method for the food and drinking water industries, specifically Method 2170, the "Flavor Profile Analysis" of "Standard Methods of Water and Wastewater" (Rice et al., 2017). The FPA has a 7-level sugar scale for the intensity of an odorant. The FPA was developed for the headspace of drinking water. It has been used for over 30 years and it is a standard method to evaluate odor problems and to serve as a quality control for specific odors in drinking water. The method was developed for air analysis studies by Burlingame (Burlingame, 1999), Burlingame et al. (Burlingame et al., 2003), Burlingame (Burlingame, 2009) and Curren et al. (Curren et al., 2014). The landfill odor wheel (**Figure 2.2**) was used to identify each odor type and intensity (Decottignie et al., 2009). Training and quality assurance measures were used (Wittet al. al, 1968).

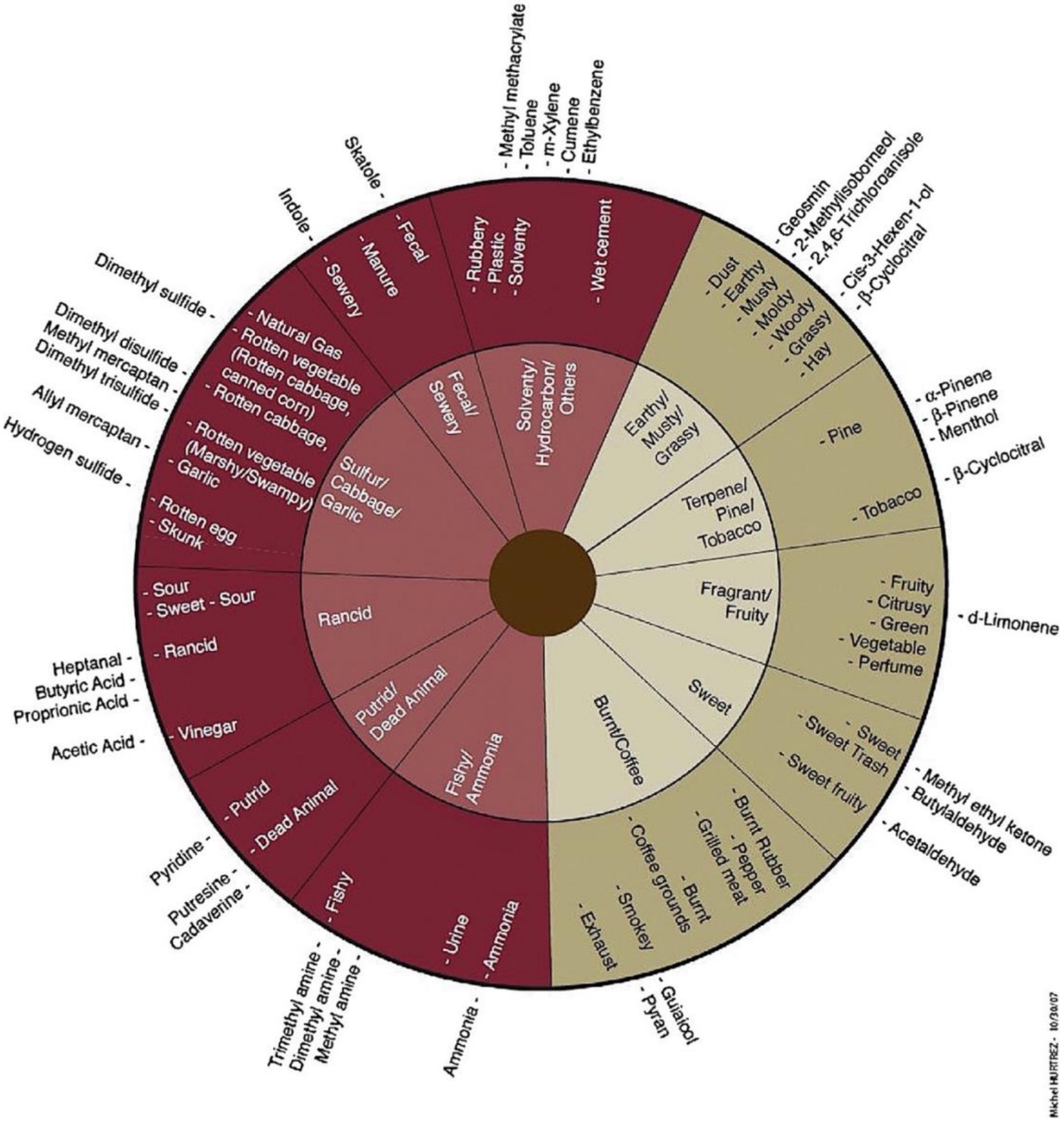

Figure 2.2. Landfill Odor Wheel (Decottignie et al., 2009).

The OPM includes (1) identifying one or more odor notes in the air sampled and (2) determining the odor intensity for each odor note (Burlingame, 1999, 2003, 2009; Curren et al., 2014). The OPM method includes:

- Screening panelists for anosmia (lack of the sense of smell) using a "scratch-n-sniff" test (Doty et al., 1984).
- Using a minimum of four trained panelists of the ten trained panelists for each OPM sample evaluation.
- Training odor panelists with the primary odorants of an odor wheel and mixtures of 2, 3 and 4 of these standard odorants over six weeks. Additionally, including training panelists on the background odors that could be found around the school as grassy.
- Teaching a standardized odor note vocabulary to panelists using the "landfill "odor wheels" (**Figure 2.2**) that consist of three rings: an inner ring of general odor categories, a middle ring of specific odor notes within each segment and an outer ring of known or potential odorants associated with each odor note.
- Panelists are calibrated to the odor intensity scale (Table 1)—threshold (1), slight (2), weak (4), medium (6), medium-strong (8), strong (10) and very strong (12)—using sugar-in-water solutions tasted by mouth that represent weak (5% sugar), medium-strong (10% sugar) and very strong (15% sugar) as defined by the FPA method (3).
- Group discussions are permitted after the individual odor evaluations to help panelists define their responses; however, panelists are ultimately instructed to work independently.
- Overall panel results for an "odor note" (an odor character with an associated odor intensity) require at least 50% agreement among panelists. The odor notes are calculated as the panel average mean with a standard deviation reported. If a panelist does not report the odor note, a zero is included in the calculation of the mean.
- If less than 50% of the panel agrees on an odor note, an "other odor note" is stated without an odor intensity.

Table 2.1. Flavor Profile Analysis: Odor Intensity Strength Scale (Burlingame et al., 2003).

Intensity Rating	Flavor Standard (% Sugar in Water)	Intensity Description
0	0	No odor
1	Threshold	Can detect odor but cannot describe the odor character
2	Very Weak	Odor barely perceptible
3	Recognized	Action Level
4	5	Odor clearly exists but takes time to describe
6	Weak–Moderate	Odor readily perceived and identified
8	10	Odor is uncomfortable to smell for extended periods of time
10	Moderate–Strong	Odor is uncomfortable to smell for extended periods of time
12	15	Odor is unbearable to smell for even short periods of time

The OPM intensity scale is based upon the Weber–Fechner Law (Fechner, 1859), in which a single odorant's intensity is proportional to the Log of the odorant's concentration.

$$\text{Odor Intensity} = k \text{ Log (Concentration)} + b$$

Whereas the concentrations are units such as ppb or µg/m^3, and k is a constant (called the Weber–Fechner coefficient) that is unique to each odorant. **Figure 2.3** shows the relationship between Odor Intensity and the Log (Concentration). The odor level of detection (1) and recognition (4) of the odor name are shown. An action level of 3 below recognition is suggested to minimize an odor problem.

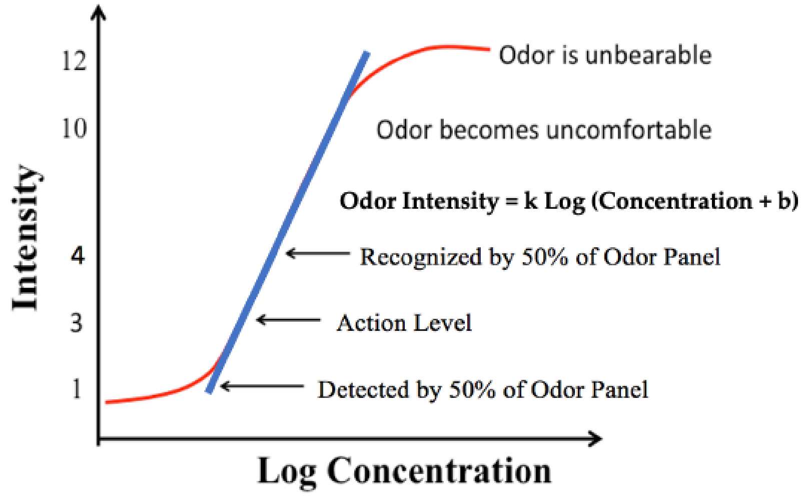

Figure 2.3. Weber–Fechner curve showing intensity vs. concentration. Note: The straight line represents the Weber–Fechner Law.

2.3.2 Odor Profiling Method vs. European Standard 16841–1:2016

The European Standard EN 16481-1: 2016 (CEN. EN 16841-1:2016, 2016) describes a grid field inspection method that uses a direct assessment of ambient air by trained panel members to characterize odor exposure in a defined area. The panelists determine whether they recognize an odor note selected from a list. The panelists write down their observations every 10 s for 10 min (60 observations). If six of those observations are a recognized odor note, then the label "odor hour" is applied (although not a full hour of odor exposure occurred) (CEN. EN 16841-1:2016, 2016). The frequency of "odor hours" is usually completed for a square of four measurement points that map an area. The grid method has been used to study industrial areas in German cities and provided a representative map of the exposure of the population to recognizable odors (Mannebeck et al., 2016). These studies took six months to one year, each with 21 panelists. Bax et al. (Bax et al., 2020) reviewed the grid field inspection method and stated that the method "cannot be used for the assessment of the odor concentration." Thus, the grid field assessment method can recognize odor notes from a selected list but cannot determine the intensity of each odor note.

Different from the EN 16481-1: 2016, the Odor Profile Method trains panelists to not only recognize odor notes from a selected list, i.e., the odor wheel, but also to detect all odor notes and define an intensity for each odor note. The panel specifies each odor character with its odor intensity. A minimum of four trained panelists is used. If over 50% of the panel agrees on an odor note, the average intensity +/–, a standard deviation, as shown in Tables 2 and 3, was calculated. The intensity is based upon the Odor Intensity Strength Scale (Table 2.1). Thus, the Odor Profile Method can be considered an expansion of the European Standard EN 16481-1: 2016 (CEN., 2016). This paper used the OPM at one location. However, the OPM method can also be used over a grid as well.

2.3.3 Odor Types Related to a Landfill

Reference (Tseng et al., 2018) indicated that during the Odor Patrol time period in the previous year to this study (from 2016 to 2017), "trash odor" was the primary odor. Additionally, a lower intensity, "rotten vegetable" and/or a "sewage/fecal" odor were also identified either from the trash gas or from landfill gas.

- Landfill Gas (LG) is described by the landfill community and inspectors for gases that are produced within the landfill from anaerobic reactions. Landfill gas, according to the Landfill Wheel (**Figure 2.2**), was within the general category (Sulfur/Cabbage/Garlic). Primary landfill gas odors in this category include rotten vegetable, rotten cabbage, and garlic. These odors are caused by the anaerobic production of sulfur compounds by microorganisms using sulfate instead of oxygen as the electron acceptors within the landfill (Higgins et al., 2006) (see **Figure 2.4**). A secondary odor of lower intensity in the Landfill Wheel (**Figure 2.2**) was within the general category (Sewage/Fecal). These secondary odors in this category are also named sewage/fecal. This odor is generated by microorganisms under the same low-oxygen conditions by degrading nitrogen compounds (e.g., proteins) to yield compounds such as indole and skatole, which have a sewery/fecal odor character described in **Figure 2.2**. **Figure 2.5** shows the microbiological origin of these odors (Chen et al., 2006). In this paper this will be referred to as a sewery odor.

- Trash Odors (TRs) are described by the landfill community generically occur when trucks filled with trash are waiting and while dumping trash at the landfill. Although soil is used to cover the trash after it is dumped, the "trash odors" can still escape. Trash Odors, according to the Landfill Wheel (**Figure 2.2**), are within the general categories (Rancid and Sweet). The "trash odor" is primarily "rancid" from the air oxidation of fats to fatty acids. The fatty acids can be further oxidized in air to aldehydes and ketones (**Figure 2.6**). The aldehydes and ketones add a "sweet" note to the "rancid" odor as presented in the "Landfill Odor Wheel" (Rancid and Sweet) general categories (**Figure 2.2**). Secondary odors of lower intensity, "rotten vegetable" and/or "sewage/fecal" odors, are produced from reduced sulfur and nitrogen compounds generated in low-oxygen (anaerobic) pockets by microbes within the load of trash that is transported to the landfill as described in the "landfill gas" odor section.

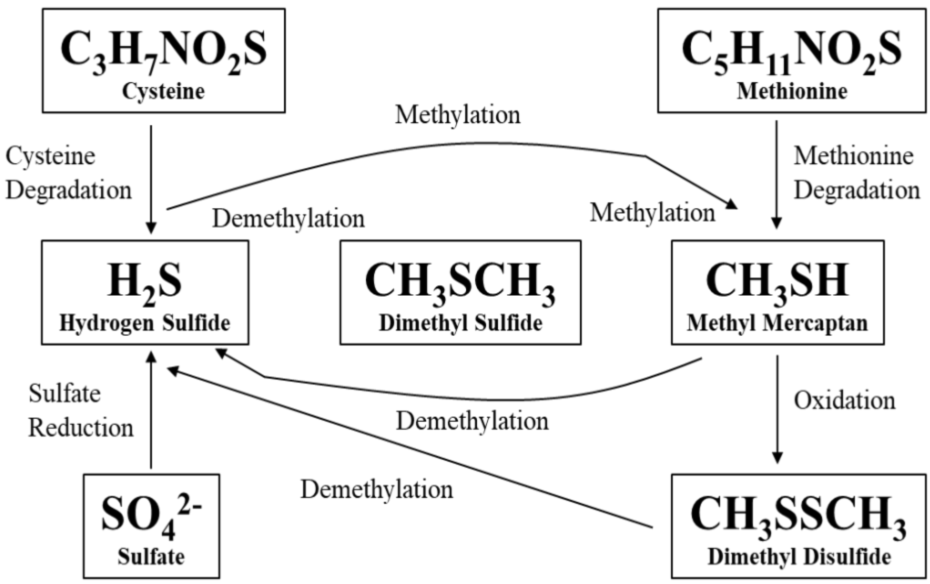

Figure 2.4. Production of odorous volatile sulfur compounds in a landfill. Based upon studies of anaerobically digested biosolids during cake storage (Higgins et al., 2006).

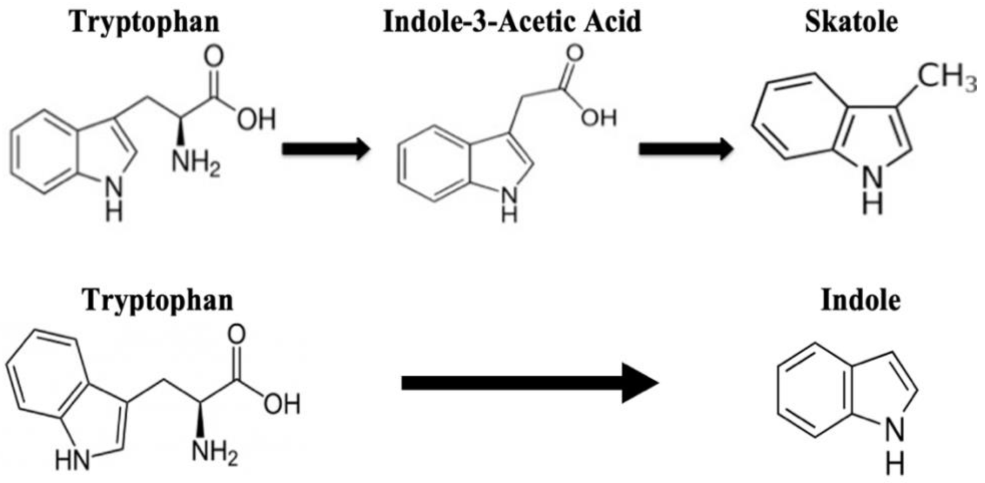

Figure 2.5. Microbial products of landfill gas sewery/fecal odors from amino acids. Based upon studies of anaerobically digested biosolids (Chen et al., 2006).

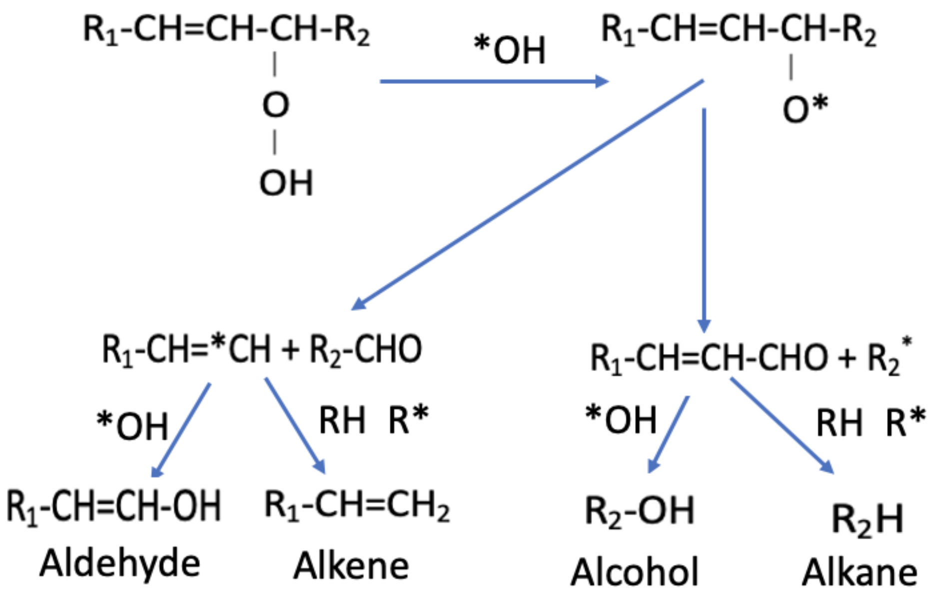

Figure 2.6. Chemical Mechanism of Lipid Oxidation (Kochhar et al., 1996)

2.3.4 Experimental Procedure

The study was conducted from 31 October 2017 to 2 May 2018 for 100 school days (except weekends, holidays and school closing days). OPM analysis was completed in an open area school playground every 20 min from 6 to 9 a.m., e.g., 6:00, 6:20 and 6:40, respectively, to 9:00. Each of the four panelists had their own data sheets. At each sampling time, the panelist logged in their own data without talking to each other. After an average of a 3-minute evaluation, the panel went to an air-conditioned, odor-free room to refresh their sense of smell before the next sampling period. If needed, the panelists discussed the sample results.

A walk around the campus before, during and after the 6–9 a.m. period was performed for the detection of environmental odors. At 9 a.m., as a quality assurance measurement, all panelists were required to open the dumpster outside of the school site, smell it and write down the odor data on their sample sheet. All data sheets were collected each day by the project manager and logged into the computer.

2.3.5 Quality Control

Each panelist was screened for anosmia (lack of the sense of smell) using a "scratch-n-sniff" test (Doty et al., 1984). All of the panelists passed the test with over 70% correct answers, which means they all had a normal sense of smell. Prior to the start date of the study, all panelists went through complete odor training on the Odor Profiling Method. The training included (1) distinguishing different odor categories by a single standard gas sample; (2) distinguishing the different intensities on the odor intensity scale by sugar water standard; (3) distinguishing odor categories from mixed standard gas samples containing 2–3 chemical mixtures. The panelists were required to repeat the training to assure they were confident to identify the odors of importance. The duration of the study was about 5 months. Thus, the panelist completed a refresher training course halfway through the study.

In the air-conditioned classroom where the panelist stayed, no one was permitted to bring food, coffee or anything that smelled. The panelists did not wear perfume or use strongly scented shampoo or body wash. Therefore, panelists returning to the classroom could relax their noses and get prepared for the next sampling time period. Panelists were required to report any nose cold and withdrew from the panel for that day. A stuffed nose dramatically affects the sense of smell.

The odor panel performed" quality control" by monitoring trash odor produced at a covered waste trash container (dumpster) for food waste near the school site. Quality control data were collected after the Odor Patrol data were completed for that day. The odors from the dumpster represented some odors expected from the trash sent to the Sunshine Landfill. These odors are the rancid–sweet and rotten vegetable odors. Thus, this refreshed the Odor Patrol's ability to recognize the odors from the landfill. This also confirmed the claim that if the school is experiencing these odors, they are coming from the trash in the landfill.

The school site is about a 1-mile distance from the landfill site. The odors that can be perceived at this school site are not limited to only the landfill. Many types of environmental odors can affect the school area. Thus, it is critical to distinguish the environmental odors from the targeted odors from the landfill. Therefore, it is noted that the panelists were trained on environmental odors, such as grassy and gasoline. The panelists were required to walk around the perimeter of the school to determine if any odor were from the nearby environment before leaving the school site. Local environmental odors, such as "smoke" during a wildfire in the area, "gasoline" from vehicle and traffic, "grassy" from mowing the lawn in the neighborhood nearby, etc., were not included in the data set.

2.4 Results

2.4.1 OPM Data by the Odor Patrol

Table 2.2 shows the total odor panel results for Week 2 on a weekly data sheet including the background odors. As **Table 2.2** shows, each day of sampling has 10 sample time slots. The yellow highlights are for samples where landfill odors were observed. The legend of **Table 2.2** indicates which odors are the background odor at the site.

Table 2.2. Exemplary Weekly Data Sheet for Week 2

WEEK 2. Odor Characteristics and Intensities of Each Odor Characteristic Observed by the Odor Profile Method Panel					
Sample Location: School Yard - Facing the Landfill Site including background odors that were observed					
		11/6/17	11/7/17	11/8/17	11/9/17
Sample #	Time: AM	ODOR	ODOR	ODOR	ODOR
1	6:00	Other odor notes: musty, fecal, rotten vegetable	Other odor notes: sewery, sweet, lemon, rancid, pine	Rotten vegetable 3.6±2.2, rancid 2.4±1.7. Other odor notes: sweet, detergent	Other odor notes: musty
2	6:20	Other odor notes: musty	Sewery 2.8±3.0, rancid 1.0±0.9; Other odor notes: sweet, pine, rotten vegetable	Other odor notes: rotten vegetable, rancid, sweet, sewery	Other odor notes: musty, rotten vegetable, pine, rancid
3	6:40	Rotten vegetable 2.8±1.1; Other odor notes: pine, grassy, rancid	Other odor notes: sweet, pine, vegetable	Not detected	Other odor notes: rancid, sweet
4	7:00	Other odor notes: pine, grassy	Other odor notes: sweet, pine, gasoline	Not detected	Not detected
5	7:20	Not detected	Grassy 2.0±2.0; Other odor notes: pine	Other odor notes: rotten vegetable	Other odor notes: musty
6	7:40	Not detected	Other odor notes: pine	Not detected	Other odor notes: sweet
7	8:00	Not detected	Other odor notes: sweet, lemon, rancid	Not detected	Not detected
8	8:20	Other odor notes: burnt	Other odor notes: gasoline, detergent, burnt	Not detected	Not detected
9	8:40	Other odor notes: lemon	Other odor notes: sewery, gasoline, burnt	Not detected	Not detected

10	9:00	Other odor notes: grassy, detergent	Other odor notes: pine, musty	Other odor notes: sweet grass	Other odor notes: rancid, sweet, sweet grass, detergent
Weather Condition		Partly cloudy, 72°/53° F	Partly cloudy, 76°/54° F	Cloudy, 77°/51° F	Cloudy, 72°/54° F

	Table 2 Legend: Odor Characteristics - Odor Wheel - Landfill Odor Wheel Used.
	Intensity Scale: 0 - odor free; 1 - threshold, 2 - very weak; 4 - weak - recognition; 6 - moderate, perceived; 8 - moderate. - strong; 10 - strong; 12- very strong
	Odor Profile Method
	Odor Character - Panel Average ± Standard Deviation
	Other Odor Note = < 50% of an odor was reported by the odor panel. This is an odor that should be below a complain level.
	Comments - Odor Notes - Primarily background odors that are not from the landfill
1	Garlic -REAL if after checking suspected odor from the kitchen area, when actually walking toward kitchen
2	Grassy - suspected from a lawn mower operation close to school; could hear the lawn mower machine.
3	Detergent- suspected from cleaning at the school
4	Gasoline- suspected from a truck or car outside of school
5	Musty- usually during cloudy weather, wet ground odor or after a rain event
6	Burnt -during the wildfire period
7	Lemon - from plants possibly
8	Solvent -unknown source at the school
9	Perfume - suspected from teachers, parents or flowers
10	Flowery -from flower blooming near the school
11	Pine - probably from trees nearby school
12	Ammonia - suspected animal urine

Table 2.3 shows only the odor panel sample data when landfill odors were observed during the study from 30 October 2017 to 2 May 2018 (100-week days over 22 weeks). The environmental background odors were not included in these sample results. Only 13 times out of 1000 odor samples evaluated in the 100-week study showed significant landfill-related odors. Each data point shown in **Table 2.3** presents information on the week, date and time of analysis. The values shown under "Odor Character" represent the average odor intensity and the standard deviation for each odor note that was detected by over 50% of the odor panel. For odor characters that were detected by less than 50% of the odor panel an "other odor notes" was recorded without an odor intensity.

Table 2.3. The 13 Odor Panel Sample Data When Landfill Odors Were Observed during the "Odor Patrol Study "of 100 midweek days. Note: environmental background odors were not included in this data set.

13 data points of Significant Landfill Odor Observed			
Week	Date	Time AM	Odor Character
2	6 Nov 2017	6:00	Rotten vegetable 2.8±1.1; Other odor notes: rancid
2	7 Nov 2017	6:20	Sewery 2.8±3.0, rancid 1.0±0.9; Other odor notes: sweet, rotten veg
2	8 Nov 2017	6:40	Rotten vegetable 3.6±2.2, rancid 2.4±1.7; Other odor notes: sweet
6	11 Dec 2017	6:20	Sewery 1.0±1.2
8	17 Jan 2018	7:40	Rancid 1.5±1.9, Other odor notes: sewery, rotten veg
9	22 Jan 2018	6:00	Rancid 2.0±2.8; Other odor notes: sewery
12	12 Feb 2018	7:00	Sewery 1.5±1.9
12	12 Feb 2018	7:20	Sewery 2.0±2.3;
12	13 Feb 2018	7:40	Sewery 2.0±2.3; Other odor notes: rancid
13	21 Feb 2018	7:20	Rotten vegetable 1.0±1.2
17	20 Mar 2018	8:40	Sweet trash 4.0±1.6
17	20 Mar 2018	9:00	Sweet trash 2.5±3.0
19	12 Apr 2018	6:40	Sewery 1.0±1.2

Figure 2.7 shows the time and frequency of the 13 detected odors in **Table 2.3**. For example, the first column shows that between the 6 and 7 a.m. time slot, rancid odor was

detected 3 times, rotten vegetable odor was detected 2 times and sewery odor was detected 3 times. The primary times of observation were 6 and 7 a.m.

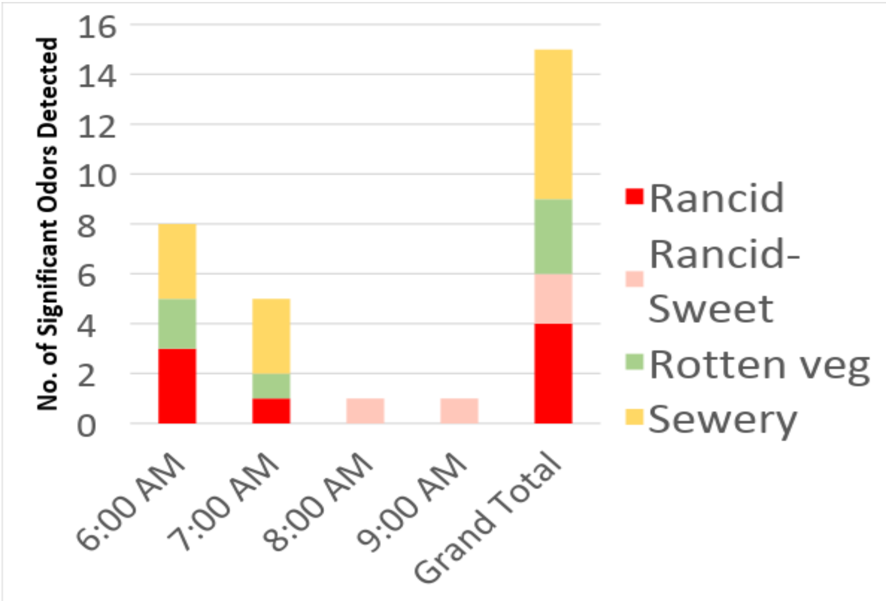

Figure 2.7. Hours of significant odors detected by the Odor Patrol. Note: if two different odors were detected at same time, it is considered two odor events.

Figure 2.8 shows the intensities of landfill odors detected by the Odor Patrol. The intensities of the Trash Odor (rancid), and Landfill Odor (rotten vegetables) and sewery odors predominate. Most of the odors were recorded with intensity between one and four. The order of intensity across types from high to low is: Trash odor (Rancid–Sweet) > Rotten vegetable > Sewery > Rancid alone.

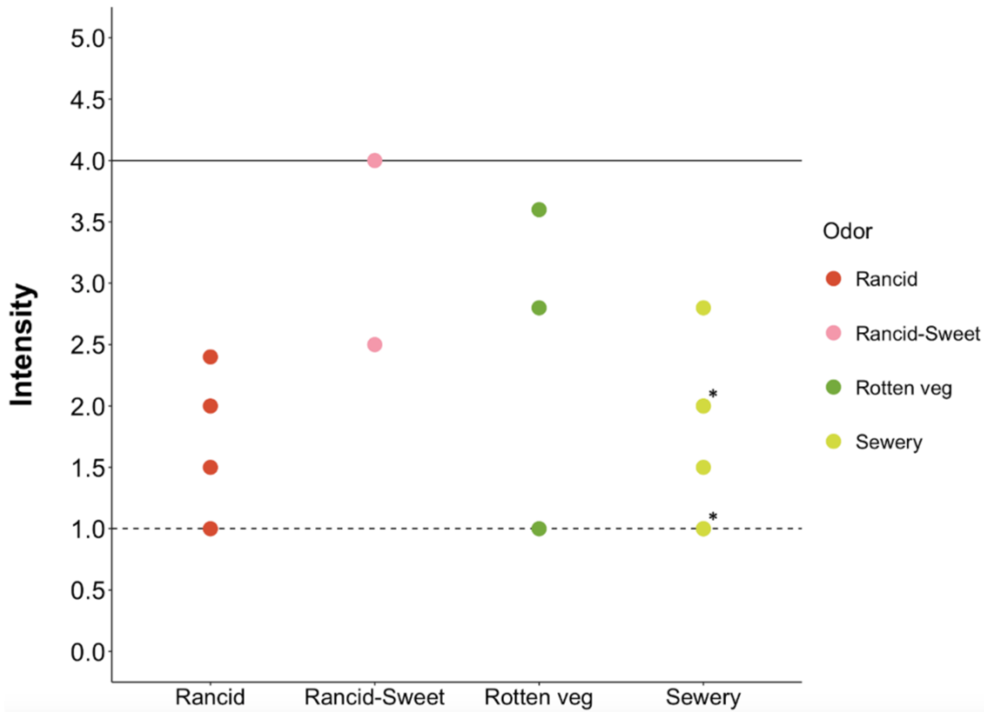

Figure 2.8. Average intensity and types of significant odors detected by the Odor Patrol. * Represents two results at the same intensity.

The first objectives of the study were to determine if the "Odor Profile Method" by an "Odor Patrol" can evaluate the odor nuisance caused by a particular odor source; i.e., determine the odor character, odor intensity of each odorant and frequency and duration of the odor problem. The first part of the objective to determine the odor character and odor intensity was accomplished. **Table 2.3** shows only the Odor Patrol sample data when landfill odors were observed during the study from 30 October 2017 to 2 May 2018 (100-week days over 22 weeks). Only 13 out of 1000 samples collected in the 100-week study showed significant landfill odors. Thus, only 1.3% of the samples were potentially attributable to the landfill during the Odor Patrol study.

Tables 2.2 and **2.3** show the second part of the first objective was capable of providing information on odor frequency and odor duration. For example, the 3 positive OPM data in **Table 2.2** and the 13 positive samples in **Table 2.3** showed the frequency of OPM data. Additionally, these tables clearly show the duration of an odor event was always within a 20 min time period.

These results appear to explain why SCAQMD odor inspectors may have missed some odor events after receiving a complaint call and the time it took to visit a complaint site.

The study demonstrated a novel approach for odor monitoring by using the Odor Profile Method with an "Odor Patrol." The OPM not only confirmed the mitigation of a landfill odor problem, but it also determined odor character, odor intensity, odor frequency and odor duration during this study period. "Landfill gas" was determined to be primarily a rotten vegetable odor with a secondary sewery/fecal odor of lower intensity, and "trash odors" were primarily a rancid and sweet odor with a secondary sewery/fecal and/or rotten vegetable odor of lower intensities generated from trash at the landfill. Quality assurance methods were used to remove local odors from the evaluation.

The OPM detected the occurrences of these specific odors. For example, **Figure 2.7** shows that from 6:00 to 6:40 a.m., a rancid odor was detected three times, rotten vegetable was detected two times and sewery/fecal was detected three times. The occurrence of most of the landfill-related odors was detected from 6:00 a.m. to 7:40 a.m. The order of intensity across types from high to low in **Figure 2.8** is: trash odor (rancid–sweet) > rotten vegetable > sewery/fecal > rancid. Thus, trash odor is the major problematic odor from the landfill site.

The results from the OPM data by the Odor Patrol show the method is capable of determining the odors from a specific odor source without mistaking the odors from the surrounding background. OPM not only can provide odor type but can also provide odor intensity. This can help develop guidelines to understand the sources of a major odor nuisance. OPM can also provide information on the time and duration of a specific odor nuisance.

2.4.2 Complaint Data from SCAQMD

Figures 2.9 and **2.10** show the primary locations of complaint data from SCAQMD during the Odor Patrol study and at the same time period the year before, respectively. The dots in **Figures 2.9** and **2.10** show the primary locations of complaints within one mile of the school during equivalent Odor Patrol periods in 2017–2018 vs. 2016–2017, respectively. The dots do not represent each complaint, only the general location of complaints.

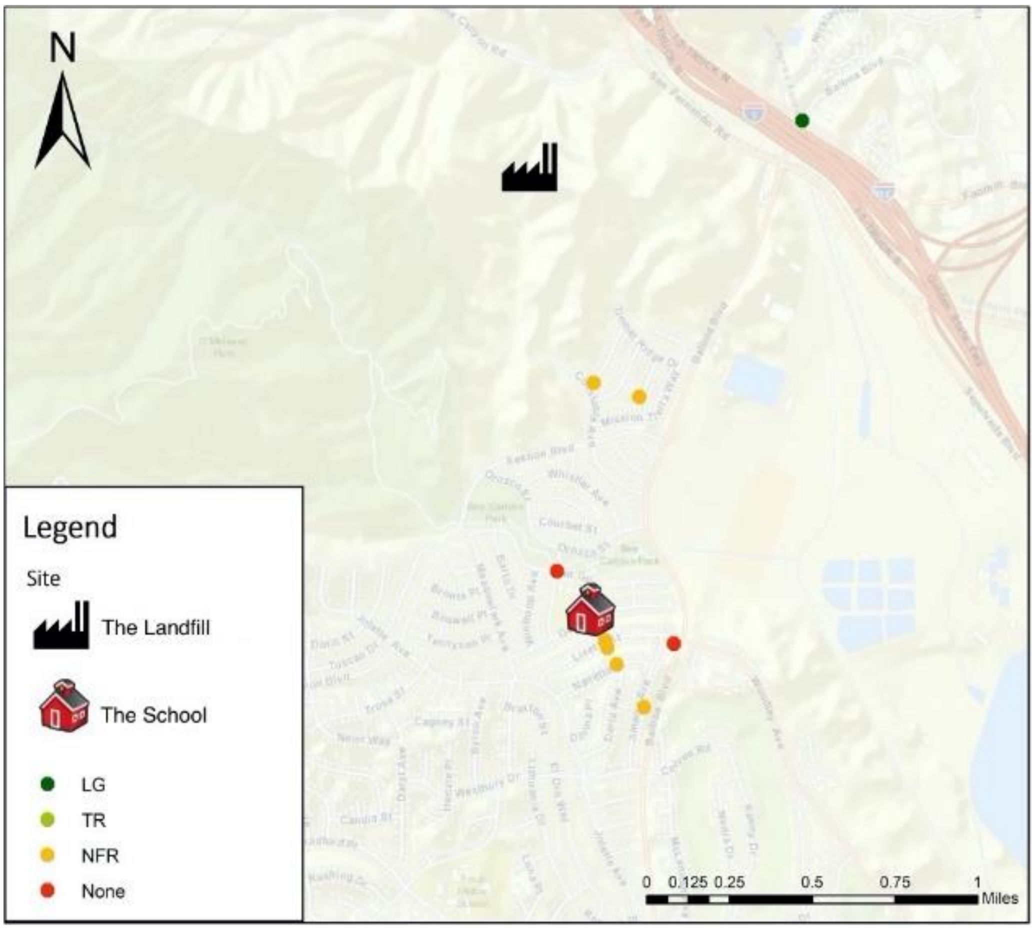

Figure 2.9. Odor complaints near the school during the Odor Patrol time period: 6–9 a.m., 2017–2018.

Note: The dots do not represent each complaint, only the general location of complaints. LG–Landfill Gas, TR–Trash Odor, NFR–No Field Response. The South Coast Air Quality Management District (SCAQMD) inspector did not go to the location. None: No odor was detected by SCAQMD inspectors at the complaint site.

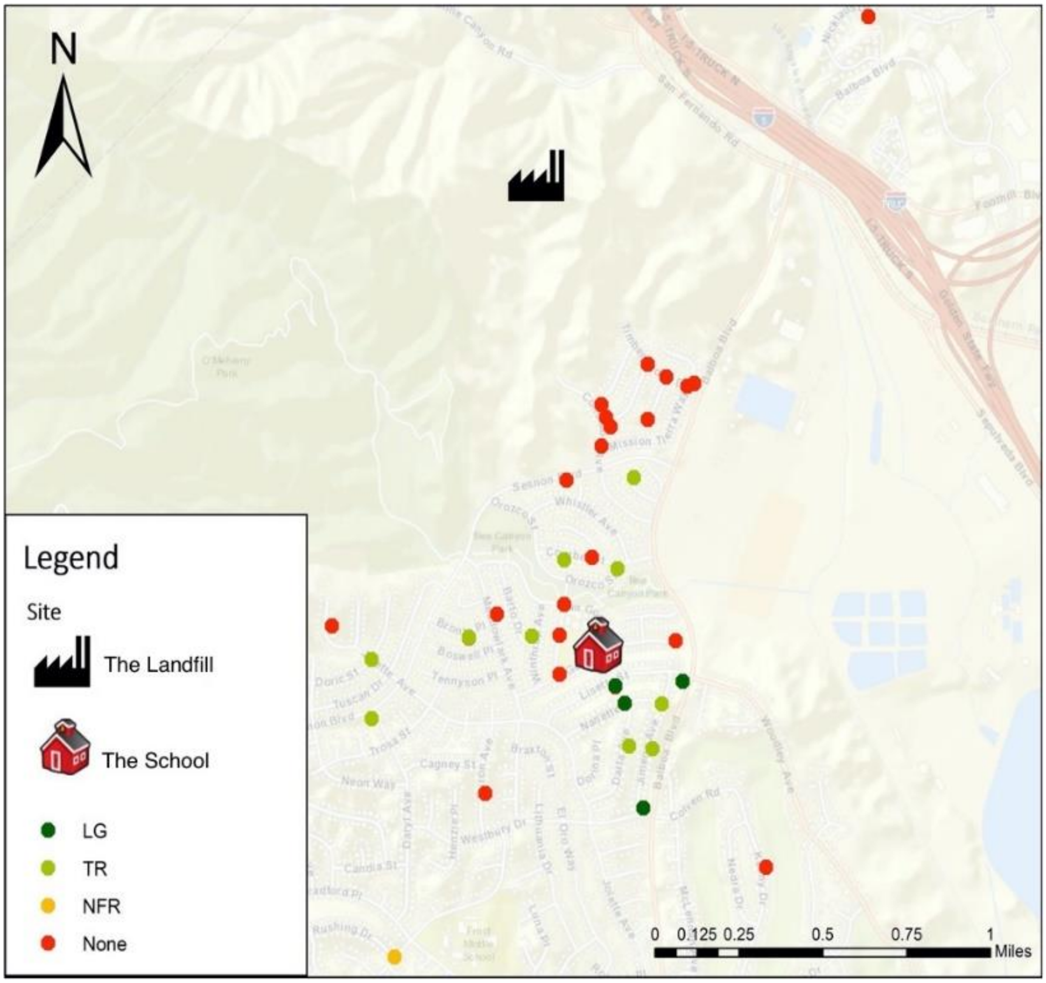

Figure 2.10. Odor Complaints near the school during the Odor Patrol time period: 6–9 a.m., 2016–2017.

Note: The dots do not represent each complaint, only the general location of complaints. LG–Landfill Gas, TR–Trash Odor, NFR–No Field Response. The SCAQMD inspector did not go to the location. None: no odor was detected by the SCAQMD inspectors at the complaint site. Complaints near the school during the Odor Patrol time period: 6–9 a.m.

The total complaints reported to SCAQMD during the Odor Patrol time period in 2017–2018 were 21 (**Figure 2.9**). There were 264 complaints reported to SCAQMD in 2016–2017 (**Figure 2.10**). In the year 2016 to 2017, there were 8 land field gas (LG) odors and 170 trash odors (TR) confirmed, while only 2 LG and no TR were reported in 2017–2018 during the Odor Patrol period.

The second objective of the study was to determine if the OPM by an "Odor Patrol" could be used to determine if the closure of a landfill between 6 and 9 a.m. could minimize odor complaints at an impacted site one mile away? The results indicate that the landfill did not contribute much to nuisance odors in 2017–2018 during the hours of 6 to 9 a.m. **Figures 2.8** and **2.9** show only the complaint data from SCAQMD. To make a reasonable comparison, **Figure 2.9** shows the complaint data from 30 October 2016 to 2 May 2017, which is the exact date and month one year prior to our Odor Patrol period. There was a dramatic decrease from the previous year: 264 complaints in 2016–2017 versus only 21 complaints in 2017–2018 from 6 to 9 a.m. (Tseng et al., 2018). Thus, the complaint data show that the odor nuisance from the landfill source has been mitigated.

The Odor Patrol data results agree with the complaint data as only 1.3% of the data points showed landfill-related odor detection, and the intensity was at low levels between one and four (see **Table 2.1** and **Figure 2.3**). Therefore, the scientifically based OPM used by the Odor Patrol can be used as a confirmation of the absence of odor complaints in 2017–2018.

2.5 Limitations and Future Improvement

Without the knowledge of the Odor Patrol, the owners of the landfill before and during the study period were completing operational changes to mitigate the odors from the landfill (1). **Figure 2.11** shows the timeline of operational changes at the landfill gas collection system, utilization of compacted soil for intermediate trash cover, the application of “PosiShell,” the utilization of “Closure Turf”, “Vegetative Covers”, etc. Thus, odor mitigation approaches were being evaluated together, i.e., closure of the landfill from 6 to 9 a.m. and operational changes at the landfill.

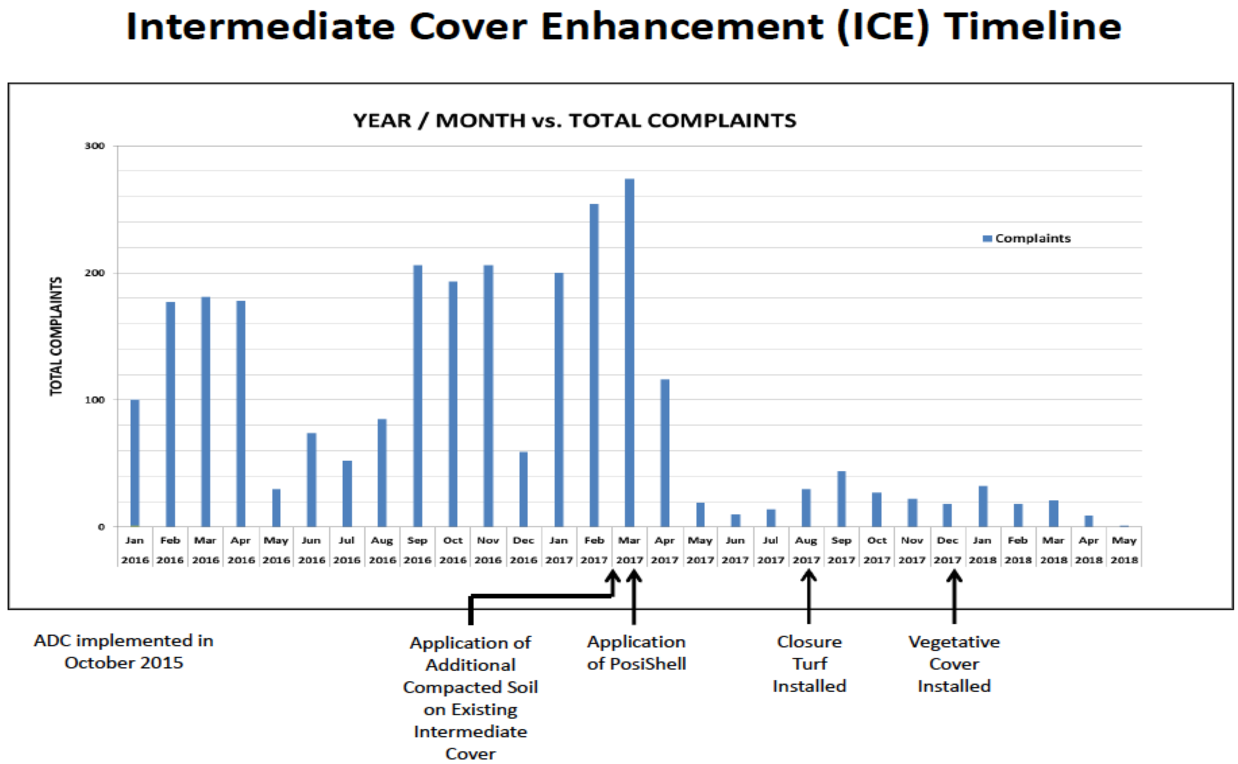

Figure 2.11. The Intermediate Cover Enhancement (ICE) timeline at the landfill (Tseng et al., 2018).

Note: The "Odor Patrol" study was from 30 October 2017 to 2 May 2018 (100 weekdays) when the Closure Turf and Vegetative Covers were installed and the total complaints dropped significantly.

Figure 2.11 shows a timeline of improvements at the landfill (Tseng et al., 2018). The "Odor Patrol" study was from 30 October 2017 to 2 May 2018 (100-week days) when the Closure Turf and Vegetative Covers were installed and the total complaints dropped significantly. Thus, either (A) optimizing the landfill operating approach, (B) closing the landfill from receiving trash at 6–9 a.m. or (C) both together lowering the odors from the landfill and decreasing odor complaints about a mile away near the school site.

The angles between wind direction and direction from complaint locations to the landfill were calculated from an air monitoring station at the landfill facing the direction of the complaint location. During the Odor Patrol time period in 2016–2017, over 65% of the winds coming from landfill to complaint locations were within ±15°, and about 90% of the winds coming from source to complaint locations were within ±30°. During the Odor Patrol time period in 2017–2018, 50% of the winds coming from landfill to complaint locations were within ±15°, and 76% of the winds coming from landfill to complaint locations were within ±30°. Due to the lack of weather station data at the landfill and the school location, a thorough meteorological study was not performed. Thus, Odor Patrol data from 30 October 2017 to 2 May 2018 were compared to the complaint data in the same period of time (30 October 2016 to 2 May 2017) in the previous year, and minimum meteorological differences were observed.

At present, it cannot be stated definitively that the closure of the landfill between 6 and 9 a.m. had no effect on the Odor Patrol data at the school or Odor Complaint data to SCAQMD. An Odor Patrol study as completed in this study could be completed with trucks delivering and dumping to the landfill at 6–9 a.m. to develop evidence that the landfill could receive trash between 6 and 9 a.m. This also should be compared to complaint data from SCAQMD. A complete meteorological study could be done during the 100 days of the Odor Patrol event to provide further information on weather influence on nuisance odor complaints.

2.6 Conclusions

This study shows that the “Odor Profile Method” by an “Odor Patrol” can evaluate the odor nuisance caused by a particular odor source; i.e., determine the specific character and odor intensity of each odorant and determine the frequency and duration of the odor problem. Additionally, the “Odor Profile Method” by an “Odor Patrol” could determine the contribution of the nuisance odors from 6 to 9 a.m. at the school site, about one mile away from the landfill. Quality assurance was maintained for the odor panel. The data show that the odor control panelists’ sense of smell was consistent throughout the 100 days of odor monitoring.

The Odor Patrol only found 13 data of the 1000 data inputs (1.3%) for the 100-day odor monitoring with landfill odor or trash odors that could cause odor complaints. This indicates the landfill did not generate much odor nuisance to the school site from 6 to 9 a.m. when the landfill was not receiving trash. The complaint data also showed a dramatic decrease in odor complaints from 2016–2017 to 2017–2018. Therefore, the Odor Patrol data and the Odor Complaint data correlate well, and the Odor Profile Method can be used to confirm the mitigation of a landfill odor problem.

The study demonstrated a novel approach for odor monitoring by using the Odor Profile Method with an Odor Patrol. The OPM defines the odors to study that come from the landfill. The OPM determined “landfill gas” was primarily a rotten vegetable odor with a secondary sewery/fecal odor of lower intensity and the “Trash odors” were primarily a rancid and sweet odor with a secondary sewery/fecal and/or rotten vegetable odor of lower intensities generated from trash reaching the landfill. The order of intensity observed from high to low was: trash odor (rancid–sweet) > rotten vegetable > sewery/fecal > rancid alone. Thus, trash odor was the major problematic odor from the landfill site. Quality assurance methods were used to remove local odors from the evaluation.

In conclusion, despite other factors such as weather and temperature differences, the closing operation of the landfill from 6 to 9 a.m. and also the implementation of odor control measures at the landfill did help mitigate the problems of unpleasant odors during the Odor Patrol time period of 6–9 a.m. in 2017–2018.

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Chapter 3

Understand odor Nuisance Masking from the Source and Developing Methods to Improve Masking Agents' Performance.

3.1 Abstract

Two types of masking effects exist in odor evaluation studies. One type of masking effect is to use the masking agent as a solution to minimize malodors that are emitted from the source. Another type of masking effect describes the situation that masking of one odor by another odor (other odors) can occur when an odor mixture is generated from an emitting source. The Weber-Fechner Curve can help understand odor nuisance masking from the source and developing methods to improve masking agents' performance.

The Odor Threshold Concentration determined from different study groups showed a large range. Thus, the Weber-Fechner Curves of the six common odorous chemicals detected from the Wastewater Treatment Plant were re-produced, and the curves were used for answering the odor persistency pattern at an Energy Development Facility (EDF). The results showed that isopropyl methyl pyrazine (IPMP) and methyl isoborneol (MIB) (the Musty odorants) have the flattest slopes on the Weber-Fechner Curve, meaning that their intensity declines less rapidly with dilution while Indole and Skatole (Fecal odorants) have the steeper slopes. The slopes indicated that for the same initial concentration, fecal odorants attenuate faster than musty odorants, making musty odor a more persistent odor nuisance for the receptors. The persistency curves at EDF showed that in an air mixture, fecal odor and sulfur odor deattenuate faster than musty odor. This information corresponds with the Weber-Fechner curves' results that fecal odorants and sulfur odorants decline faster than the musty odorants. The masking effect detected from the persistency curves that musty odor was masked by the fecal and rotten vegetable odor was explained by the cross-over of Weber-Fechner curves.

The case study at France evaluated the Weber-Fechner curves of the odorants and the masking agents. The results showed that more effective masking agents should have a flatter slope in the

Weber-Fechner curve than the odorants if they were to be spayed at the odor emitting source. Otherwise, the masking agent can perform better if spayed at a much higher concentration at the source or sprayed further downwind from the odor emitting location.

3.2 Introduction

The majority of the air quality complaints by the public around the world are odor complaints. When odorous chemicals causing air emissions that are not possible to capture at the source such as from landfills, composting and sludge drying beds, chemicals have been added to the air at the source to minimize the off-odors. The chemical agents can be divided into neutralizers that can react with the odorants and remove them (Bruchet et al., 2009) and masking agents that superimpose a pleasant odor and become the primary odor observed. Neutralizers are specific for a few compounds and their successful use requires rigorous chemical analysis to define the chemicals causing the odor. Masking agents are more often used as they are supposed to overcome multiple odor types at the same time and do not require rigorous chemical analysis.

Many odor studies have shown that adding masking agents at the source have failed to alleviating odor nuisances. For example, Choi et al (2012) evaluated a masking agent's performance by evaluating whether there have been changes of the concentration of reduced sulfur compounds (Choi et al., 2012). This study assumed that the masking agent reacted with the reduced sulfur compounds that were presented. However, analyzing reduced sulfur compounds is not equivalent with an odor evaluation and masking agents that do not react with the odorant compound(s). Masking agents are supposed to become the dominant odor upon dilution from the source and are not intended to react with the odorant. A second example is a masking agent study that have evaluated the hedonic tone of dairy manure after application. The result showed that the unpleasant odor of manure significantly decreased when the masking agent was added, but lost its effect after 30 days (Fabian et al, 2011). A third example by Rousseille et al. (2018) did an evaluation on two masking agents using both chemical analysis of Volatile Organic Compounds (VOCs) and sensory analyses using the hedonic tone. The results again showed the masking agents did not work. No reasons were given why the masking agent did not work.

Another type of masking of one odor by another odor can occur when an odor mixture is generated from an emitting source (Vitko et al., (2014) and Zhou et al., (2017). Vitko, et al., (2014), showed that an odor which was not observed as an odor nuisance at a Waste Water Treatment Plant (WWTP) was reported as an odor nuisance by the neighbors near the site. A musty odor was detected by residents near the WWTP but it was not observed at the WWTP. Later, Zhou et al. (2017) showed that the WWTP's odor of decaying vegetable, rotten eggs and fecal could mask the more persistent musty odor which became an off-site odor nuisance (Zhou et al, 2017).

These previous studies showed that the persistence of the odors are important. The important parameters to determine the cause of an odor nuisance are the knowledge of the odor dilution of a chemical odorant from the source to the location of the odor nuisance in the community. The dilution rate of an odorant's intensity and its relationship to concentration are based upon the Weber-Fechner law (Fechner, 1859). The Weber-Fechner law states (**Figure 3.1**) that the intensity (I) of an odorous chemical is proportional to the log of the concentration (C) of the odorant.

$$I = k \text{ Log } C/C_o \quad (1)$$

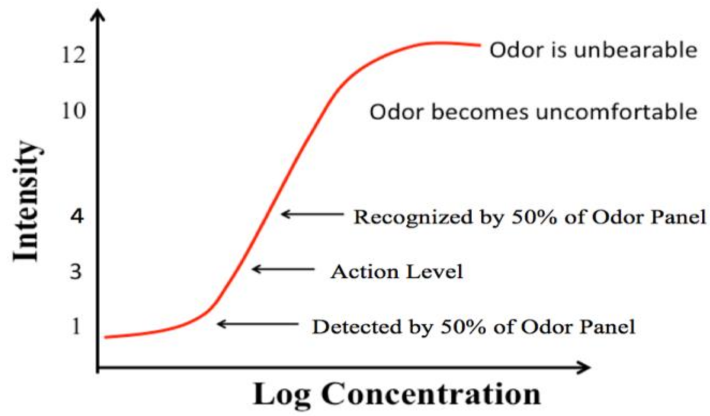


Figure 3.1. Intensity Scale for Each Odor by Weber-Fechner Curve.

The Odor Threshold Concentration that a person can detect is equivalent to the intensity of 1 on the Weber Fechner Curve. An odorant is an odor causing compound. An odor is one type of odor characteristic, for example rotten vegetable odor can consist of multiple odor-causing compounds (odorants). Each odorant has its unique Weber-Fechner Curve. A higher k value (slope) of the Weber-Fechner Curve indicates the odor decrease with dilution. Lower k-values indicate that the odor will persist in the air for a longer time. Thus, the differences between the slopes of each odor indicates the dilution of each odor.

In a real-world scenario, a primary odorant at the source upon dilution could be masking (covering) another malodor in a community after dilution as described above. The only way to observe this is by evaluating the persistency (dilution) of all the odorous chemicals present that are causing the odor at the source. A persistency curve shows the intensity change of each odor type in an odor mixture with the dilution ratios, whereas the Weber-Fechner curve shows the intensity change of the odor generated by each odorant with its change in concentration.

Two types of case studies for masking were evaluated in this project. The first case study considered the masking effect of multiple odors emitted simultaneously from an odor producing source. Here the odor nuisance to a community was a different odor than at the odor emission source. A new approach of understanding how this masking occurred can be defined by the Weber-Fechner curve using the Odor Profile Method. The second case study was the evaluation of adding masking agents at a landfill and how that affected the odors leaving the landfill. A new approach of understanding how to develop a masking agent for that situation can be defined by the Weber-Fechner curve of specific odorants.

The objectives of this study were to:

1) Analyze if the Weber-Fechner curves of the six odorants observed in a previous WWTP study can be reproduced and directly used for this study.
2) Demonstrate how the data from a previous study can show the importance of the Weber-Fechner curve for indicating the persistency of odorants and evaluating odor masking of odors from an odorous source (EDF).
3) Demonstrate using the Weber-Fechner curve in a case study to show why the masking failed and suggest ways of selecting and designing masking agents that can work.

3.3 Method

3.3.1 Sensory Method - Odor Profile Method

The Odor Profile Method was based upon the Flavor Profile Analysis (FPA) method for the food and drinking water industries, specifically Method 2170, the "Flavor Profile Analysis" of "Standard Methods of Water and Wastewater" (APHA, AWWA and WPCF, 2017). The FPA has a 7 - level sugar scale for intensity of an odor. The FPA was developed for the headspace of drinking water. It has been used for over 30 years and is a standard method to evaluate odor problems and for quality control of odors in drinking water. The method was developed for air analysis studies by Burlingame, (1999), Burlingame et al. (2003), Burlingame (2009) and Curren et al. (2014). The wastewater odor wheel (**Figure 3.2**) was used to identify each odor type and intensity (Burlingame et al., 2004). The “wastewater odor wheels” consist of three rings: an inner ring of general odor categories, a middle ring of specific odor notes within each segment and an outer ring of known or potential odorants associated with each odor note (APHA, AWWA and WPCF, 2017).

The OPM includes (1) identifying one or more odor notes in the air sampled and (2) determining the odor intensity for each odor note

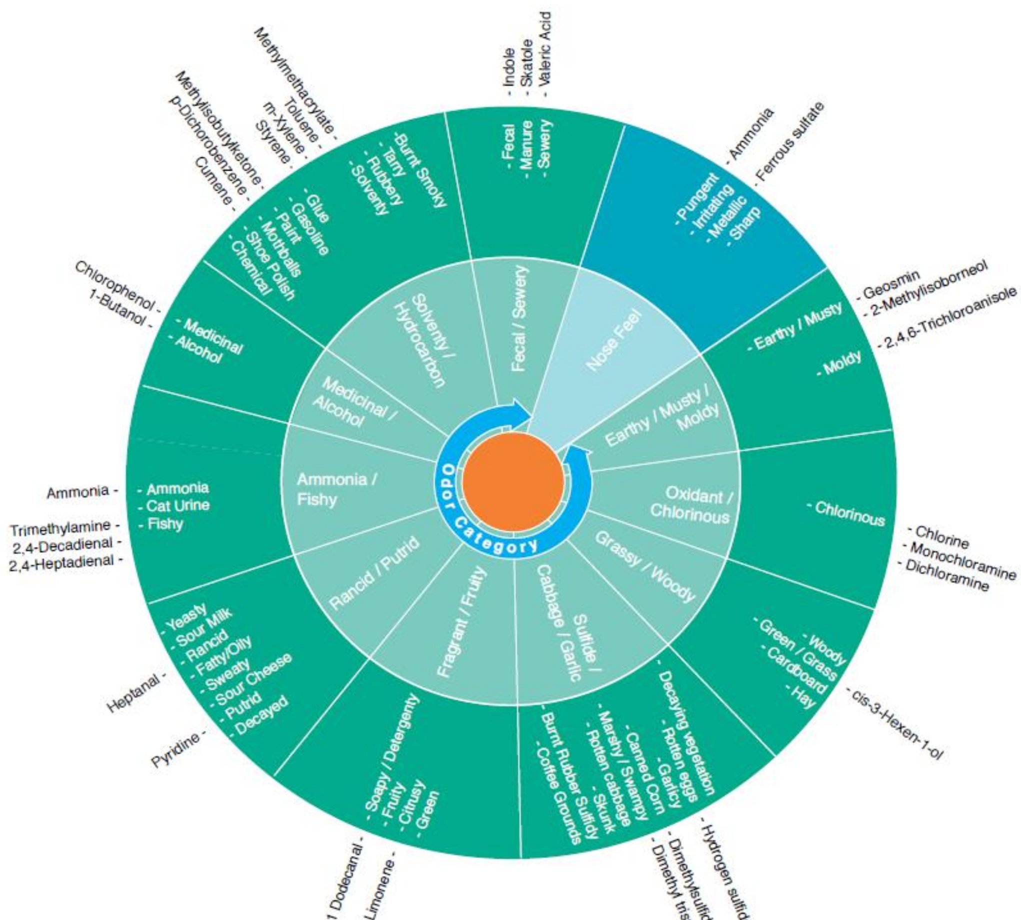


Figure 3.2. Wastewater Odor Wheel (Burlingame et al., 2004)

Table 3.1 presents the OPM intensity scale that is based upon the Weber-Fechner Law (Fechner, 1859) that a single odorant's intensity is proportional to the Log of the odorant's concentration, Equation 1.

Table 3.1. OPM Odor Intensity Strength Scale (Burlingame et al., 2003)

Intensity Scale	Intensity Description	Concentration of Sugar in Water
0	Odor-Free	0%
1	Threshold (OTC)	
2	Very Weak	
4	Weak (ORC)	5%
6	Weak-Moderate	
8	Moderate	10%
10	Moderate-Strong	
12	Very Strong	15%

The OPM method includes:

- Screening panelists for anosmia (lack of the sense of smell) using a "scratch-n-sniff" test (Doty et al., 1984). Using a minimum of 4 trained panelists for each OPM sample evaluation.
- Training odor panelists with the primary odorants of an odor wheel and mixtures of 2, 3, and 4 of these standard odorants over a 6-week period. Also, the panelists were trained on the background odors that could be found near the odor site.
- Teaching a standardized odor note vocabulary to panelists using the "wastewater odor wheels"
- Panelists are calibrated to the odor intensity scale (**Table 1**) – threshold (1), slight (2), weak (4), medium (6), medium strong (8), strong (10), and very strong (12) – using sugar-in-water

solutions tasted by mouth that represent weak, intensity 4, (5% sugar solution), medium intensity 8, (10% sugar solution) and strong, intensity 12 (15% sugar solution).

- Group discussions are permitted after the individual odor evaluations to help panelists define their responses; however, panelists are ultimately instructed to work independently.
- If an odor character is reported by 50% or more of the panelists, the OPM results will be the average and standards deviation of the responses that include a zero-intensity value for the panelist who do not identify the odor.
- If an odor character was reported by less than 50% of the panelists, the odor will be reported as an "other odor notes" without an intensity score and excluded from further analysis as a minor constituent. (Fechner, 1859; Suffet et al., 1995). Since the intensity ratings are proportional to the logarithm of the concentration of the odor, a large standard deviation is not as critical as it would be if it were on a linear scale for concentration.
- At the odor threshold intensity of 1, an odor panelist can state that the odor is different than clean air.
- Only at an odor intensity of 4 can the panelist easily recognize the odor characteristic. An average odor intensity of 3 is considered as an action level for to avoid odor nuisance complaints as shown on **Table 3.1** (Burlingame, 2004).

3.3.2 Olfactometry

The AC'SCENT International Olfactometer (Croix Sensory Inc., Stillwater, MN) was used as the instrument to perform the OPM testing on the Weber-Fechner Curves and the odor persistence curves. It is a dynamic dilution venturi nozzle style olfactometer used for determination of detection and recognition thresholds of odorous air samples, including odorant mixtures or pure compounds. The AC'SENT mixes odorous air samples with odor-free blank air in specific ratios (dilution ratios) for presentation to a panelist. The dilution levels of the olfactometer includes 14 levels (**Table 3.2**). The general air flow coming out from the nozzle is at 20 liters per minute.

Table 3.2. Specific Dilution Ratios for Presentation to a Panelist by the AC'SCENT International Olfactometer

Dilution Level	Odorous Air Flow	Dilution Ratio
1	0.31 cc/min	64,000
2	0.63 cc/min	32,000
3	1.25 cc/min	16,000
4	2.50 cc/min	8,000
5	5.00 cc/min	4,000
6	10.0 cc/min	2,000
7	20.0 cc/min	1,000
8	40.0 cc/min	500
9	80.0 cc/min	250
10	160 cc/min	125
11	320 cc/min	63
12	630 cc/min	32
13	1250 cc/min	16
14	2500 cc/min	8

The test mode used for the Weber-Fechner curve generation is the Direct Presentation Mode. In the Direct Presentation Mode, the panelist is presented with an odor sample at each specific concentration for a specified amount of time (3 seconds in this study).

3.3.3 Experimental Procedures

3.3.3.1 Reproduction of the Weber-Fechner Curves

The Odor Threshold Concentration indicates where 50% of the panelists could state that a sample was different from odorless air. The OTCs of six odorants were determined by different methods, (Nagata, 2003; Rosenfeld et al., 2007; Amore, 1983; Ömür-Özbeket et al., 2011; Sala et al., 2004; Ruth, 1986). The large variation of the OTC values in different studies are shown in **Table 3.3** for odors that could cause nuisance problems.

Table 3.3. Comparison of Odor Threshold Concentrations

Chemical	Reference OTCs*	Wastewater Wheel Odor Character

	ng/L in air	
DMS	2.5-12	Canned Corn
DMDS	0.1-8.5	Decaying Vegetation
MIB	0.09-0.5	Earthy/Musty
IPMP	0.005-0.05	Earthy/Musty
Indole	1.4-6.7	Fecal
Skatole	0.0004-0.3	Fecal

* Combined data from Nagata, 2003; Rosenfeld et al., 2007; Amore, 1983; Ömür-Özbeket et al., 2011; Sala et al., 2004; Ruth, 1986.

The Weber-Fechner curves of the six odorants defined in a previous study (Vitko et al., 2016) were tested to determine if the curves are reproduced and could be directly used for this study. Twelve to fourteen panelists completed the Weber-Fechner Curves for the six odorants in **Table 3.3** (Vitko et al., 2016). In this study, four well trained panelists repeated the determination of Weber-Fechner curves for these compounds to compare the consistency between different groups. Standard chemical solutions were prepared and injected into Teflon sampling bags. The sampling bags were connected to the olfactometer for different levels of dilution sniffing tests. The direct presentation mode was used to present the odorant at each dilution level to each panelist. Each panelist has their own data sheet to record their own answer for the odor character and odor intensity perceived at each dilution level. When using an olfactometer for odor dilution, the experiment always starts at the highest dilution ratios (lower concentration of the original sample) and end with the lowest dilution ratio (high concentration). In this way, panelist can prevent nose fatigue from smelling strong odor at the beginning.

3.3.3.2 Generation of the Persistency Curves of Odors to Determine if Any Odors in the Source Were Masked

An Energy Development Facility (EDF) is one of the possible facilities that could cause an odor nuisance to a nearby community. The EDF produces clean, green renewable energy while producing a feedstock for composting. It processes “wet” organic waste material that is collected primarily from commercial industries. The waste includes food waste and residential waste (mainly yard trimmings), which would otherwise go to a landfill. The UCLA odor panel used two samples from different days to perform an odor persistency study for the EDF. The samples were collected in Teflon bags and shipped overnight to UCLA. Then, the evaluation of odor persistency using the OPM with dilutions from the Olfactometer were completed with the direct presentation mode. The odor panelists for this study were the same four panelists who completed the Weber-Fechner Curve reproducible study in section 1. Each panelists have their own data sheet, on which they reported the odor character and odor intensity for each odor they distinguished from the air sample.

3.3.3.3 Evaluation of the Masking Agent Performance for Landfill Odors

A landfill odor control study in France evaluated the performance of a set of masking agents in a gel that were placed on 3- foot platforms around the outer edge of landfill (Decottignie, 2007).

In order to understand how the odor masking agents could be used to reduce the odor from the landfill, the seven detected odorous chemicals from the landfill and the seven common molecules used in commercial masking agent products were studied (Decottignie, 2007). The raw data that were used to general the Weber-Fechner Curves were provided in the study report (Decottignie, 2007). An in-depth evaluation of the data using the theory of the Weber-Fechner Curves for the odorous compounds and the masking agents were used to re-evaluate the data and show how to improve the use of masking agents. Two methods of how a masking agent could work more efficiently were demonstrated.

3.4 Results

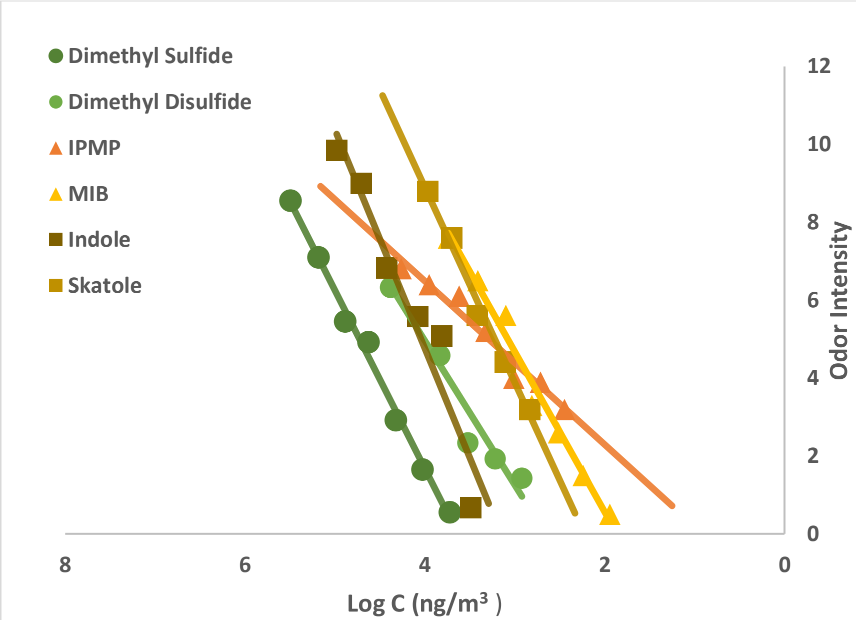
3.4.1 Reproduction of the Weber-Fechner Curves for Six Common Odorant Compounds Detected from Wastewater Treatment Plant

Figure 3.3a showed the Weber-Fechner curves for the six odorous compounds from a WWTP study by Vitko et al, (2017) using the OPM method with 12-14 panelists. The slope of Weber-Fechner persistency curve shows that IPMP and MIB have the flatter slopes. Indole and skatole have much higher slopes. Thus, the earthy/musty odors of IPMP and MIB are more persistent in air compared to the fecal odorants: indole and skatole. In another word, if an odor emitting source has a high concentration of indole and skatole compared to IPMP and MIB, receptors close to the source might be smelling the strong fecal odor, but receptors at the fence-line might not be smelling fecal odor but musty odor. The fecal odor generated by indole and skatole disappear faster than the musty odor generated by IPMP and MIB. The earthy/musty odors were actually observed and confirmed by the OCSD study (Vitko et al, 2014) by neighbors outside the OCSD WWTP, whereas in-plant the fecal odors were high from some unit processes.

The 2019 experiment at UCLA using the OPM included 4 well trained panelists from UCLA. The same six odorants were selected to generate the Weber-Fechner Curves (**Figure 3.3b**). The results showed similarity compared with the 2016 study. The change of the musty odor's intensity generated by IPMP with dilution is the most gradual. MIB also has a low persistence slope. Indole and skatole again showed steeper persistence curves. Even though the slopes of these six odorants were similar between the two tests, the regression lines (**Table 3.4**) were not identical with the regression lines from the previous study in 2016 study. Comparing the regression lines, to perceive the same intensity level of an odorant, the UCLA, 2019 panelists required a higher concentration compared to the 2016 panelists. Thus, the 2019 panelists are less sensitive compared to the 2016 panelists.

In conclusion, the Weber-Fechner data comparison indicated that the trends were consistent but the slopes were different. Thus, it is recommended that each odor panel should test the Weber-

Fechner curves of their target odorant compounds in order to provide consistent understanding of odor persistence caused by these odorant compounds at the fence-line.



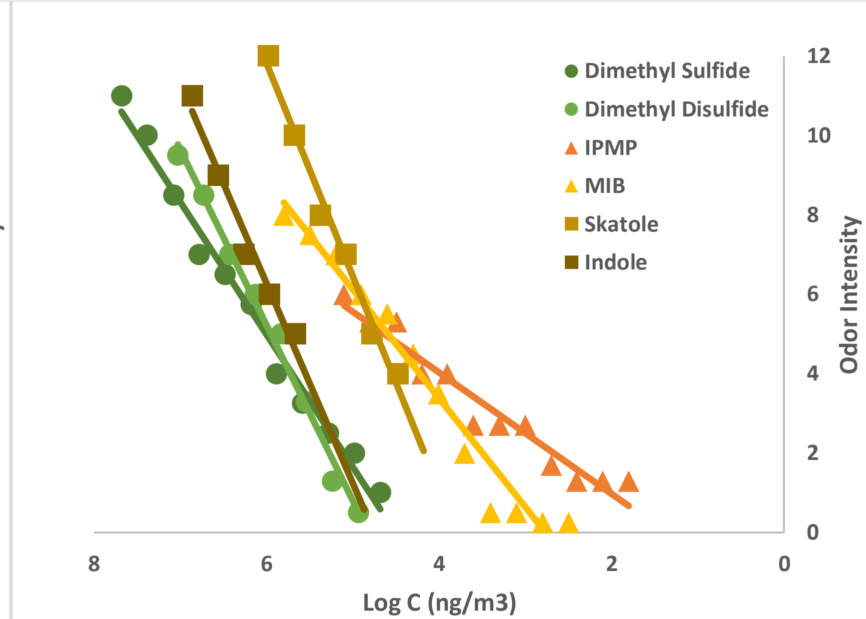


Figure 3.3a. Weber-Fechner Curves 2016 (Zhou et al, 2017)

Figure 3.3b. Weber-Fechner Curves (UCLA Panel 2019)

Table 3.4. Regression Comparison of the Weber-Fechner Curves

Chemical	Regression 2016	Chemical	Regression 2019
IPMP	y = 2.1x – 1.9	IPMP	y = 1.5x – 2.1
Dimethyl Disulfide	y = 3.7x – 9.8	MIB	y = 2.7x – 7.6
MIB	y = 4.1x – 7.7	Dimethyl Sulfide	y = 3.3x – 15.0
Dimethyl Sulfide	y = 4.6x – 16.6	Dimethyl Disulfide	y = 4.4x – 21.3
Skatole	y = 5.0x – 11.2	Indole	y = 5.0x - 24
Indole	y = 5.6x – 17.7	Skatole	y = 5.4x – 20.3

3.4.2 Case Study

3.4.2.1 Case Study at EDF – Understanding Odor Masking Effect

As part of a project to identify the odor from different sources, odor dilution curves on two different days were examined from a biofilter at an Energy Development Facility. **Figure 3.4a** and **Figure 3.4b** show the odor dilution curves of Intensity versus Log of Dilution ratio of the concentration of the chemical(s) causing these odors. The results showed that for both events the rotten vegetable odor and the fecal odor decreased and eventually dissipated completely with dilution while a musty odor appeared and persisted. Dilution of the initial concentration(s) of the odorants present were logarithmic over a 2.5 to 3.0 log units. When comparing **Figure 3.4a** and **Figure 3.4b**, the rotten vegetable odor in day one decreased faster than the fecal odor, while in day two it decreases slower than the fecal odor indicating that the compounds that had these odors were at different levels. It should be noted that the odor dilution curves are probably for an odor mixture of more than one chemical that produces these odors. For example, the fecal odor might come from a mixture of indole, skatole and other compounds producing the fecal odor and the rotten vegetable odor might come from a mixture of methyl mercaptan, dimethyl sulfide, dimethyl disulfide and other sulfur compounds. Therefore, the odor dilution curve cannot be equivalent with the Weber-Fechner curve, but to serve as a case study that explained the odor persistency difference provided by the Weber-Fechner curve, and what will happen in a real-life scenario.

This odor dilution curves of the odors in **Figures 3.4a** and **3.4b** and correlate well with the Weber-Fechner curves in **Figure 3.3a** and **3.3b**. The fecal odorants of skatole and indole and the sulfur odorants of dimethyl sulfide and dimethyl disulfide have steeper slope than the musty odorants of IPMP and MIB which have flatter slopes. The decrease of concentration of the chemical odorants are also presented as a log dilution by concentration over about 3 log units as does the dilution curves indicating that the log dilution of odorants causing the odor are correlated with the specific chemicals causing the odor.

This evaluation shows a theoretical reason for the masking effect. For both events, musty odor was not detected for the overall OPM results (**Figure 3.4a, 3.4b**). However, the lower dilution ratios of the fecal odor and rotten vegetable odor masked the musty odor. With sufficient dilution, the musty odor was observed. This was explained by the crossover of Weber-Fechner curves showed in **Figure 3.5**. For example, the Weber-Fechner curve of IPMP and Skatole showed before the cross over point, the odor generated by skatole is the dominant odor. After the two curves cross each other, the fecal odor from skatole showed a lower intensity than the musty odor generated from IPMP, leaving musty odor the dominant odor.

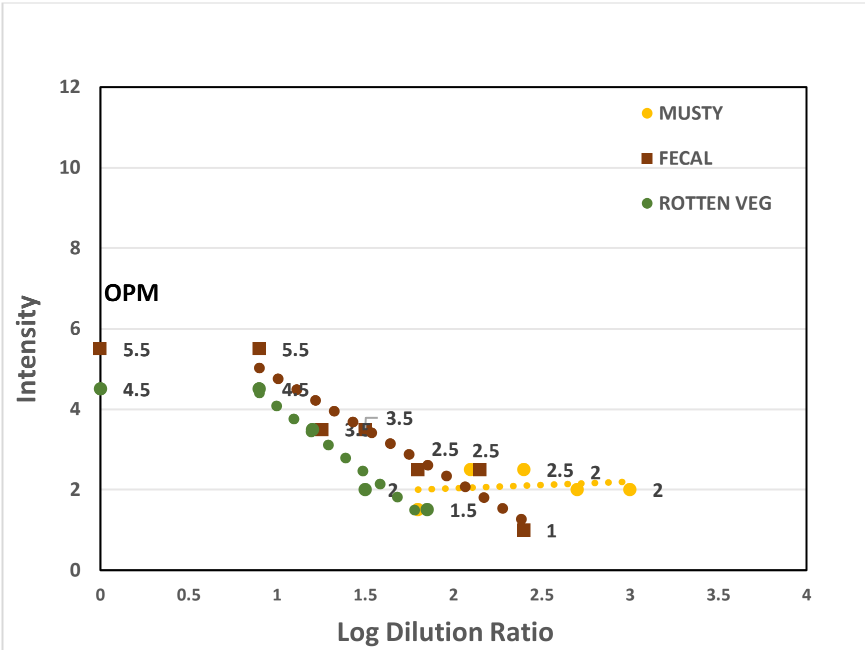


Figure 3.4a. Persistency Curve at EDF Biofilter in Day 1

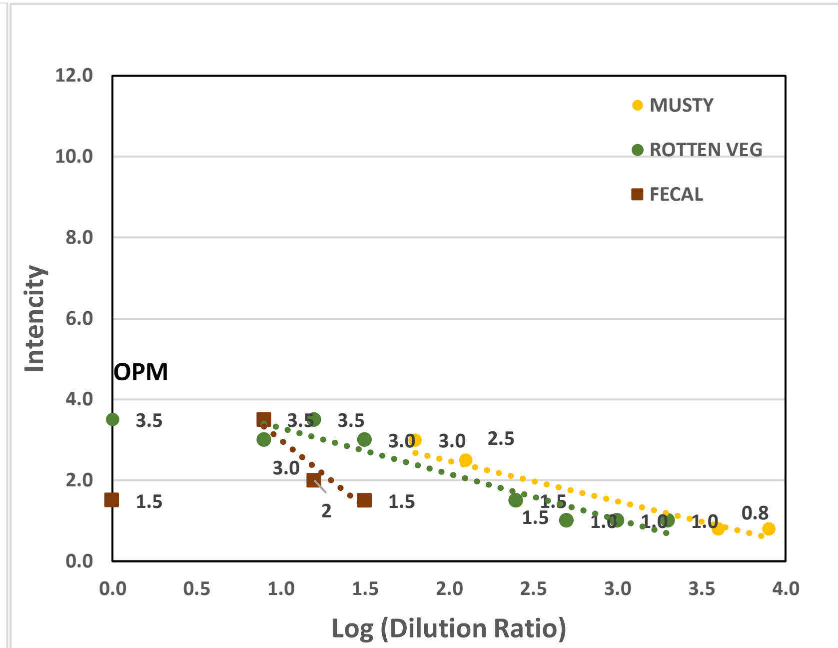


Figure 3.4b. Persistency Curve at EDF Biofilter in Day 2

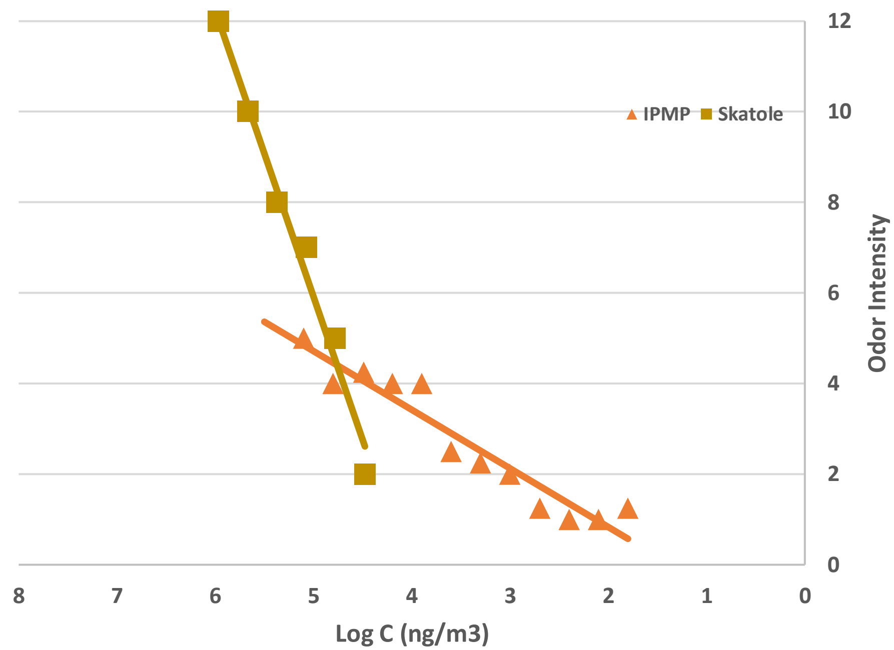


Figure 3.5. Masking Effect Illustration by the Cross-Over of Weber-Fechner Curves

3.4.2.2 Case Study at French Landfill - Masking Agent Evaluation and Selection

Figure 3.6 shows the Weber-Fechner curves of odor intensity range of a set of chemical malodorants found at a landfill site. The Weber-Fechner curves are in the log Concentration range of 4 to 6 for odors with an intensity of Log 2-10 for the fishy odorant – trimethyl amine, decaying vegetation odorants- methyl mercaptan and dimethyl sulfide, rancid odorant - butanoic acid, sweet odorant - acetaldehyde and fecal odorant - skatole and cadaverine.

It is assumed based upon the highest concentration of each odorant in case study one that a masking agent should have a lower slope and a sufficiently high concentration to mask any of these odor causing chemicals, if one has knowledge of the odorant's concentration. **Figure 3.7** shows the Weber-Fechner curves for the masking agents in the mixture that were used in the study. The combination of the masking agents was placed on Gel Plates and were place around the landfill, just above the landfill surface.

Figure 3.7 shows that the masking agents need a log concentration of 6 to 8 to generate an odor intensity between 2 -10. This indicates that the masking agents requires a much higher concentration in order to have the same order of odor intensity with the odorants. The application concentration of the masking agents has to be much higher than the malodorants. **Table 3.5** shows a comparison of the slopes of the masking agents and the odorants. The slopes shows that many of the malodor compounds have lower slopes than the masking agents and thus, dissipate less rapidly than the masking agents. Specifically, trimethylamine, acetaldehyde, cadaverine, and skatole all have low to medium slopes and thus, they are more persistent than the other three off-odors compounds. The masking agents - alpha-pinene, alpha-terpineol and eugenol show low to medium slopes, and the values were very close to the slopes of some malodor chemicals. The other four masking agents: decanal, limonene, benzaldehyde and eucalyptol have higher slope values than all the odorants detected at the landfill. Thus, the odors of these four masking agent compounds dissipate faster that the odor caused by the odorants. In other words, with dilution, the masking agents will not be able to mask any of the odorants that were detected from the Landfill. This explained why the masking agent did not work well at the Landfill. Thus, the community away from the landfill would still smell only the malodors.

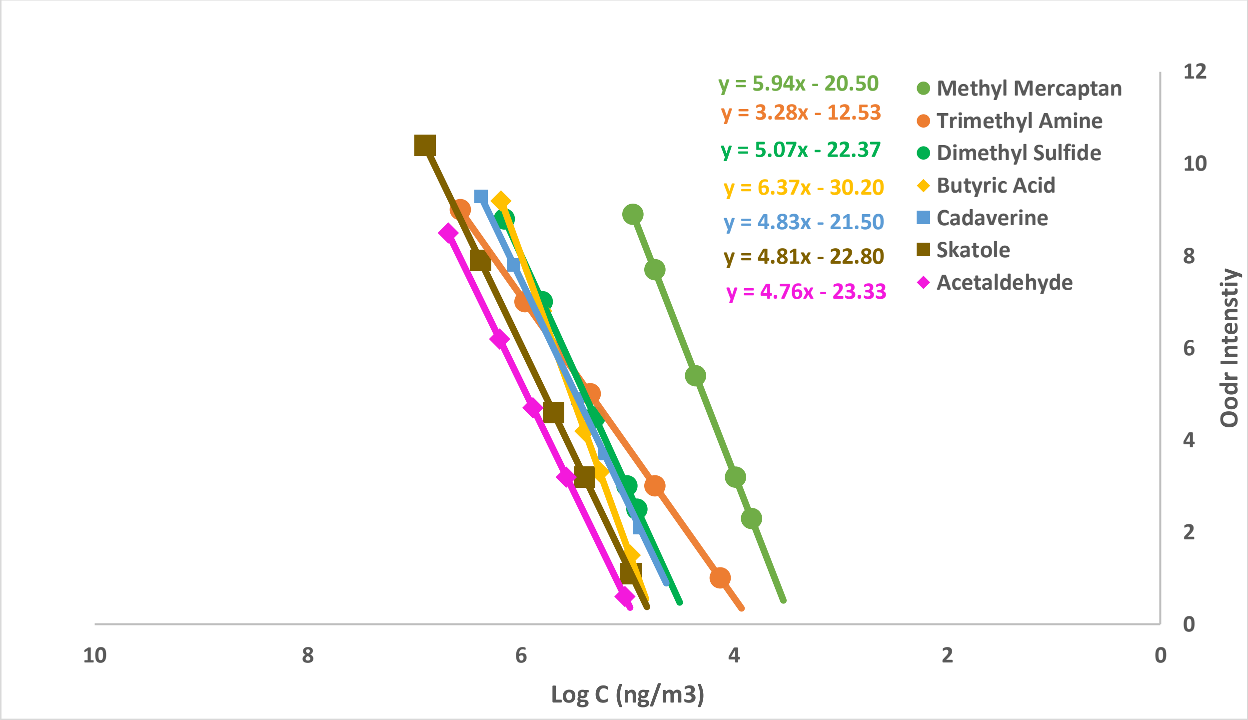


Figure 3.6. Weber-Fechner Curves of the Seven Odorants from a French Landfill (Decottignie, 2007)

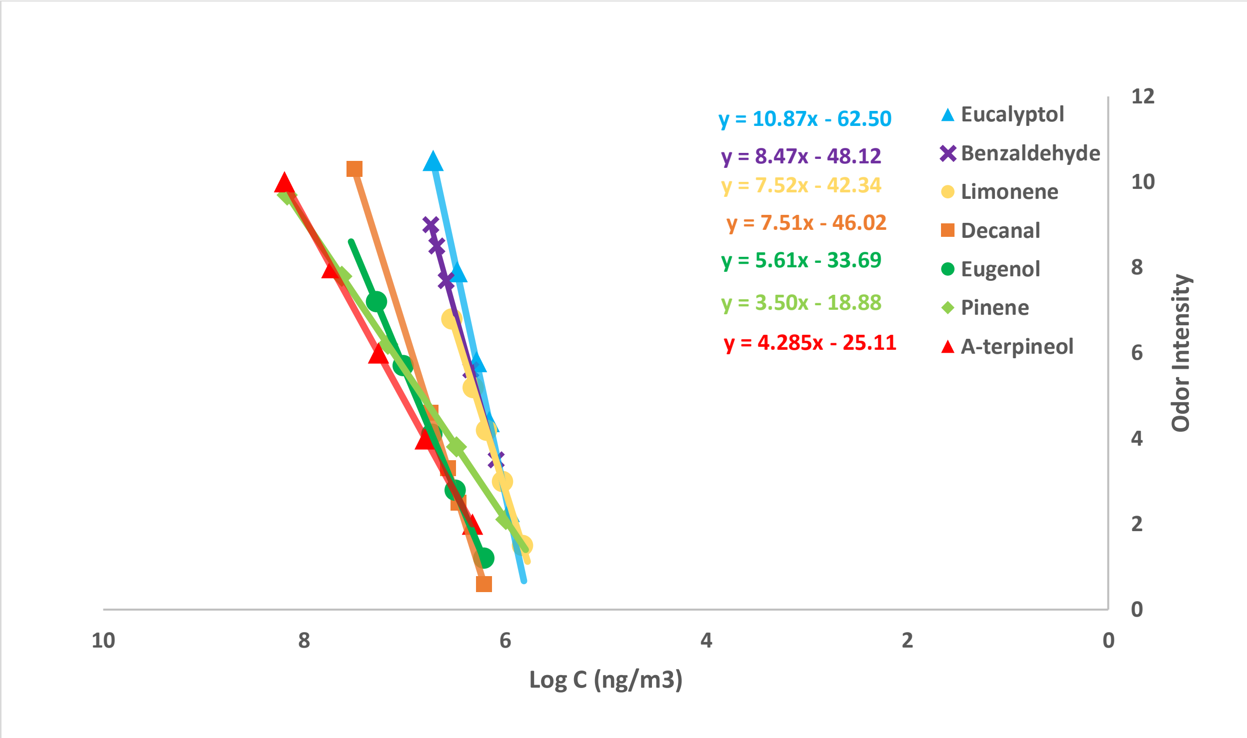


Figure 3.7. Weber-Fechner Curves of Seven Common Masking Agents (Decottignie, 2007)

Table 3.5. Slopes of the Weber-Fechner Curves for the Odorants and Masking Agents from the French (Decottignie, 2007)

Odorous Compounds Studies	Odor Character	Slopes of Weber-Fechner Curves
Trimethyl Amine	Rotten Fish	3.28
Acetaldehyde	Fruity	4.76
Skatole	Fecal	4.81
Cadaverine	Dead Animal	4.83
Dimethyl Sulfide	Rotten Vegetable	5.06
Methyl Mercaptan	Rotten Cabbage	5.94
Butyric Acid	Rancid	6.37
α- Pinene	Pine Tree	3.50
α- Terpineol	Floral	4.28
Eugenol	Clove	5.61
Decanal	Citrus Peel	7.51
Limonene	Lemon	7.52
Benzaldehyde	Almond	8.47
Eucalyptol	Eucalyptus	10.87

In order to overcome the poor performance of the odor masking agents, two possible solutions are illustrated in **Figure 3.8a** and **3.8b.** that could work for some odorants. **Figure 3.8a** and **3.8b** used the Weber-Fechner curves of limonene and trimethyl amine to show how a masking agent could work. **Figure 3.8a** shows the situation where the masking agent has a flatter slope than the malodor. This describes an ideal situation when the masking agent and the odorant were at the same initial concentration, with same dilution level in the surrounding air and at a distance from the landfill. This is the best case for masking as the odor caused by the odorant decrease faster than the odor caused by the masking agent. At a higher dilution level, the odor caused by the masking agent will remain longer and at a higher intensity than the malodor.

However, since most of the masking agents have steeper slopes than the malodorants, finding a masking agent as in **Figure 3.8a** might not be possible. **Figure 3.8b** demonstrates another way of maximizing masking agent's performance even if the masking agent has a flatter slope than the odorant. The key point is to create a huge concentration difference between the malodorant and the masking agent at the time of masking agent application.

Two situations are considered. First, if the masking agent were to apply at the odor emitting source, then its initial concentration has to be much higher than the odorant's initial concentration. In this way, with a same level of dilution, the odor generated by the masking agent will remain at a higher intensity than the odor produced by the odorant. If the initial concentration of the malodor is also high, then to prevent the neighborhood at a further distance from smelling the malodor, the application location of the masking agent can move to a distance closer to the neighborhood of concern. Thus, at this new application location, the masking agent has a much higher initial concentration compared to the odorant's concentration, which will be the same at the first situation.

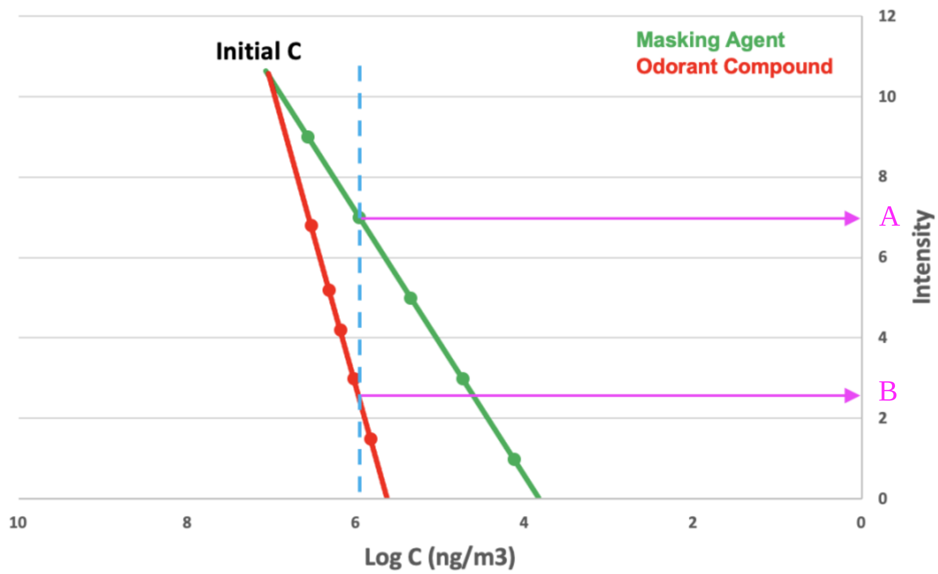


Figure 3.8a. Ideal Situation Where a Masking Agent Can Mask an Odorant at the Source

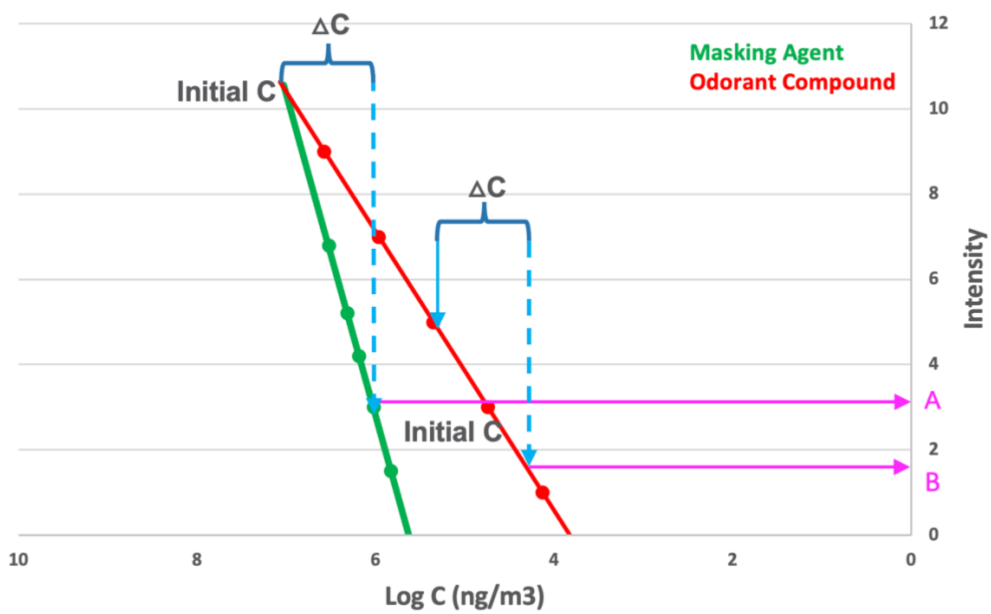


Figure 3.8b. Nonideal Situation Where a Masking Agent Can Mask an Odorant

One problem with these scenarios is always the question of, would a good masking agent mask the malodor or instead add a new odor to the odor mixture. Thus, an OPM analysis is needed to be performed for the mixture of odorous sample plus the masking agent. The OPM can determine if the masking agent add a new odor to the malodor or it actually masked the malodor.

3.5 Conclusion

The Weber-Fechner curves generated from the Vitko et al, (2016) study and this study showed a similar pattern. The musty odorants IPMP and MIB has a lower slope value, sulfur odorants dimethyl sulfide and dimethyl disulfide has a medium slope value and the fecal odorants indole and skatole has the highest slope. However, the regression lines of the Weber-Fechner curves are not identical between the two experiments. The results showed that different panels developed different Weber-Fechner curves due to sensitivity differences between panel, but in general the magnitude of slopes was similar between different groups. Therefore, it is recommended that each odor panel needs to develop their own Weber- Curve to undertake these types of studies.

The odor dilution curves from the biofilter at EDF demonstrated the same information provided by the Weber-Fechner curves where the fecal odor and sulfur odor dissipates faster than musty odor. Also, the masking effect is observed that fecal and sulfur odor can mask musty odors. This can be explained by the cross-over of Weber-Fechner curves. However, since the odor dilution curves represent the persistency of each odor type instead of the persistency of one specific odorant, the persistency pattern showed in the persistency curves will not be identical with the persistency pattern showed in the Weber-Fechner curves. When analyzing an odor persistency study, it is important to keep the same panelist, then the Weber-Fechner curves from these panelists can be used to explain the odor persistency for an actual unknown odor mixture sample.

The case study in France showed the value of Weber-Fechner curve to evaluate the ability of odor masking agents. The slopes of the Weber-Fechner curves showed that the majority of the masking agent has a higher slope than the odorous chemicals. Thus, the masking agent dissipate faster than the odorous chemicals, and will not be able to mask the malodor after dilution occurs naturally in the air. The use of the Weber-Fechner curve can also help to choose the best masking agent to cover the odor nuisance from an odor emitting facility. The masking agent should have a lower slope than the odorants if it were to spayed into the odor emitting source. A second way that the masking agent can work could be if it is spayed into the odor emitting source at a higher concentration, but this method may be very expensive. Alternately, applying the masking agent not at the source but further downstream from the odor emitting location could be the best method to maximize the performance of a masking agent.

This study proved that looking at only OPM as sensory data is not enough; OPM can only tell the odor perceived from the source location but not the odor perceived further away at the receptor's location. Weber-Fechner curves have to be tested in order to understand how each odorant dissipates. Weber-Fechner curves can help determine how persistent a chemical is by looking at the steepness of the slope and this information can be used to explain the odor masking effect.

3.6 Reference

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Chapter 4
The Importance of the Odor Profile Method and Odor Dilution Curves to Evaluate the Odor Attribution and Masking from Different Nuisance Odor Sources

4.1 Abstract

An "Odor Attribution Study" to gather data from a series of specific odor sources that impacted a community was evaluated. The odor sources included a Resource Recovery Park (RRP), which consist of a landfill, a material recovery centre and a composting facility; a Wastewater Treatment Plant (WWTP) and an Energy Development Facility (EDF).

This study, used uniquely the Odor Profile Method (OPM) and Odor Dilution Curves to identify each odor character, intensity and its dilution (persistency). Odor Activity Value were used to prove if the OPM and persistency data correspond with the chemical analysis. Odor Dilution Curves were determined by an olfactometry follows the ASTM E679-04 standard practice with a flow rate of 20 L/min.

The results of the OPM data showed the consistency between the air sample from the inside locations of the facility with the air sample from the downwind. RRP and WTP showed no odor was perceived at the downwind sampling location. Only EDF showed a medium level of rancid odor for the downwind air location. Comparing the OPM data at different locations of the EDF can help target the odor emitting source. The indoor receiving area in EDF has the same odor types received from the downwind of EDF. Thus, if the receptors are receiving the same rancid odor, then EDF might be contributing to the odor nuisance. The odor dilution curves showed that with higher dilution ratios, most of the odor characteristics disappeared. However, in some locations, the odor dilution curve showed the unmasking effect of musty odor. Musty odor were not detected at OPM or lower dilutions but started to appear after the higher intensities of fecal, rancid or rotten vegetable odor disappeared. The comparison of OAV data and the OPM data proved that OPM as an odor sensory method works well on telling odor characters and intensities. However, not all the data correlate with each other due to the unknown synergistic or antagonistic effect for odor

mixtures. Thus, using only chemical analysis or only odor sensory data is not enough. The combination of the two should be performed for any type of odor attribution study. Persistency curve and OPM together can provide predictions on the odor nuisance not only from the source level but also at the receptors level.

4.2 Introduction

The majority of the total air quality complaints at the Bay Area Air Quality Management District (BAAQMD) is for odor complaints. A local community in the BAAQMD area has been impacted by nuisance level odors for many years. Over the years, various odor control approaches have been implemented with different levels of success, but a persistent and ongoing odor issues continues to impact the local communities. Thus, a study was developed to determine the contribution of these odor sources to the odors present in the community. This is the first study to ever try to do complete an odor attribution study.

It has been determined that the nuisance odors from the impacted area are originated primarily from three closely located facilities:

- A Energy Development Facility (EDF);
- A Resource Recovery Plant (RRP), comprised of a landfill, a material recovery facility, and a composting facility; and
- A Wastewater Treatment Plant (WWTP).

The Energy Recovery Plant (EDF) produces clean, green renewable energy while producing a feedstock for composting. It processes “wet” organic waste material that is collected primarily from commercial industries. The waste includes food waste and residential waste (mainly yard trimmings), which would otherwise go directly to a landfill. The indoor EDF contains an indoor collection floor area with digesters and compost tunnels. The indoor EDF area was open to the outdoor air. Also, a biofilter was operated above the collection floor area. The EDF indoor collection floor is similar to previous studies completed at a biomass collection facility study by Rosenfeld and Suffet (2007) and a Trash Transfer Station study by Curren et al. (2016). These studies indicate that the time at the facility was a critical issue in the quantity of odor production.

The Resource Recovery Plant (RRP) consists of a composting facility, landfill, a material recovery facility. The RRP accepts and processes a wide variety of municipal, recyclable, and industrial waste from the surrounding communities. These wastes can include green waste, limited food waste (e.g., spoiled milk solids), commercial waste, residential waste, and biosolids material. There are six process areas for processing the wastes entering the RRP facility – material recovery facility, working face of the Landfill, green waste receiving and grinding area, composting area, biosolids stockpiling area, and the landfill gas collection area. Typically, the wastes enter the facility from the east via trucks and are dumped at various locations throughout the site for further processing, depending upon the types of waste. The compost facility and the landfill facility generated unique odor characteristics as exemplified by the previous studies of compost odors by Suffet et al. (2007, 2009), Rosenfeld et al. (2007); and landfill odors by Decottignie et al. (2009).

The Wastewater Treatment Plant (WWTP) is a tertiary publicly-owned WWTP, including pretreatment, primary treatment, sludge digestion, secondary treatment, and tertiary treatment. Wastewater entering the WWTP is divided into two key treatment processes: liquid treatment and solid treatment. The Wastewater Treatment Plant have some common and some different odor characteristic from the previous two locations as exemplified by studies of Abraham et al., 2015, Zhou et al. (2016), Vitko et al, (2017) and Vitko et al. (2021). The odor characteristics should follow the latest edition of the Wastewater Odor Wheel (Fisher et al., 2018).

The traditional methods of evaluating odor are the use of odor units from dilution to threshold and/or hedonic tone. The problem with measuring the D/T odor units is the lack of ability to distinguish specific odor types, their individual odor intensities and correlation with specific chemicals that are present that can cause an odor type. An odor attribution study should be based upon specific odor types and their intensities, and the chemicals that correlate with these odor types can be used to determined which source(s) of the odor nuisance are affecting the receptor community. Various studies have shown the ineffectiveness of dilution to threshold method. The panelist perceived some environmental odors but could not be measured by dynamic dilution olfactometry (Guillot et al., 2012). Some countries, such as Switzerland, prefer not to use the D/T method but using the questionnaires and complaints (Lebrero et al., 2011). For the drinking water industry, dilution-to-threshold limits did not resolve underlying taste-and-odor problems and correlated poorly with customer complaints (Suffet et al., 2013). A novel assessment of odor sources was conducted in Korea (Lee et al, 2012) that used the OAV, D/T, hedonic tone data with resident monitoring records. This study focused on the correlation between the sum of OAV (including reduced sulfur compounds, nitrogenous compounds and carbonyl compounds) with the resident monitoring records. However, this study failed to explain why the major complaint was for “burnt” and “other” smell, nor did it explain which source generated which type of odor and its contribution to the odor nuisance.

In this study, the Odor Profile Method (OPM) was used to identify the odor types and the intensities of each odor type at each sampling location. Also, the persistency of the odor types, intensities of each odor type and the masking/unmasking effect in the odor mixtures were evaluated by the use of Odor Dilution Curves. As explained in Chapter 3, the Odor Dilution Curves describe the rate of decrease of a perceived odor, thus can be used to understand offsite nuisance levels of these key facilities, and then help model the dilution of the odorous chemicals as it moves beyond the fence line of the facilities that are producing odors. Odor intensities decrease with dilution at different rates for different odors. An olfactometer was used to dilute each sample from different locations with 12 log dilution levels. The OPM results using the olfactometer were used to generate a persistency curve for each odor character and its intensity from each sample location.

Two sampling events were carried out. The first event was completed in mid-Fall, the week of October 19th, 2020. The second event was performed in early Spring, the week of May 17th, 2021. The overall objectives of the study were to:

1). identify from each odor source of each facility their odor character and intensity, the change of odor characteristics and their intensity with dilution; and if possible, the odorant compounds probably causing the odors that were impacting the community.

2). Evaluate the relationship between OAV and OPM to determine if results from sensorial and chemical analysis are consistent. Then, the relative contribution and variability of the odors from the different emitting sources could be evaluated.

4.3 Method

4.3.1 Odor Profile Method

The OPM is based upon the Flavor Profile Analysis (FPA) method for the food and drinking water industries, specifically Method 2170, the "Flavor Profile Analysis" of "Standard Methods of Water and Wastewater" (APHA, 2012). The FPA has a 7- level sugar scale to determine the intensity of each odor characteristic. The FPA was developed for the headspace of drinking water. It has been used for over 30 years and is a standard method to evaluate odor problems and quality control of specific odors in drinking water. The method was developed for air analysis studies by Burlingame (1999), Burlingame et al. (2003), Burlingame (2009) and Curren et al. (2014) as the OPM by smelling collected air in sampling bags from a location instead of the headspace from drinking water. The odor characteristics from suspected odorous chemicals that have been developed from past studies of defining the Compost Odor Wheel (Suffet et al., 2007), the Wastewater Odor Wheel (Fisher et al., 2018) and the Landfill Odor Wheel (Decottignie et al., 2009) were used to identify odor characteristics. These odor wheels show specific chemicals that have been indicated, for example, the causes of decaying vegetation, earthy/musty, fecal, rancid and sweet odors.

The OPM includes identifying one or more odor notes in the air sampled and determining the odor intensity for each odor note. Panelists have been calibrated to the odor intensity scale: threshold (1), slight (2), weak (4), medium (6), medium-strong (8), strong (10) and very strong (12). The calibration used the sugar-in-water solutions tasted by mouth that represent weak 4, (5% sugar), medium-strong 8, (10% sugar) and very strong 12, (15% sugar) as described by the standard method 2170 AWWA et al. (2017). Curren et al. (2014) showed that the sugar solution intensity calibration method for the OPM works as well as the butanol intensity standard method, ASTM, Method E544-10 (2004) that is traditionally used to determine the intensity of gaseous samples.

4.3.2 Weber-Fechner Law

The OPM method follows the Weber–Fechner Law (Fechner, 1859), where a single odorant's intensity is proportional to the Log of the odorant's concentration.

$$\text{Odor Intensity} = k \, \text{Log (Concentration)} + b \quad (1)$$

Whereas the concentrations are units such as ppb or $\mu g/m^3$, and k is a constant (called the Weber–Fechner coefficient) that is the slope of dilution in air. The slope k is unique to each chemical odorant. **Figure 4.1** shows the relationship between Odor Intensity and the Log (Concentration). The odor level of detection (1) (something that smells different that pure air) and odor level of recognition (4) where specific odor characterization can be observed. An action level of 3 below recognition has been suggested as an odor intensity that can minimize an odor problem. An odor panel of four is the minimum number of panelists needed for an OPM analysis.

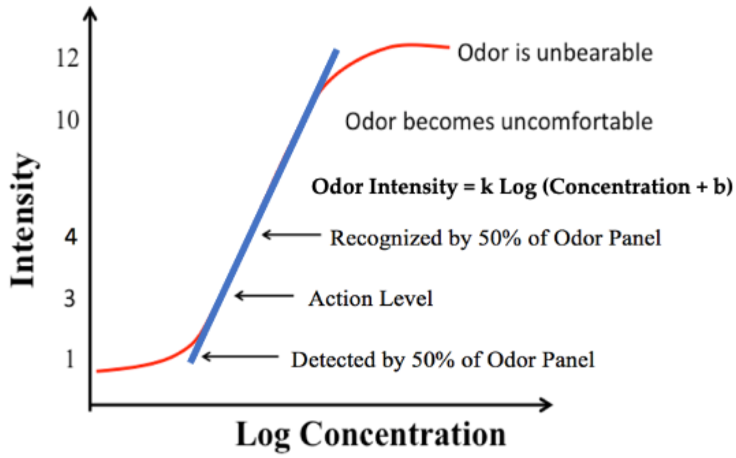

Figure 4.1.: Weber-Fechner Curve

4.3.3 Olfactometry for Developing the Odor Persistency Curves

The AC'SENT International Olfactometer (St. Croix Sensory, Inc., 2005), a dynamic dilution venturi-nozzle style olfactometer was used to develop the odor dilution curves of individual odor characteristics in an air sample. The olfactometer mixes odorous air samples with odor-free blank air at different levels of dilution for presentation to an OPM odor panel of four to develop persistency curves of individual odor characteristics in an air sample. Olfactometry follows the ASTM E679-04 (2011) and the EN 13725 (2003) Standard of Practice of Olfactometry using a total flow rate at 20 liters per minute.

The Direct Presentation Method (St. Croix Sensory, Inc., 2005) was used to generate odor persistency curves of odor intensity vs the log Dilution Ratio. The Direct Presentation Method is a method for presenting an odor sample at a specific concentration to a panelist for a specified amount of time of 3 seconds at each dilution level. The test administrator selects different dilution levels in the odor persistency analyses. Four panelists use the OPM to determine, the character and intensity of different odors that were present at each dilution level. The average of the 4 panelists at each dilution was used for each point on a persistency curve. Thus, the odor dilution curves (intensity vs log dilution ratio) were generated for each odor characteristic.

The dilution level used in this study is from level 3 to level 14. The dilution ratio is higher at low level and lower at high level. For example, level 3 has a dilution ratio of 16,000 while level 14 has a dilution ratio of only 8 (**Table 4.1**). The OPM actually is the original odor which means, no dilution. Thus, the OPM represent a dilution ratio of 1 (original concentration: diluted concentration = 1:1). When using the olfactometer, the experiment should always start from the lower dilution level that has a high dilution ratio. Therefore, panelists will be smelling low concentration of odor first, and eventually go to higher concentration. This approach prevents the panelists from getting nose fatigue if they were to smell the strong odor first.

It should be noted that the olfactometer for the odor dilution curves uses a nose cone at a flow rate of exactly 20 L/min for 3 seconds whereas the OPM method is determined by opening a sample bag's stopcock and squeezing a bag with a panelist's nose close to the stopcock. Thus, the delivery to the nose is less precise than by an olfactometer. The initial odor of the olfactometer dilution ratio is thus a more precise method of determining the OPM character and intensity. In fact, it has been observed that the Olfactometer OPM is usually greater than from the general OPM procedure. Graphical representation will show the OPM intensity values by bag squeezing method as an OPM value is always lower than the first point from the persistency curve as an Olfactometry OPM value.

Table 4.1. Dilution Levels of an Olfactometer for Persistency Curves

Dilution Ratio	Log
16000	4.2
8000	3.9

4000	3.6
2000	3.3
1000	3.0
500	2.7
250	2.4
125	2.1
63	1.8
32	1.5
16	1.2
8	0.9
1	0

4.3.4 Odor Activity Value

The Odor Activity Value (OAV) is actually a method using both the odor sensory data (OTC concentration) and chemical analysis data (measured concentration) to represent estimated odor potency. OAV is represented by the ratio of measured concentration of an odorant to its odor threshold concentration (OTC) (Patton and Josephson, 1957). OAV can provide measurement of which compounds in a mixture are likely to present the greatest odor nuisance. Different from the D/T ratio, which can only provide total odor level, this relative ratio provides more meaningful information about which odorants pose an odor nuisance problem. Determination of sensorially relevant odorants is:

$$OAV = C_0 / OTC$$

C_o = measured concentration

OTC = odor threshold concentration

OAV is generally a number without units. The number means how many dilutions is needed for one specific odorant to disappear. OAV number not only provide information on which compound in a mixture are likely to cause the greatest odor nuisance, but also can be used as a proof for the chemical detected.

4.3.5 Experimental Procedure

Samples were collected for a continuous of four days. After each sampling day, the collected samples were sent to UCLA by overnight FEDEX service to avoid odorants in the air sample from degradation or loss due to time, temperature or bag material. Sampling locations at each of the three facilities were determined based on historical odor measurement, site visit information and member expertise from AQMD. For the three targeted locations, air sample from sub-locations inside the facilities were collected, so did the upwind and downwind samples.

The samples were received each second day in the morning at 10 AM. OPM and olfactometry tests were performed at UCLA as soon as possible to avoid sample alteration. Chemical analysis was done by an outside lab which followed the analytical method described in **Table 4.2**.

Table 4.2. Chemical Analytical Method from Outside Lab (ALS Lab, California)

Odorant	AQMD Analytical Method	US EPA Analytical Method	Industry Accepted Analytical Method
Reduced Sulfur Compounds	ST-11 (BAAQMD 1982) ST-08 (BAAQMD 1982)	TO-14 (EPA 1999) EPA Method 16M	ASTM D5504 Method by Modified GC/SCD with sulfur chemiluminescence detection.
Hydrogen Sulfide	ST-21 (BAAQMD 1982)	EPA Method 16M	Jerome (< 50 ppm) Draeger tubes (> 50 ppm) Odalog/Acrulog (> 0.1 ppm) ASTM D5504 Method by Modified GC/SCD with sulfur chemiluminescence detection (5 ppb MRL).
Carboxylic Acids	NA	NA	ALS (sorbent tube) Method 102 (their unique standard method)

4.4 Results

4.4.1 OPM Data Evaluation at the Source of Odor Nuisance

4.4.1.1 Energy Development Facility

Table 4.3 indicates that for both the fall and spring events, the air had a weak musty odor before reaching the EDF. The air sample leaving the EDF included a high level of rancid odor and a mild level of sweet odor. The rancid and sweet odor came primarily from the interior space area where waste was assembled to be placed in the energy production process. The production of the rancid and sweet odors is similar to when trucks are filled with trash waiting at the location and while dumping soil is used to cover the trash after it is dumped, at a landfill, from aerobic oxidation of fats to fatty acids. The fatty acids apparently are further partially oxidized in air to aldehydes and ketones, adding a “sweet” note to the “rancid” odor (**Figure 2.6**). The odor appeared downwind from the EDF, thus, EDF could be a source of the odor nuisance to the receptor.

The biofilter effluent from the EDF showed a medium level of rotten vegetable and fecal odors which were probably partially removed by using air sweeping and other process presented at the EDF. These odors were anerobic odors probably from anaerobic microbial production of sulfur compounds by microorganisms using sulfate instead of oxygen as the electron acceptors (**Figure 2.4**) (Higgins et al., 2006; Chen et al., 2006). These odors did not appear to be produced sufficiently to contribute to the projected odor nuisance at the downwind location.

4.4.1.2 Resource Recovery Park

Table 4.4 indicates that for both events, air before reaching the RRP and after leaving the RRP has nearly no odor. The landfill gas (with a 100 dilution) has a very high rotten egg odor and a mild fecal odor during the October 19^{th}, 2020, fall sampling. The landfill working face had a high rancid and sweet odor. Odors from the landfill working face did not change much during the May 17^{th}, 2021, spring sampling, but the intensity of the rancid odor decreased. For landfill gas, the intensity of the rotten egg odor decreased and a mild rotten vegetable odor was detected instead of the fecal odor. This OPM analysis follows what has been observed in previous landfill studies (Bian et al., 2021).

Landfill gas was produced within the landfill from anaerobic reactions according to the Landfill Odor Wheel (Decottignies et al., 2009). It is within the general category (Sulfur/Cabbage/Garlic) which produce rotten egg, rotten vegetable, rotten cabbage, and garlic odors. These odors are caused by anaerobic production of sulfur compounds by microorganisms using sulfate instead of oxygen as the electron acceptors within the landfill (Higgins et al., 2006; Chen et al., 2006). A secondary odor of lower intensity in the Landfill Wheel, is sewage/fecal generated by microorganisms under the same low oxygen conditions by degrading nitrogen compounds (e.g., proteins) to yield compounds such as indole and skatole (Chen et al., 2006). When trucks filled with trash are waiting and while dumping soil is used to cover the trash after it is dumped, the "trash odors" are produced. According to the Landfill Wheel (Decottiginies et al., 2009) "trash odors" are within the general categories "rancid" from air oxidation of fats to fatty acids. The fatty acids can be further oxidized in air to aldehydes and ketones, adding a "sweet" note to the "rancid" odor as presented in the "Landfill Odor Wheel" (Decottignies et al., 2009). Secondary odors of lower intensity, "rotten vegetable" and/or "sewage/fecal" odors are produced from reduced sulfur and nitrogen compounds generated in low-oxygen (anaerobic) pockets by microbes within the load of trash that is transported to the landfill as described above.

Table 4.4 shows that during the first sampling, October 19th, 2020 (fall sampling) the OPM analyses of the compost pile has a mild musty and medicinal odor. During the second sampling, May 17th, 2021, (spring sampling), the OPM analysis of the compost pile showed totally different odor characters. The OPM analysis showed a medium level of pine and rancid odors. The composting process has been shown to have different odors as a function of the composting time (Suffet et al., 2009). The study indicated how the microbiological processes during composting changed the odors in three different compositing tests during a month of processing. A less odorous product as earthy/musty was produced from initial odorants of fecal and rotten vegetable. Composting is a slow aerobic oxidation process of primarily anerobic waste products from sewage sludge and waste from the EDF (energy development facility). In this study, the samples from the fall showed a final product of composting of musty and medicinal odor and the spring showed about a 75% product of pine and rancid odors. The rancid (fatty acid) material has not been completely composted. If the composting area was sampled at the beginning of the process, then more fecal, rotten vegetable and rancid odors would be present. Obviously, the source of the original compost would affect the amount of the odorous components present. A composting wheel of the major odors produced by composting can be used as compost odor reference and is found in Suffet et al., (2009) and Rosenfeld et al., (2004).

4.4.1.3 Wastewater Treatment Plant

Table 4.5 shows that for both the fall and spring events, air before reaching the WTP and after leaving the WTP were odor free. Samples collected from East Primaries have a medium level of rotten egg and fecal odor for both events. This is expected as shown in previous study (Vitko et al., 2017). Primary sedimentation does not have any air introduced while heavy particulates settle to the bottom. The water is an anerobic soup and previous waste water OPM analyses (Burlingame, 2004; Fisher et al., 2018) produce these odors as described in references (Higgins et al., 2006; Chen et al., 2006).

On the second event in the spring, the sample from bioreactor was separated into two locations: the aerobic zone and the mixing zone. Sample from the aerobic zone only has a mild musty odor.

These OPM data were consistent with the results from the previous study at WWTP (Vitko et al., 2017). Multiple locations at the WWTP produced similar odors. Specifically, the sulfur odors of Rotten vegetable, Rotten eggs, canned corn that were produced primarily from methyl mercaptan, hydrogen sulfide and Dimethyl sulfide, respectively. It is also noted that selectively musty and earthy odors are produced at trickling filter and activated sludge sites where high oxygen levels are present and more compete oxidation of chemicals occur. This apparently occurs by further oxidation of chemicals through the biological cycle to produce earthy/musty compounds that include MIB, and different pyrazines that are difficult to further oxidize biochemically. Sample from the mixing zone had a medium level of fecal and rotten egg odor. The fecal odor corresponds with the odor detected from bioreactor as one location in the fall sampling event. Thus, the fecal odor in the bioreactor location of WTP was mainly produced by the mixing zone. The mixing zone should be the target odor treatment location.

Table 4.3. Odor Profiling Analysis Data at the Energy Development Facility

	Energy Development Facility Event #1	Energy Development Facility Event #2
Sample Location	OPM Odor Characteristics and Avg. Intensity by Four Panelist by the Direct Presentation Method	OPM Odor Characteristics and Avg. Intensity by Four Panelist by the Direct Presentation Method
Upwind	musty 1.0±1.2;	musty 1.8±1.7
Downwind	rancid 5.0±2.0, sweet 3.5+1.0; other odor notes: rotten vegetable	rancid 3.0±1.2, sweet 1.0±1.2; other odor notes: musty
Biofilter Effluent	fecal 5.5±2.5, rotten vegetable 4.5±5.3;	fecal 1.5±1.9, rotten veg 3.5±2.5
Interior Space	rancid 10.0±1.6, sweet 10.0±1.6;	rancid 5.5±1.9, sweet 2.0±2.3

Note: If less than 1/2 of the panelists name an odor, this is called “other odor notes” and no intensity is included

Table 4.4. Odor Profiling Analysis Data at the Resource Recovery Park

	Resource Recovery Park Event #1	Resource Recovery Park Event #2
Sample Location	OPM Odor Characteristics and Avg. Intensity by Four Panelist by the Direct Presentation Method	OPM Odor Characteristics and Avg. Intensity by Four Panelist by the Direct Presentation Method
Upwind	NA	NA
Downwind	other odor notes: musty	other odor notes: musty
Compost pile	musty 2.5±1.9; medicinal 1.0±1.2	pine 4.5±1.0, rancid 3.0±2.6
Landfill Working Face	rancid 7.5±2.5, sweet 7.5±2.5; other odor notes: fecal	rancid 4.5±1.9, other odor notes: sweet, rotten veg, musty
Landfill Gas	rotten egg 8.5±5.7, fecal 2.0±2.3; other odor notes: sweet rancid, medicinal	rotten egg 5.0±2.0, rotten veg 2.5±3.0; other odor notes: fecal

Table 4.5. Odor Profiling Analysis Data at the Wastewater Treatment Plant

<table>
<tr><th></th><th>Wastewater Treatment Plant Event #1</th><th>Wastewater Treatment Plant Event #2</th></tr>
<tr><td>Sample Location</td><td>OPM Odor Characteristics and Avg. Intensity by Four Panelist by the Direct Presentation Method</td><td>OPM Odor Characteristics and Avg. Intensity by Four Panelist by the Direct Presentation Method</td></tr>
<tr><td>Upwind</td><td>NA</td><td>NA</td></tr>
<tr><td>Downwind</td><td>NA</td><td>NA</td></tr>
<tr><td>East Primaries</td><td>rotten egg 5.0±5.8, fecal 4.0±4.9;</td><td>rotten egg 4.0±3.3, fecal 4.5±3.0;
other odor notes: ammonia, rotten veg</td></tr>
<tr><td>Bioreactor (aerobic zone)</td><td rowspan="2">fecal 4.0±0.0,
other odor notes: rotten veg
(Was as one location)</td><td>musty 2.5±1.9;
other odor notes: fecal</td></tr>
<tr><td>Bioreactor (Mixing zone)</td><td>fecal 4.0±2.8, rotten egg 3.0±3.8;
other odor notes: ammonia, rancid, rotten veg</td></tr>
</table>

The OPM data showed above were similar with findings from previous studies. Even though the OPM data from the RRP and WTP determined here did not appear to contribute to the odor nuisance downwind from the WWTP. The wind direction and other meteorological effect might bring the odor from these location to the receptors in different areas. The importance of obtaining the OPM data is to correlate certain location with odor nuisance at the receptor. The next step is the evaluation of the OPM data and understanding an odor nuisance downwind. This can be evaluated by the persistency of the odors (dilution rate of the odor from the source to areas downwind).

4.4.2 Masking/Unmasking Effect showed by the Odor Dilution Curves

The OPM data shows only the odor character and intensity from the source level, meaning the character of each odor and the respective intensity are perceived as if the receptor lives inside these three facilities. To better understand the contribution of each source to the actual receptors live further away, the change of odor characteristics and their intensity with dilution should be studied. Then, the relative contribution and variability of the odors from the different emitting sources could be evaluated. OPM data is equivalent to 1:1 dilution level, thus showed as 0 log (Dilution Ratio) on the x-axis.

For both events, samples from the EDF biofilter (**Figure 4.2, 4.3**) have showed that musty odor was masked by the rotten vegetable odor and the fecal odor that were at high intensities. After dilution, musty odor started to appear while rotten vegetable and fecal odor decreased. Samples from the EDF interior space (**Figure 4.4, 4.5**) also showed the similar situation where sweet and rancid odor at high intensity masked the musty odor. When high dilution occurred, with the decrease of sweet and rancid odor, low intensity of the musty odor were observed. The EDF downwind sample from event 1 (**Figure 4.6**) again showed the masking effect where sweet and rancid odor masked the musty odor at lower dilutions.

The Landfill working face at event 1 (**Figure 4.7**) showed a high level of rancid odor and a medium level of sweet odor, at a lower dilution level. A weak musty odor was detected at high dilution levels, meaning the musty odor was masked by the rancid and sweet odors.

The bioreactors as one location in event 1 (**Figure 4.8**) showed that a fecal odor at a medium intensity masked the rotten vegetable odor. The OPM data showed no rotten vegetable odor but with the increasing dilution level, some rotten vegetable begins to appear. This case showed that not only musty odor can be masked, other odors with a low intensity can also be masked by the strong odors.

Thus, for odor prediction for the EDF biofilter, EDF interior space and RRP landfill working face, musty should also be included as possible odor nuisance at the level of the receptors. For odor prediction for the WTP bioreactor, rotten vegetable should be added as a possible odor nuisance for the receptors.

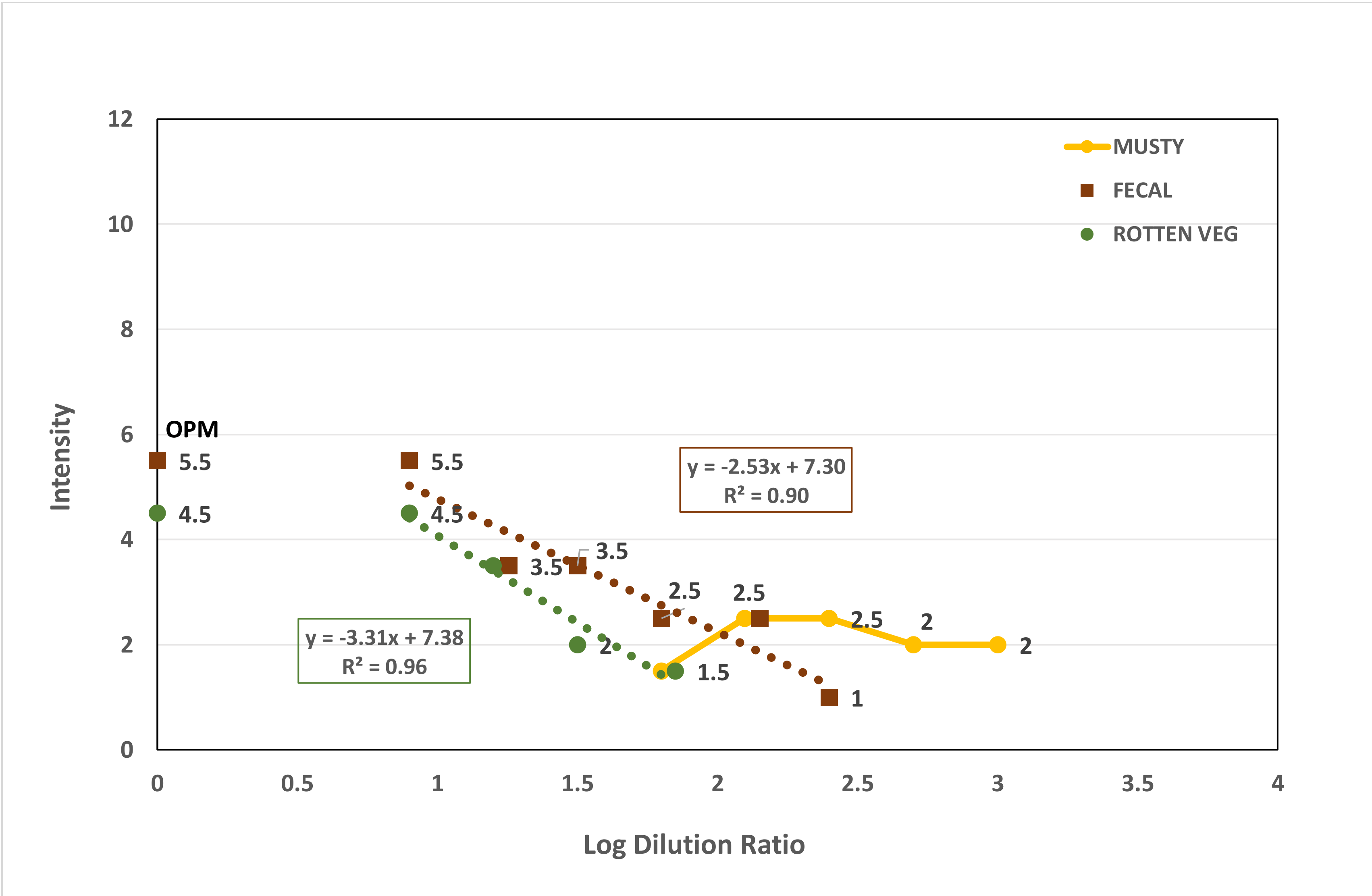

Figure 4.2. Persistency Curve for Event 1 – EDF Biofilter

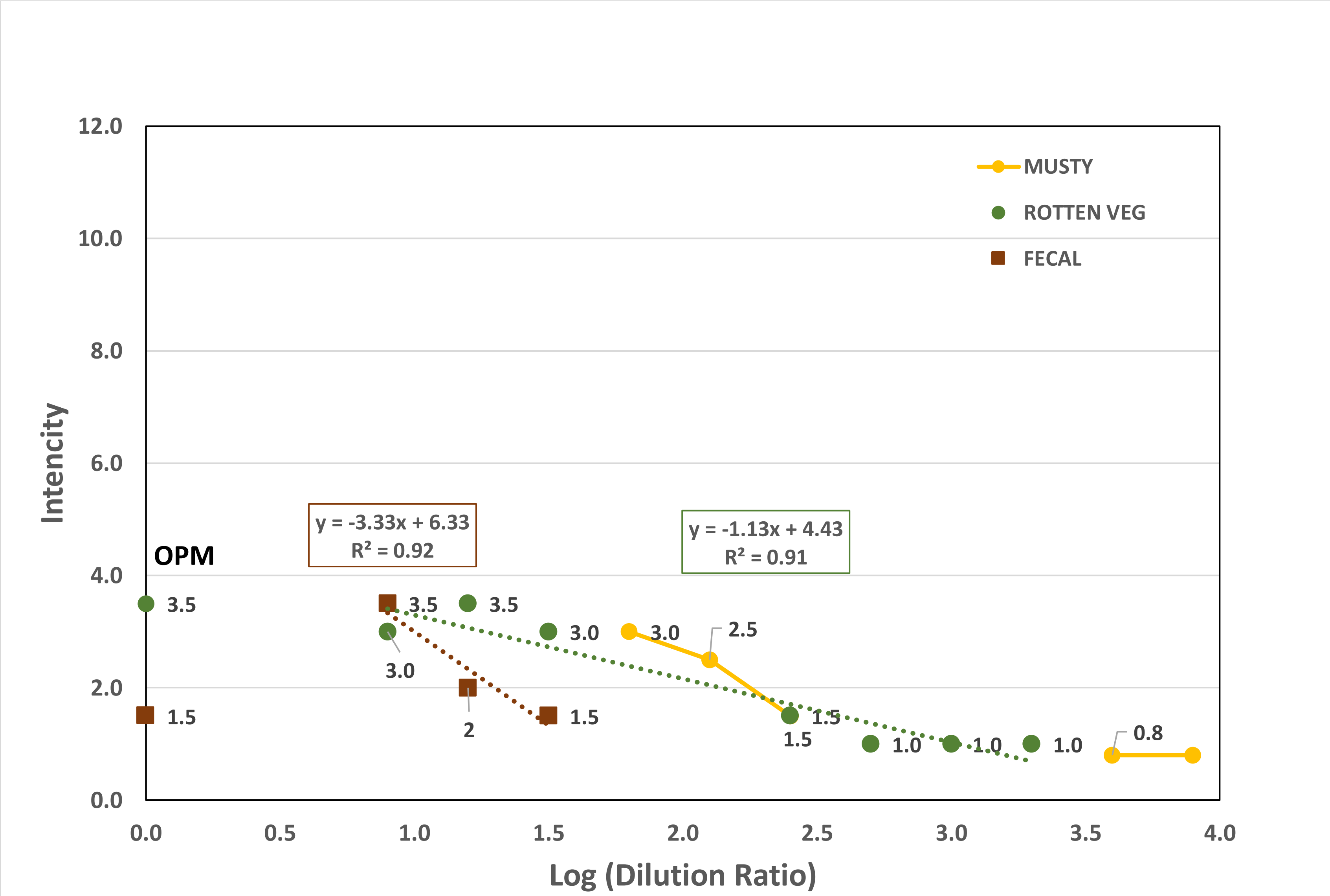

Figure 4.3. Persistency Curve for Event 2 – EDF Biofilter

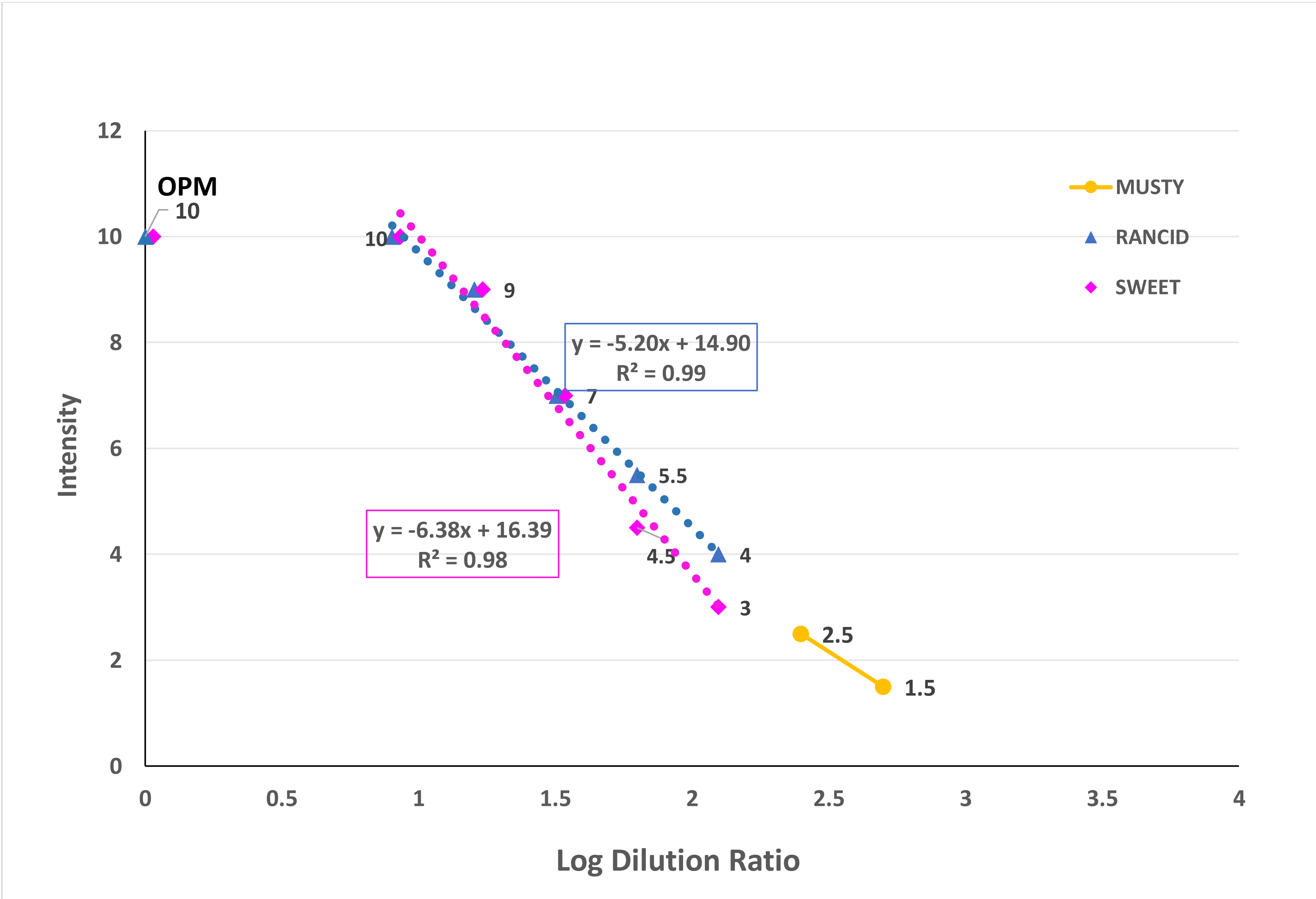

Figure 4.4. Persistency Curve for Event 1 – EDF Interior Space

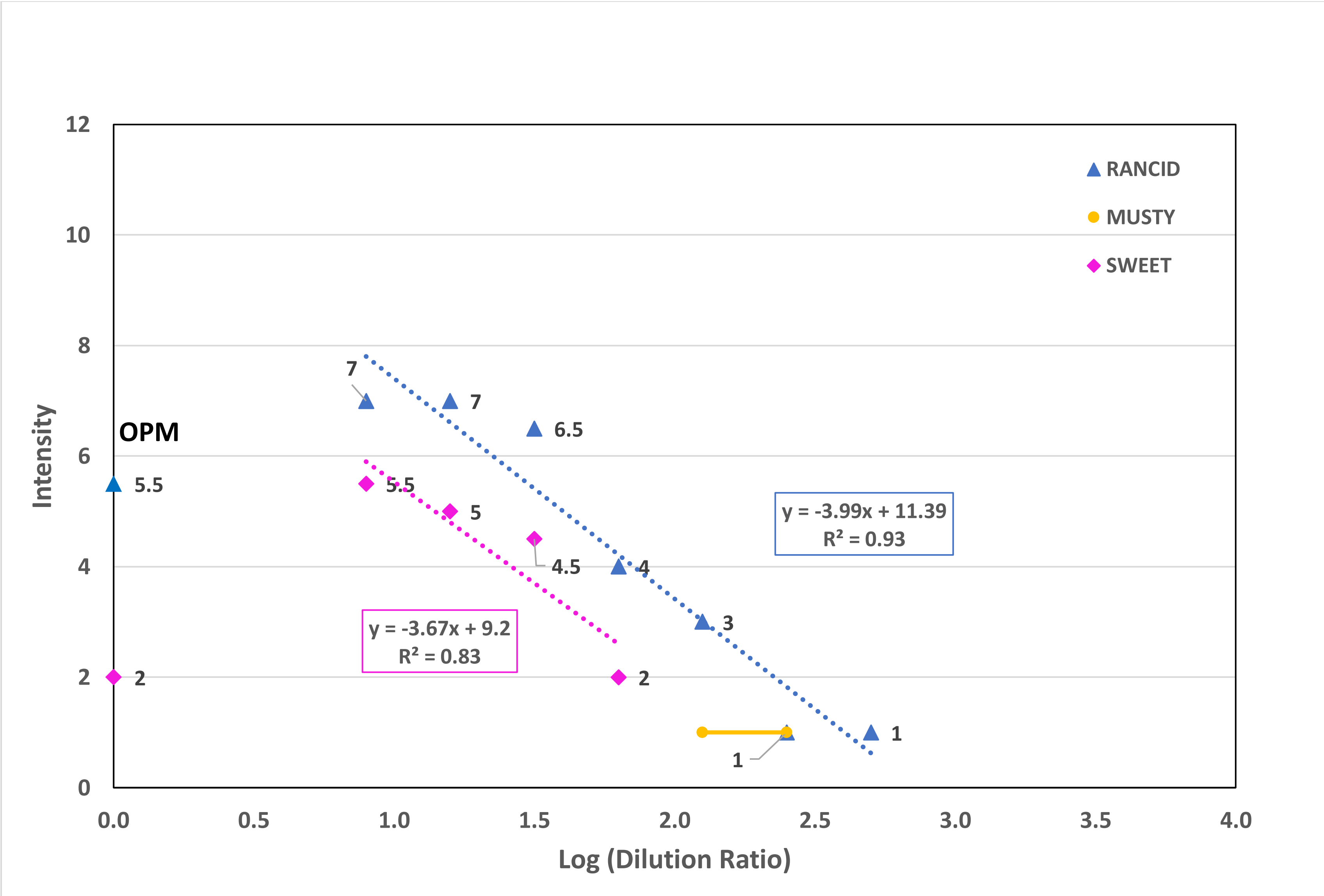

Figure 4.5. Persistency Curve for Event 2 – EDF Interior Space

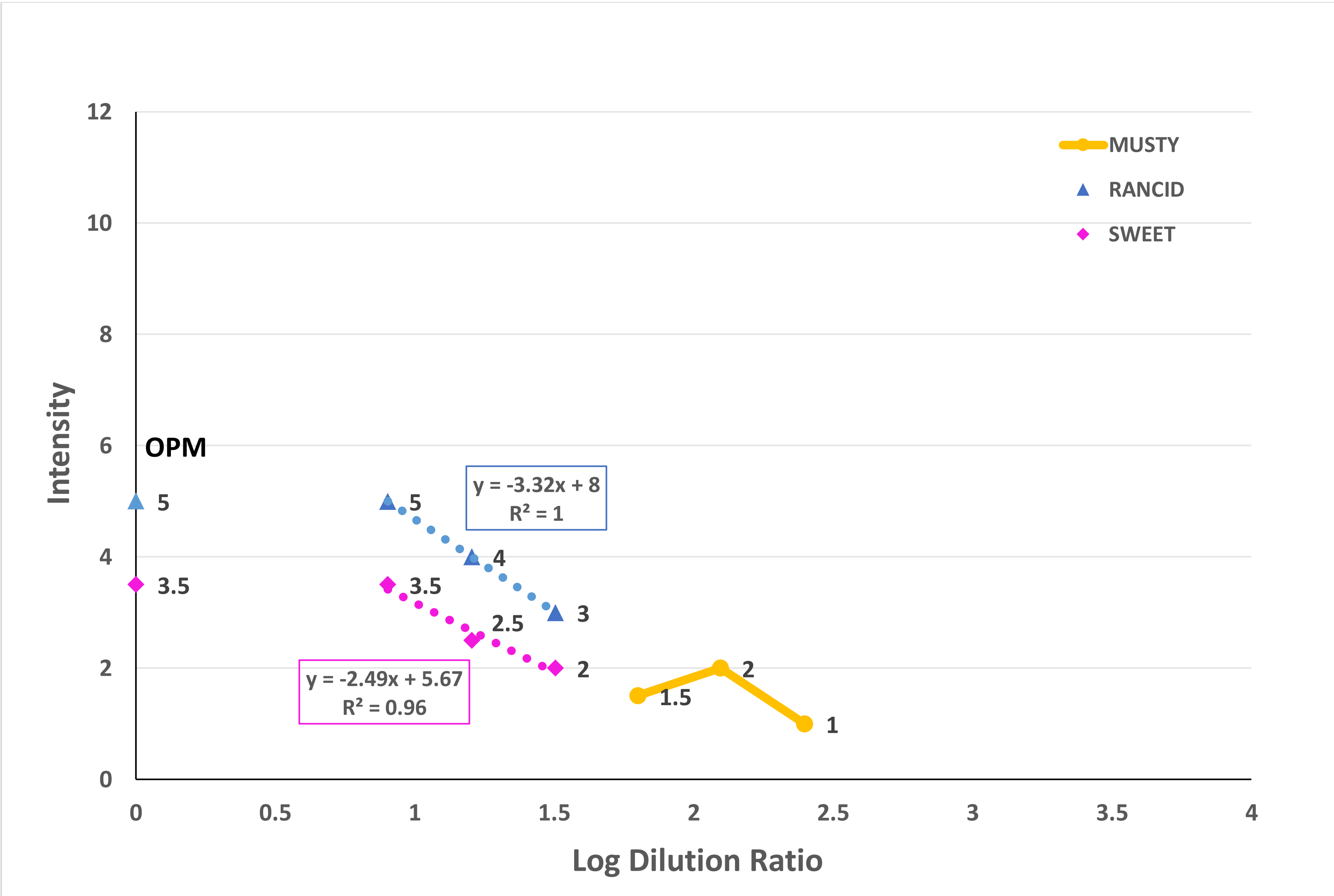

Figure 4.6. Persistency Curve for Event 1 – EDF Downwind

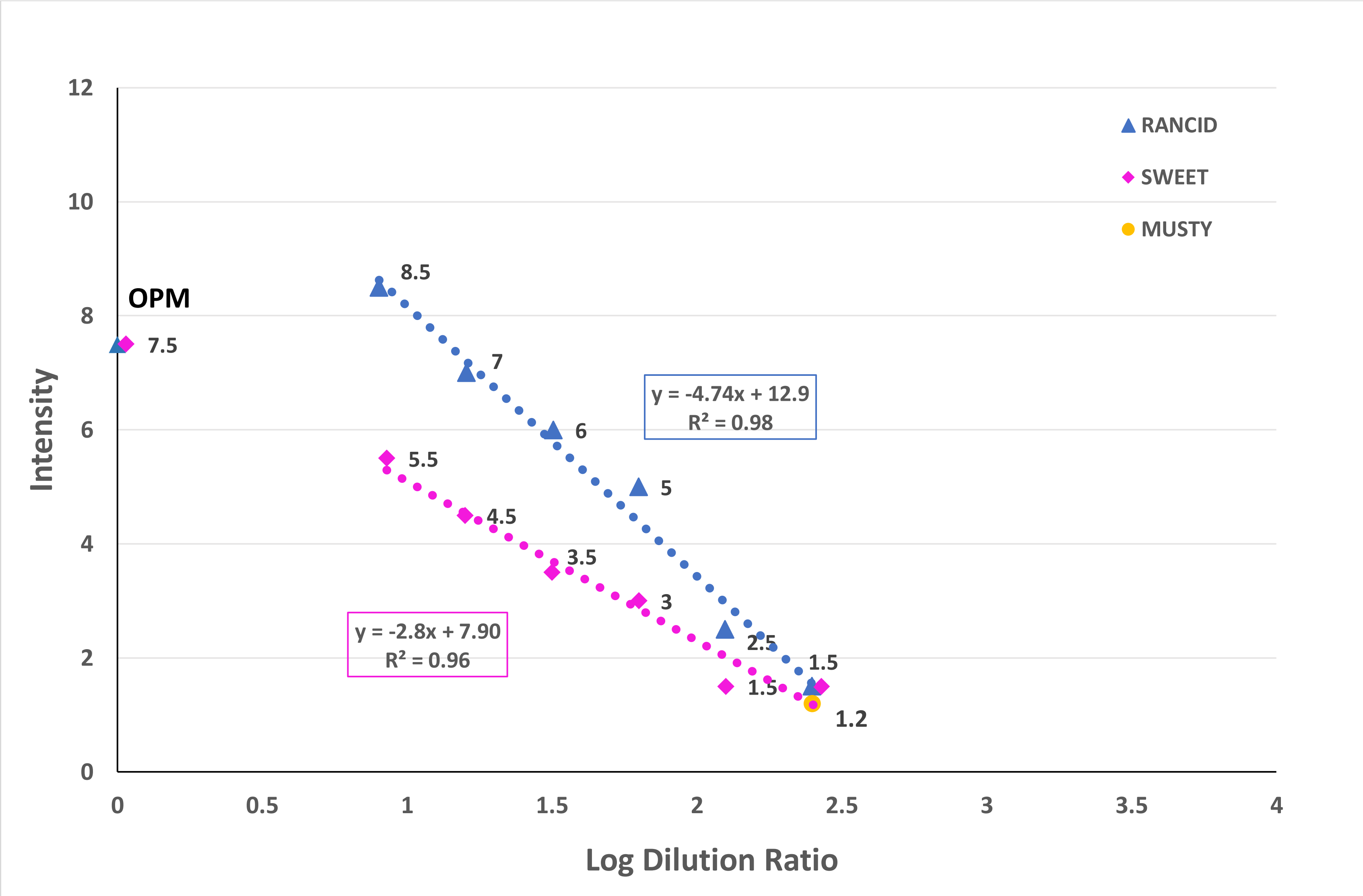

Figure 4.7. Persistency Curve for Event 1 – RRP Landfill Working Face

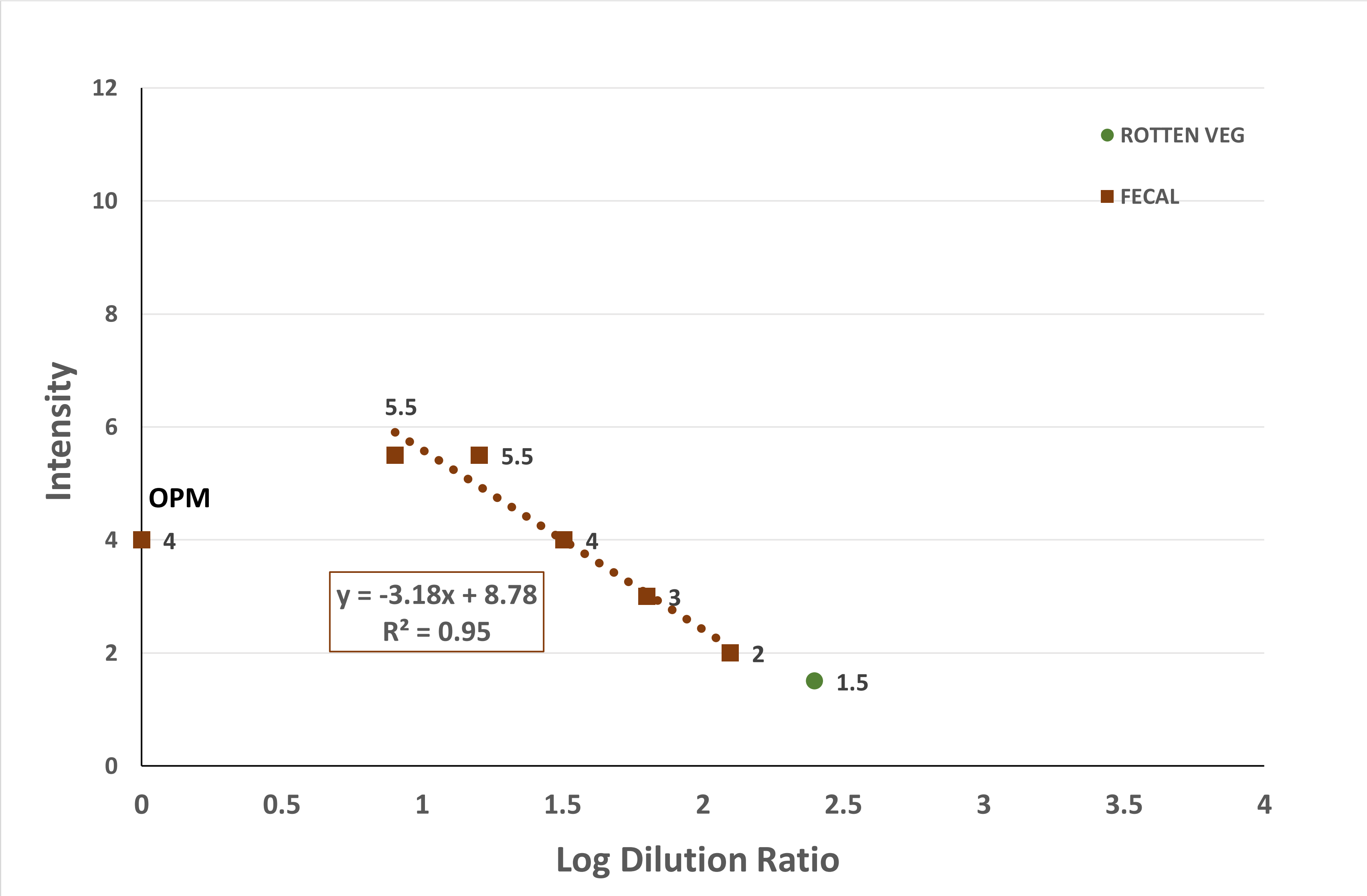

Figure 4.8. Persistency Curve for Event 1 – WTP Bioreactor

The comparisons of the odor dilution curves and the OPM data showed that there was a difference between the OPM and the odor dilution curve's odor character and their intensity levels. The differences between OPM and the odor detected from diluted sample were caused by the different way of presenting the air sample. The OPM data was done by a bag sniff where panellists squeezed the sampling bag and sniffed from the opening of a port on the bag. The persistency curves on the other hand, used the olfactometer where the air flow rate is set precisely at 20L/min. Thus, to standardize the OPM data, we should modify the olfactometer dilution level to include no dilution in the system and present the original air sample to the panellists from the olfactometer instead of a bag sniff.

The odor dilution curves showed the value of detecting odor characters that were masked by the odors at higher intensities. Since the OPM values are showing odor levels from the source location, they cannot show how the odor will be at a further distance from the source (the receptor's level). The odor dilution curves on the contrary, are able to show how persistent each odor is after leaving an odor source by dilution. Another importance of the odor dilution curves is its ability to show masking and unmasking of other odor that may occur as odor nuisances. It should be noted that no other factors such as, wind direction, wind velocity, topography or any other nature factors was considered in this study.

4.4.3 Odor Activity Value

A comparison of the OAV values with the OPM data for both events were presented for the first time to see if they match with each other. It is observed that many of the detected odorants' OAV match with the OPM odor character and intensity. However, not all results corresponded with each other.

From **Figure 4.9** and **4.10**, methyl mercaptan were detected to be the highest OAV detection for EDF biofilter and interior space. Butyric acid from interior space has the highest OAV. Thus, removing methyl mercaptan and butyric acid should be the primary focus when designing the odor treatment procedure. Interestingly for RRP, the highest OAV detected for the sulfur compounds is hydrogen sulfide (**Figure 4.11**) which is different from Methyl Mercaptan from EDF. Thus, the treatment for hydrogen sulfide should be the focus for RRP. Butyric acid has the highest OAV among the carboxylic acids that were detected (**Figure 4.12**). For WTP, both hydrogen sulfide and methyl mercaptan were detected as the higher OAV compounds (**Figure 4.13**). Thus, treatment for both hydrogen sulfide and methyl mercaptan should be implemented as odor removal processes for WTP. Comparing the OAV level for each location, the RRP has the highest OAV value for all detected compounds, followed by WTP and then EDF. Thus, RRP should be the primary location that can have greater influence on the odor nuisance. It should be noted that even though hydrogen sulfide and methyl mercaptan produce similar sulfur odors, they need to be removed by different processes. Methyl mercaptan cannot be sufficiently removed by the usual scrubbing methods for hydrogen sulfide as described in a previous study (Vitko et al., 2021): caustic bleach chemical scrubbers or granulated activated carbon did not successfully remove methyl mercaptan, the emissions from these scrubbing technologies remain odorous.

From the comparison of the OPM data and the OAVs, it showed some consistency between the two results. The OAV for carboxylic acid at EDF interior space (**Figure 4.10**) decreased from 484.2 to 6.9 with the OPM for rancid odor decrease from 10.0 to 5.5. For RRP landfill gas (**Figure 4.11**), the OAV for sulfur compounds has the highest value of over eight million and decreased to 35 thousand, the OPM for rotten egg odor also decreased from 8.5 to 5.0. For WTP east primary, the highest OAV was detected for sulfur compounds at over 50 thousand for the first event and decreased to 1100 in the second event, and the OAV for bioreactor mixing zone in event 2 has the OAV at 1100. The OPM corresponded with a 5.0 rotten egg odor at east primary in event 1, which later decreased to 4.0 in event 2; and the bioreactor mixing zone in event 2 has a similar rotten egg intensity of 3.0 with east primary. No carboxylic acid was detected for WTP which corresponded with the OPM data of no rancid odor detected for WTP locations.

The comparison of the OPM data and the OAVs also showed inconsistency. When EDF interior space from both events showed a medium level of sulfur compounds OAV (**Figure 4.9**), but the sulfur odor related with these OAV numbers were not detected in the OPM data. This might be caused by the high rancid odor masked the rotten vegetable odor. Similar situation was seen in RRP where landfill gas has a high intensity of rotten egg odor which corresponded with the high levels of the sulfur OAV, but no rancid odor was detected even with the high level of carboxylic acids (**Figure 4.12**) OAV detection. This might be caused by the rotten vegetable odor at high intensity masked the rancid odor that supposed to be shown in the OPM data. The inconsistency indicated a new finding that one odor type at a high intensity might be masked by the major odor type at a high intensity. The odor that was being masked did not show after the major odor type decreased by dilution, as the odor being masked might have a similar persistency slope with the major odor. When the major odor dissipates, the masked odor also has disappeared. Leaving no evidence on the existence of the masked odor. Other possible reasons for the inconsistency between OAV and OPM phenomenon are:

1. Different odorants from an air mixture might have an antagonism effect.
2. Different odorants from an air mixture might have a synergistic effect.
3. Odors are caused by other chemicals outside of the detection list.
4. Chemical analysis error

5. OPM analysis error

From above, part of the OPM data were confirmed by the OAV data. The inconsistency of the OAV and OPM indicated a new odor masking scenario where an odor at a high intensity can mask another odor at a high intensity. However, with dilution the unmasking of the odor will not occur. Overall, the chemical analysis and odor sensory analysis have to cope with each other to understand an odor attribution study. None of the methods alone is superior enough to tell what odor is detected and which compounds should be removed to control the odor.

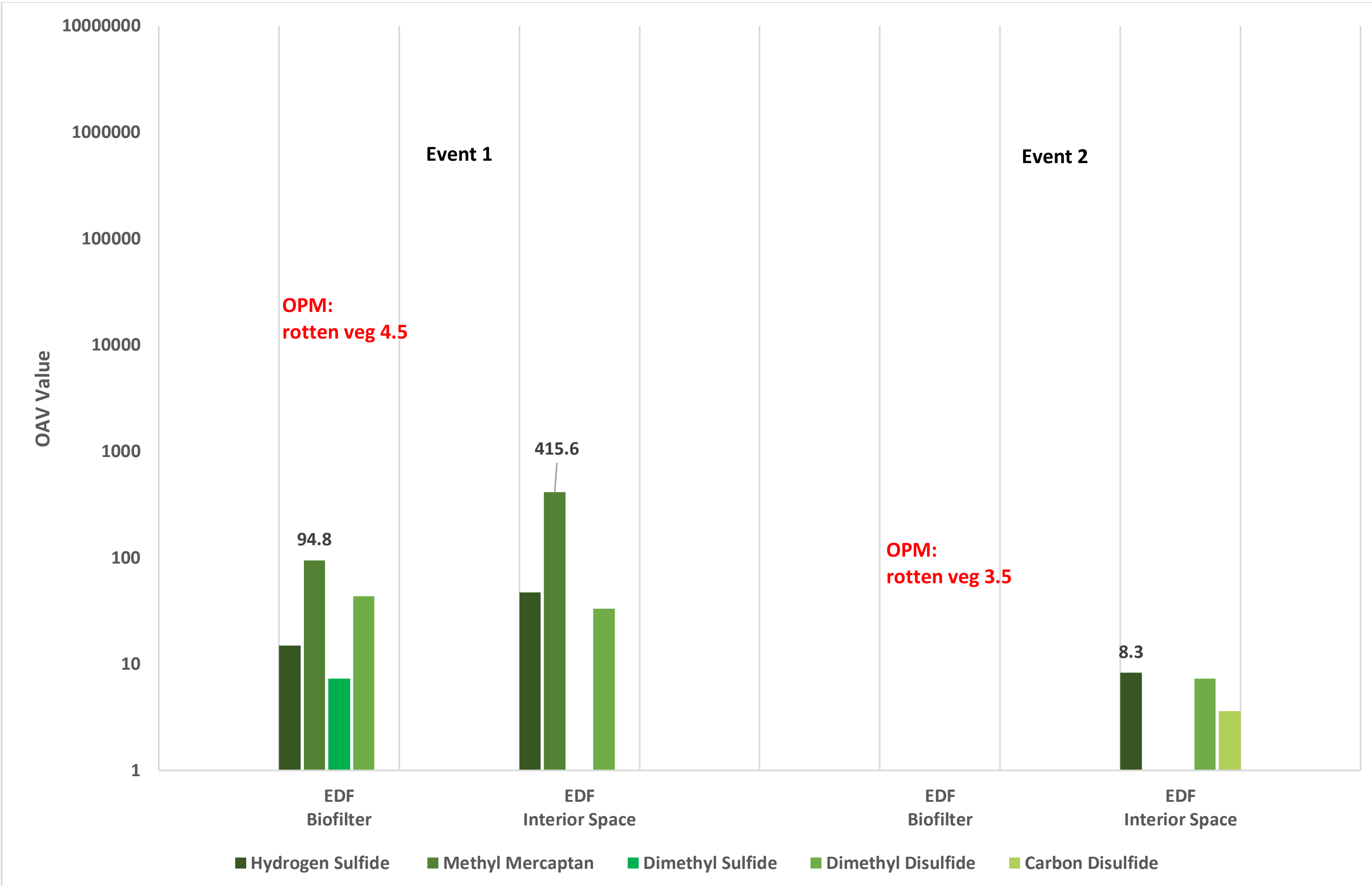

Figure 4.9. Sulfur compounds OAV vs. OPM at EDF

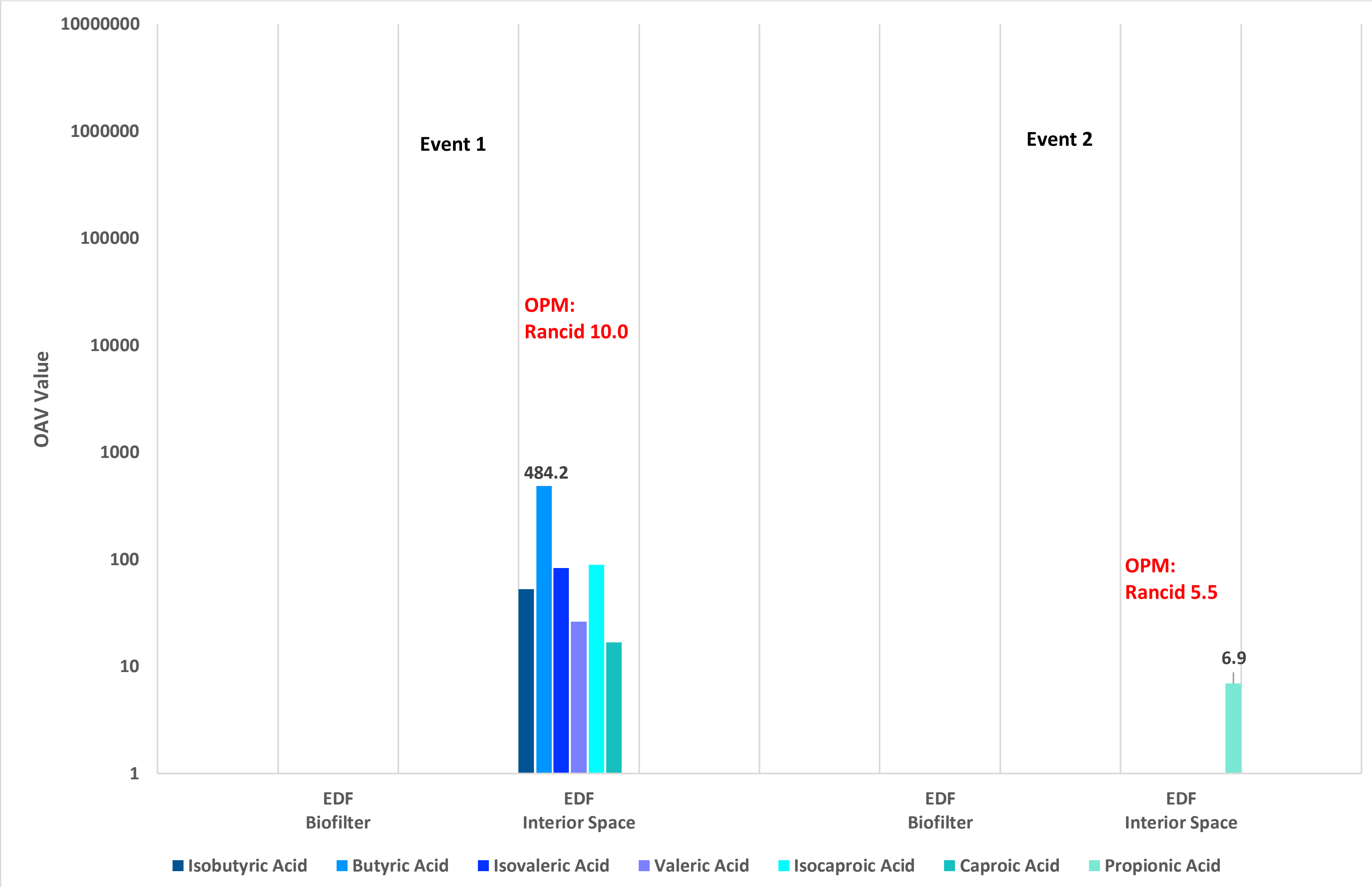

Figure 4.10. Carboxylic acid compounds OAV vs. OPM at EDF

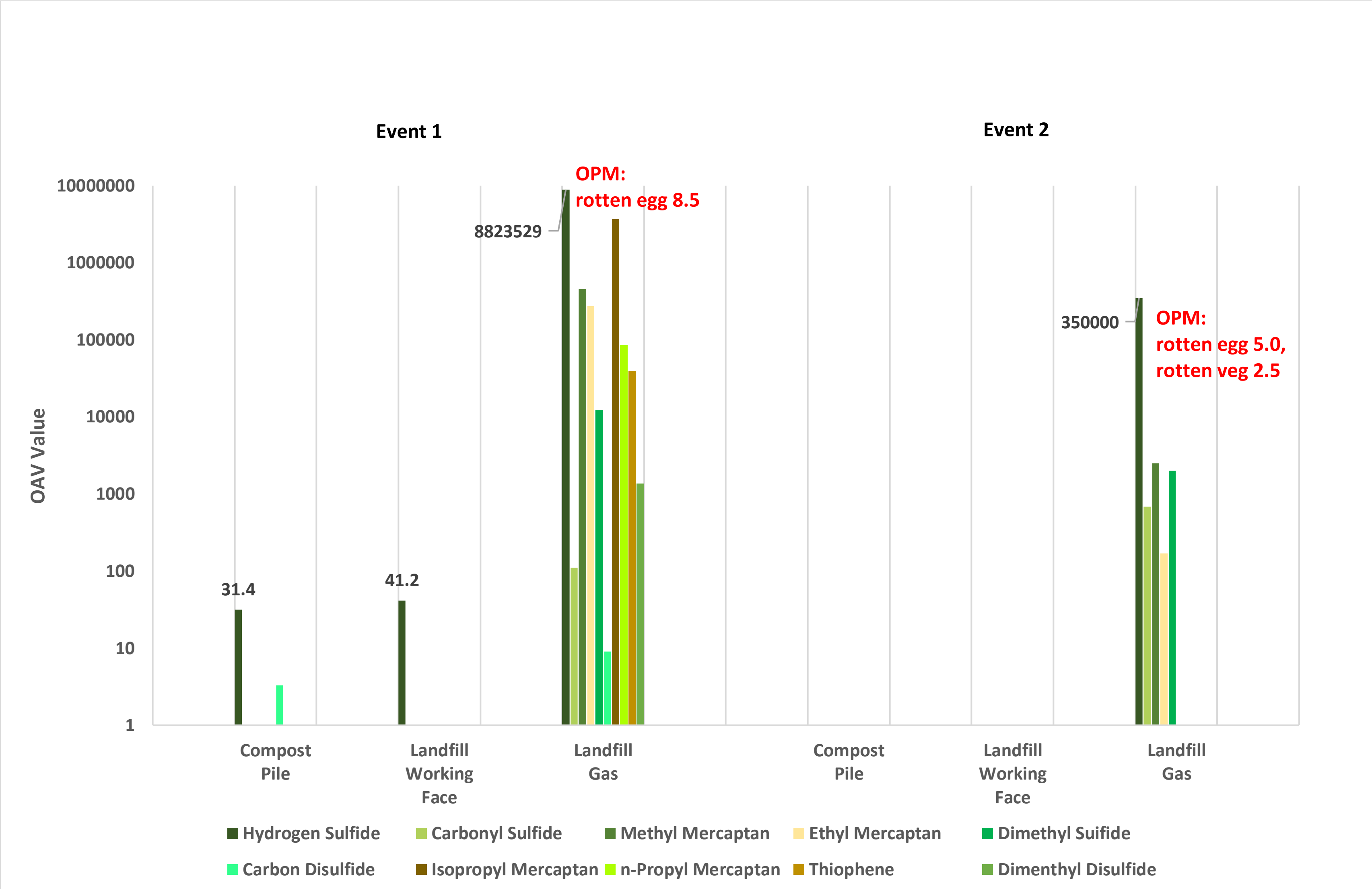

Figure 4.11. Sulfur compounds OAV vs. OPM at RRP

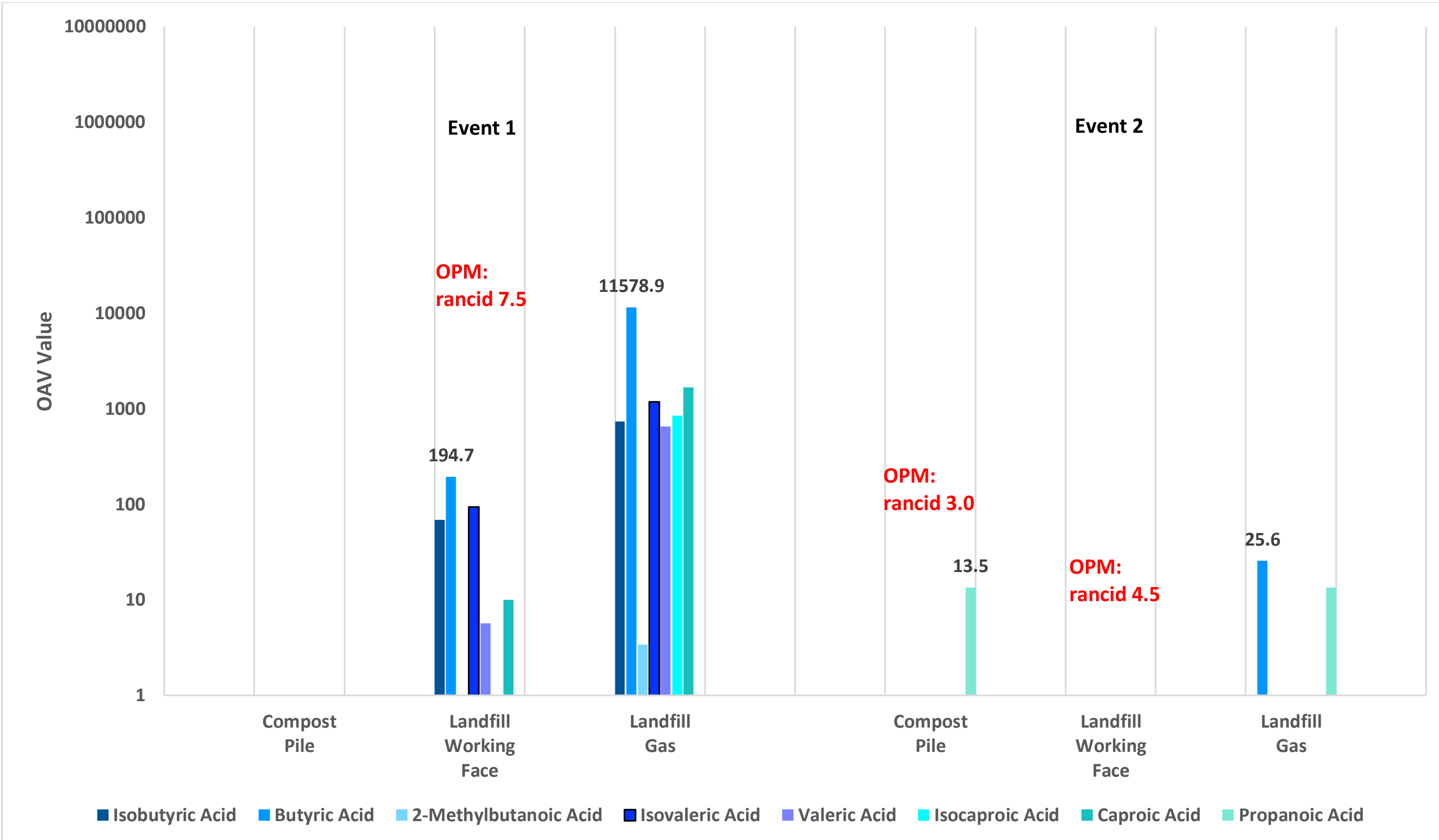

Figure 4.12. Carboxylic acid compounds OAV vs. OPM at RRP

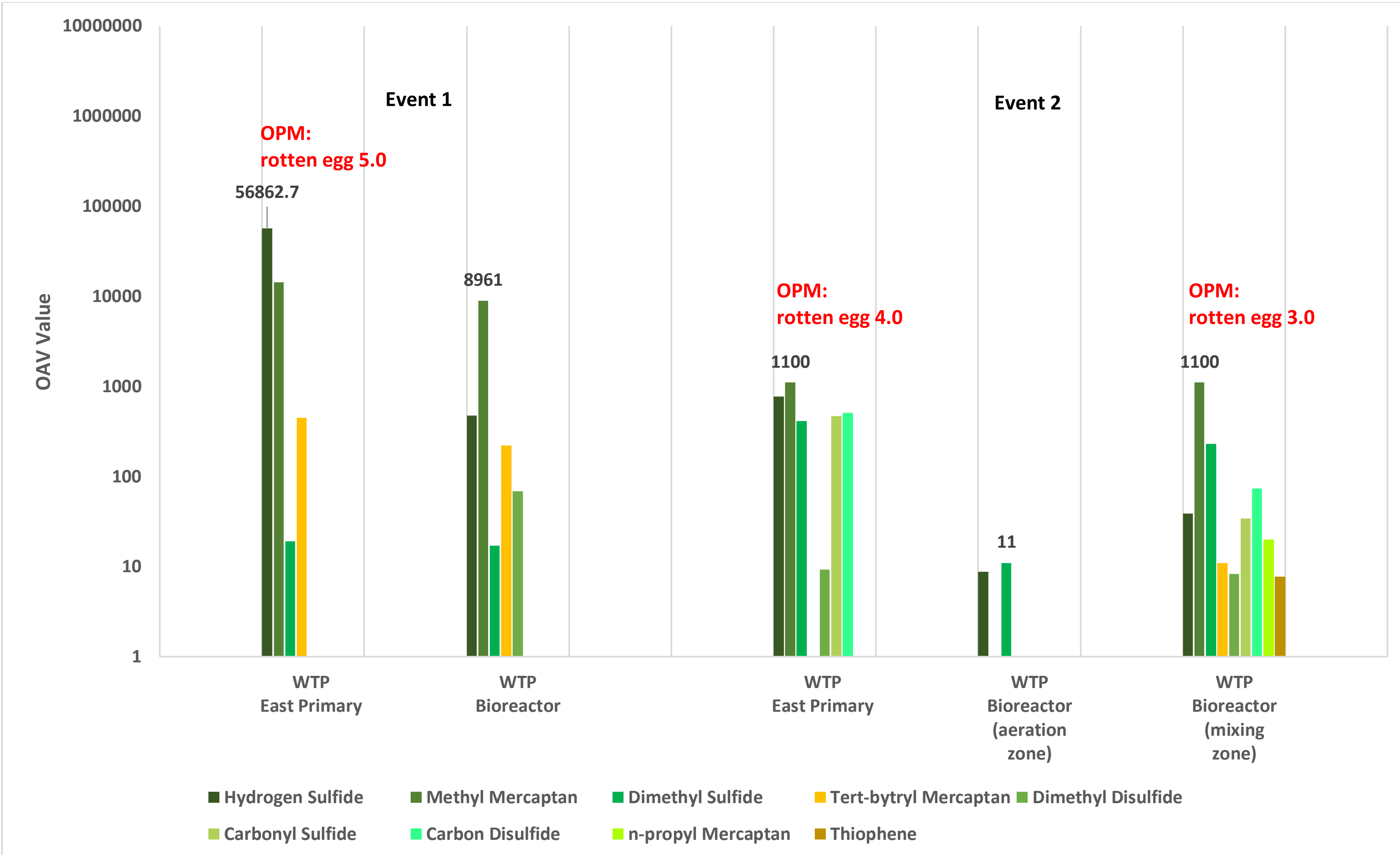

Figure 4.13. Sulfur compounds OAV vs. OPM at WTP

4.5 Conclusion

OPM can provide information on each odor character and its intensity from different locations. For the Energy Development Facility, the upwind sample had a minimum background musty odor. The biofilter area has a medium level of fecal and rotten vegetable odor, which did not contribute to the downwind air to the community. This indicates that the indoor area of the EDF was the primary source of the odor to the downwind location because of a very high level of rancid odor. All the odors detected at the EDF were higher in event one than event 2. For RRP, due to wind direction and other factors, no odor was perceived from the downwind location air sample. The landfill gas showed high rotten egg odors, and landfill working face showed high rancid odors, and the intensity went down from event 1 to event 2. The compost pile did not show much of a malodor other than musty and medicinal, but in event 2, there was pine odor and rancid odor. The OPM results showed similar odor characteristics with previous studies. However, the OPM data described only odor perceived from the source. The information cannot 100% describe what the receptors are receiving.

The odor dilution curves from both events showed consistency; most malodors disappear fast as the dilution level goes up. The odor dilution curves at the EDF showed that other than rancid, sweet, rotten vegetable and fecal odor, the musty odor will appear as the dilution level increases. The odor dilution curves at the RRP Landfill Working face also showed that musty odor can appear after dilution. The odor dilution curves at the WTP Bioreactor showed that rotten vegetable odor can appear after dilution. Thus, if the odor emitted from these sources were able to reach the receptors area, the odor perceived might not be rancid, rotten vegetable or fecal odor, but musty odor. Looking at the slopes of each odor dilution curves, fecal odor tend to dissipates faster than all other odor, and musty odor has the lowest disappearing rate, these results corresponded with the Weber-Fechner curves in chapter 3. The odor dilution curves help to show how persistency an air mixture is and provides a better estimate of what odor nuisance is received from the receptors.

The OAV data provided insights on which odorant has the most significant potential of causing odor nuisance. The comparison between the OAV and OPM showed that part of the sensory data was consistent with chemical data in this study. The OAV data indicates that different odor treatments should be implemented for different types of odorant chemicals. The EDF and WTP should focus on Methyl Mercaptan removal while the RRP should focus on Hydrogen Sulfide removal. The OAV value generally corresponds with the OPM data, especially for carboxylic acid and sulfur compounds. However, there were cases when the OAV shows a high OAV value for the chemicals, but no corresponding odor was detected. This might due to the masking effect of one strong odor to another strong odor. There might also be antagonism or synergistic effects for the odorants in the mixture, chemical analysis or odor sensory analysis errors.

Overall, to better understand an odor attribution study, both chemical and odor sensory analyses should be done. For odor sensory analysis, the most important ones are the OPM and the odor dilution curves. The information provided by the OPM and the odor dilution curves can be used for modelling estimates on odor perceived at the receptor.

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Chapter 5
Conclusions and Future Research

5.1 Conclusions

Odor Profiling Method determined the odor character, odor intensity, odor frequency and odor duration at a school affected by a landfill. The OPM successfully determined the odor nuisance decrease at the school affected by a landfill, as only 1.3% of the data showed an odor nuisance possibly caused by the landfill. The OPM results were consistent with the odor complaint results. OPM determined the odor character and intensity at the three primary odor emitting sources (EDF, RRP and WTP). The OPM data at each location were compared and determined if these locations were causing the downwind odor nuisance. Thus, the OPM can determine odor character, odor intensity, odor frequency and duration, and if a source is causing the odor nuisance at the downwind location closed by. However, OPM cannot determine the odor nuisance at further distances and locations.

Different study groups can reproduce Weber-Fechner Curves. The compared results of the Weber-Fechner curves showed that the IPMP and MIB as the musty odorants have flatter slopes compared to Skatole and Indole as the fecal odorants. However, the Weber-Fechner Curve results have similarities but are not identical. In order to be precise with the sensorial data when performing an odor study, a study group should always generate their working Weber-Fechner curves for at least the primary odorants detected from their study. The persistency curves from the biofilter at EDF demonstrated the same information provided by the Weber-Fechner curves where the fecal odor and sulfur odor dissipates faster than musty odor. And the masking effect that fecal and sulfur odor can mask musty odor can be explained by the cross-over of Weber-Fechner curves. In the French case study, the odor masking agent has a higher value of the Weber-Fechner curves than the detected odorants, which explained the reason for the poor performance of the odor masking agents. The solution for the poor masking agent performance includes selecting the masking agent with a low Weber-Fechner curve, applying high concentrations of odor masking agent at the source, or applying masking agent at a further distance from the odor emitting source. A thorough understanding of the slope in the Weber-Fechner Curves provided insights on the proper selection and application of the odor masking agents. Thus, the OTCs are important in evaluating if an odorant can be perceived at a lower concentration. The Weber-Fechner curve can provide information on the persistency of each odorant.

Odor dilution curves help show how persistent an air mixture is and provide a better estimate of the odor nuisance(s) perceived at the receptor. Some odors at a lower intensity can be masked by other odors in the mixture at higher concentrations. With the dilution, the unmasking effect may show additional odor types in the odor dilution curves. The odor dilution curve cannot show which location is of the highest attribution to the odor nuisance because of the lack of knowledge of odor mixture synergistic and antagonistic effects, typography, wind speed and other meteorological situation influences. However, this information can be used for odor dispersion modelers as real-life scenario information.

The results showed an inconsistency between the OAV and the OPM results. Synergistic or antagonistic effects by OPM may occur, which cannot be measured by this methodology. Analytical and sensorial methods can both result in errors. Thus, the study showed the importance of using chemical and sensorial analysis when evaluating an odor problem.

The OPM, odor dilution curves and associated chemical analysis (Odor Activity Values) have been used for the first time to determine the cause of different odor sources to a community. This thesis has developed a unique approach of using the Odor Profile Method and the Persistency Curves to support the evaluation of odor nuisances.

5.2 Future Research

- Unknown odorants in an air sample can be determined by using the GC-sniff method. This should be done to detect odorants that are not in the primary odorant list of an air sample.
- Future studies should develop more sensitive analytical methods to narrow the gap between MRLs and OTCs to identify more odorants.
- Odor masking effects that do not show the unmasking effect should be tested by smelling the odor mixture to see if the masked odor can be perceived after the other odorant is removed.
- Improving the olfactometer program to include a dilution level for performing an OPM should be implemented to reduce the OPM error caused by the different presentation flow rates.
- Furthermore, the interaction between odors in a mixture (whether synergistic or antagonistic) should be investigated to understand the odor masking/unmasking effect better.