RISN Resource Innovation and Solutions Network

Ozone Precursor, Particulate Matter and Particulate Matter Precursor Emissions from Composting Operations

A Literature Review and Estimates Report prepared for:

Maricopa County AIR QUALITY DEPARTMENT

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Table of Contents

Acknowledgements 2

Table of Contents 3

List of Tables 5

List of Figures 6

Acronyms 7

Executive Summary 8

1. Introduction 14

2. Background 15

Materials Used in Composting 15

Phases of Composting 16

Methods of Composting 17

Emissions from Composting 19

Air Quality in Maricopa County 20

3. Literature Review 22

Literature Review Methods 22

Research Question 1: How comprehensive is the existing literature on VOC, NO_x, PM, SO_x, and NH_3 emissions, and EFs from composting operations? 23

Research Question 2: How do VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations contribute to air pollution? 24

Research Question 3: How do biophysical characteristics and management of compost piles (e.g. temperature, age, moisture, pile configuration and composition, other management practices, etc.) affect the rate of VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations? 29

Research Question 4: What are recommended VOC, NO_x, PM, SO_x, and NH_3 EFs from composting operations, and are existing EFs appropriate for Maricopa County's climate and composting methods? 35

Research Question 5: What is the recommended methodology for estimating compost-related VOC, PM, and NH_3 emissions for composting operations? 40

Research Question 6: What are the best management practices (BMPs) for the reduction of compost-related VOC, NO_x, PM, SO_x, and NH_3 emissions; and are these BMPs appropriate for Maricopa County's climate and composting methods? 43

4. Survey of Composting Operations in Maricopa County 46

Research Question 7: What is the estimated contribution of VOC, NO_x, PM, SO_x, and NH_3 from composting operations to annual emissions of these compounds in Maricopa County? 47
5. Conclusions 53
Works Cited 56
Appendix A: List of VOCs Emitted from Greenwaste Compost Operations 63
Appendix B: Relative Reactivity of Compost Pile VOCs 65
Appendix C: EFs for Crushed Stone Processing Operations (lbs./ton) 66
Appendix D: Compost Control Techniques 67
Appendix E: Summary of May 2017 Survey Results from Composting Operations in Maricopa County 68

List of Tables

Table 1. Review of different composting methods used in the U.S. 17
Table 2. Advantages and disadvantages of different composting systems................... 17
Table 3. Location and number of studies on VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations. 24
Table 4. CARB (2015a) recommended VOC EFs for composting................................. 35
Table 5. Summary of composting VOC EFs approved by SJVAPCD & SCAQMD. 36
Table 6. Greenwaste stockpile VOC EF. 36
Table 7. Greenwaste windrow VOC EF active-phase vs. curing phase. 37
Table 8. Summary of composting operation PM10 emissions....................................... 38
Table 9. CARB (2015a) recommended NH_3 EFs for composting. 39
Table 10. Control techniques and CEs for composting. 41
Table 11. Results of eASP study (pounds of pollutant per wet ton). 43
Table 12. BMP for VOC emission reduction for Colorado 44
Table 13. Estimated contribution of large-scale bulk composting operations to the annual VOC inventory in Maricopa County. 51
Table 14. Estimated contribution of large-scale bulk composting operations to the annual PM10 inventory in Maricopa County.. 52
Table 15. Estimated contribution of large-scale bulk composting operations to the annual NH_3 inventory in Maricopa County... 53

List of Figures

Figure 1. The industrial composting process. 16
Figure 2. Maricopa County PM10 and ozone (8-hour) NAAs. 21
Figure 3. Percent of total VOC emissions (TVOC) from composting operations, categorized by the Maximum Incremental Reactivity (MIR) scale. 26
Figure 4. Source sector ammonia contributions in the New York Metropolitan Area..... 29
Figure 5. Photo of flux chamber set up used for compost pile VOC and NH_3 emission estimation........ 50

Acronyms

ADEQ - Arizona Department of Environmental Quality
APCD - Air Pollution Control District
AQMD - Air Quality Management District
BMP(s) - Best Management Practice(s)
CARB - California Air Resources Board
CIWMB - California Integrated Waste Management Board
COAPCD - Colorado Air Pollution Control Division
CO_2 - Carbon dioxide
EF(s) - Emission factor(s)
EPA - Environmental Protection Agency
MCAQD - Maricopa County Air Quality Department
NAA(s) - Non-attainment area(s)
NAAQS - National Ambient Air Quality Standards
N - Nitrogen
NH_3 - Ammonia
N_2O - Nitrous oxide
NO - Nitric oxide
NO_2 - Nitrogen dioxide
NO_x - Nitrogen oxides
O_3 - Ozone
PM - Particulate matter
PM10 - Particulate matter less than 10 microns (µm) in diameter
PM2.5 - Particulate matter less than 2.5 microns (µm) in diameter
RISN - Resource Innovation and Solutions Network
SCAQMD - South Coast Air Quality Management District
SIP - State Implementation Plan
SJVAPCD - San Joaquin Valley Air Pollution Control District
SO - Sulfur monoxide
SO_2 - Sulfur dioxide
SO_3 - Sulfur trioxide
SO_x - Sulfur oxides
VOC(s) - Volatile Organic Compound(s)
USCC - United States Composting Council

Executive Summary

Many municipalities within Maricopa County are exploring composting as a method to divert organic waste from landfills as part of their plans for waste management (e.g. Cities of Tempe and Phoenix). Composting is beneficial to communities because it recycles nutrient rich organic materials and reduces methane emissions from landfills. However, numerous gaseous compounds are emitted during the natural breakdown of organic materials in greenwaste and compost that can contribute to air pollution, including ozone precursors such as volatile organic compounds (VOCs); reactive oxides of nitrogen (NO_x), including nitric oxide (NO) and nitrogen dioxide (NO_2); particulate matter (primary PM), and PM precursors (also called secondary PM) such as ammonia (NH_3) and oxides of sulfur (SO_x). Ozone, NO_2, sulfur dioxide (SO_2), and PM are regulated pollutants that must be controlled under the Clean Air Act to protect human health and welfare (EPA, 2014).

In order to limit emissions of air pollutants and comply with the requirements of the Clean Air Act, state and local air pollution control agencies must explore ways to reduce emissions of regulated pollutants as part of the State Implementation Plan (SIP), the federally-enforceable plan for each State which identifies how that State will attain and/or maintain the primary and secondary National Ambient Air Quality Standards (NAAQS) (EPA, 2017a). The Environmental Protection Agency (EPA) designates areas as meeting (attainment) or not meeting (nonattainment) the NAAQS. Maricopa County currently faces several air quality challenges associated with two nonattainment areas: one for PM10 and one for ozone.

To date, the contribution from composting operations to emissions of ozone precursors, primary PM, and PM precursors in Maricopa County is unknown.

The goal of this report is to identify the factors that affect the type and rate of VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations and to determine whether current research on emissions factors (EFs) are relevant for Maricopa County. Additionally, we analyzed data from a limited facility survey to estimate total VOC, PM, and NH_3 emissions from composting in the county.

In this report, we answer the following research questions:

1. Research Question 1: How comprehensive is the existing literature on VOC, NOx, PM, **SOx, and NH3 emissions, and EFs from composting operations?**
2. **Research Question 2: How do VOC, NOx, PM, SOx, and NH3 emissions from composting operations contribute to air pollution?**

3. **Research Question 3: How do biophysical characteristics and management of compost piles (e.g. temperature, age, moisture, pile configuration and composition, other management practices, etc.) affect the rate of VOC, NOx, PM, SOx, and NH3 emissions from composting operations?**
4. **Research Question 4: What are recommended VOC, NOx, PM, SOx, and NH3 EFs from composting operations, and are existing EFs appropriate for Maricopa County's climate and composting methods?**
5. **Research Question 5: What is the recommended methodology for estimating compost-related VOC, PM, and NH3 emissions for composting operations?**
6. **Research Question 6: What are the best management practices (BMPs) for the reduction of compost-related VOC, NOx, PM, SOx, and NH3 emissions; and are these BMPs appropriate for Maricopa County's climate and composting methods?**
7. **Research Question 7: What is the estimated contribution of VOC, NOx, PM, SOx, and NH3 from composting operations to annual emissions of these compounds in Maricopa County?**

Result 1: Using multiple search methods, we found 56 papers or reports related to compost VOC, NO_x, PM, NH_3, and SO_x emission rates and EFs. Twelve of the 56 studies were conducted in Southern California, where maintenance of air quality has been a long-term challenge. Although composting activities have been identified as a potential source of primary PM emissions, no studies have quantified primary PM fluxes or developed primary PM EFs from composting operations. EFs related to VOCs and NH_3 were identified in nine and eight studies, respectively. However, no EFs were identified for SO_x or NO_x for compost piles. At present, no studies have explored ozone precursor, primary PM, or PM precursor emissions from composting facilities under the environmental conditions and potentially unique management practices of Arizona.

Result 2: VOCs can significantly differ in their ozone-forming potential based on numerous factors, including how fast the VOC reacts, how quickly NO is converted to NO_2 by reacting with VOC's, the effect of VOC reactions on radical levels, the effects of reactions on NO_x levels, the availability of NO_x, the sensitivity of NO_x to radical levels, and the amount of time the VOCs have to react (Derwent, 2004). Determining the contribution to ozone formation by any individual VOC is therefore difficult to quantify because it is dependent on numerous variables.

A life-cycle based study on composting by Komilis and Ham (2004) reported that direct diesel combustion was responsible for the production of a relatively large percentage of the NO_x produced by composting operations. Although biogenic NO is likely emitted from compost or stockpiles during the composting process, no studies to date have quantified these emissions.

Life-cycle based studies on waste management indicate that SO_x emissions are primarily produced due to electricity consumption and therefore are mainly produced outside the boundaries of the composting facility itself. No studies to date have quantified SO_x emissions from compost piles or stockpiles. Additionally, no studies have characterized primary PM emissions from compost piles.

Studies report a wide range of estimates for the percentage of total nitrogen lost as NH_3 during composting. The volatilization of ammonia from any compost operation can be highly variable and can depend on the carbon-to-nitrogen (C:N) content of the source stock, temperature, pH, storage time, aeration, and pile configuration.

Result 3: To date, 56 studies have estimated rates of VOC, NO_x, SO_x, or NH_3 emissions from composting operations in the US. These studies identified a suite of biophysical and management variables that are likely to drive emission fluxes from compost piles, including feedstock type, stockpile age, compost pile age, temperature, pH, moisture, aeration, and configuration of compost piles.

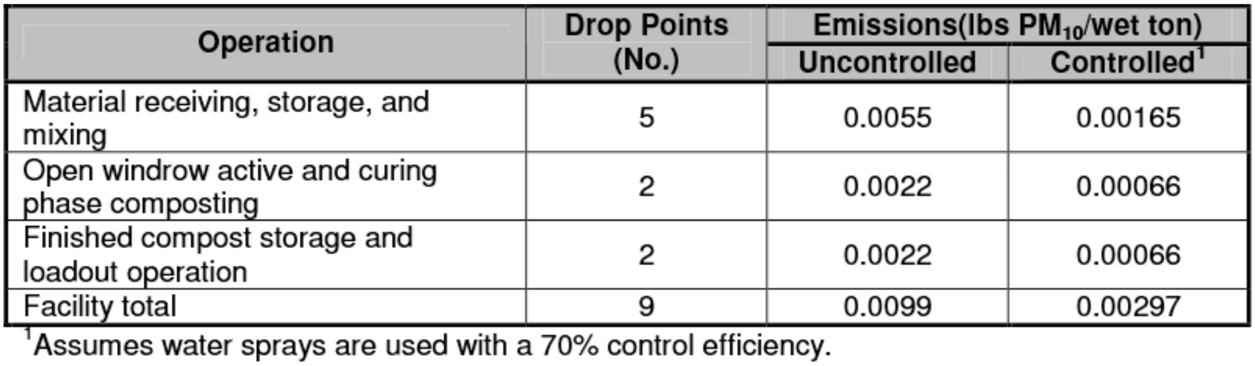
Result 4: The California Air Resources Board (CARB) EFs are the most recent and geographically relevant studies for estimating regulated pollutant emissions from composting operations in Maricopa County. The CARB (2015a) recommended VOC and NH_3 EFs for composting are shown in the following table. In this table, the Stockpile and Composting Process columns consider greenwaste and food waste, while the Co-composting column considers greenwaste mixed with animal manure, biosolids, or poultry litter.

CARB (2015a) Recommended VOC and NH_3 emission factors

Pollutant	Stockpile (lbs./wet ton-day)	Composting Process (lbs./wet ton)	Co-composting Process (lbs./wet ton)
VOC	0.20	3.58	1.78
NH_3	N/A	0.78	2.93

Only one set of primary PM EFs from composting operations have been developed to date. These EFs were estimated by the San Joaquin Valley Air Pollution Control District (SJVAPCD) by using existing EFs for crushing stone. The estimated rate of emissions from composting (uncontrolled and controlled by water spray) are shown in the following table. This table includes the estimated number of drop points per wet ton of compost material (points at which material is moved or dropped).

San Joaquin Valley Air Pollution Control District estimated rate of primary PM emissions from composting (SJVAPCD, 2006)



Operation	Drop Points (No.)	Emissions(lbs PM_{10}/wet ton)	
		Uncontrolled	Controlled[1]
Material receiving, storage, and mixing	5	0.0055	0.00165
Open windrow active and curing phase composting	2	0.0022	0.00066
Finished compost storage and loadout operation	2	0.0022	0.00066
Facility total	9	0.0099	0.00297

[1] Assumes water sprays are used with a 70% control efficiency.

No EFs were identified for SO_x or NO_x for compost piles.

Result 5: California and Colorado are the only states that have adopted rules using VOC EFs from composting. Colorado uses California's EFs, so the methodology reviewed in this report is entirely from the state of California.

The VOC, primary PM, and NH_3 EFs from California are unlikely to accurately predict emissions from Maricopa County composting facilities because of differences in seasonal environmental conditions (temperature, moisture) and management practices (compost pile configuration and location, stockpile and compost pile age). High external/ambient temperatures may indirectly influence emission rates by altering internal humidity and process time (A. Agapiou, personal communication, December 24, 2017). To date, no focused studies have been conducted on the effects of high external temperatures on VOC, primary PM, or NH_3 emission rates from composting.

Estimates for VOC, NH_3, and PM for Maricopa County were calculated using the following equations from CARB (2015a; VOC and NH_3) and SJVAPCD (2006; PM):

Total Annual VOC Emissions = (CPEF x (1-CE) x TP) + (SEF x SD x TP)
Total Annual NH_3 Emissions = (CPEF x (1-CE) x TP)

- CPEF = Composting Process EF (lb-VOC or NH_3/wet ton)
- SEF = Stockpile EF (lb-VOC/wet ton/day)
- SD = Stockpile duration: Average number of days material is stockpiled (days)
- CE = Control Efficiency (percentage)

- TP = Total annual facility throughput (wet tons)

Total annual PM emissions = (PMEF (controlled or uncontrolled) x TP x # Drop Points)

- PMEF (controlled or uncontrolled) = PM EFs for controlled or uncontrolled operations (lbs./wet ton)
- TP=Total annual facility throughput (wet tons)
- # Drop Points = Number of points where compost was moved or dropped (e.g. material receiving, storage and mixing, during open windrow active and curing phase composting, compost screening, or finished compost storage and loadout operations).

Result 6: Numerous BMPs have been developed for composting to reduce compost-related gaseous emissions. One of the more effective techniques in VOC reduction is the use of aerated static piles (ASP). Instead of rows, this technique places large static piles over a network of pipes that supply air. This technique is effective in reducing VOCs by reducing the amount of times the pile is turned, therefore keeping the VOCs within the pile while decomposition occurs. Another management practice that can reduce VOC emissions involves covering compost piles with a “cap” of finished compost (also called a biofilter). One study found that biofilters reduced VOC emissions by 75% over the first two weeks of composting (CalRecycle, 2015). Biofilters were also recommended in one study for controlling odorous sulfur compounds. Although no studies measured NO_x or SO_x emissions directly from compost piles, biofilters may be an option for reducing these emission types as well. Improving fuel efficiency and/or reducing combustion of fossil fuels and electricity use will likely have a significant impact on reducing SO_x and NO_x emissions from composting operations.

BMPs for primary PM control from composting are currently identical to BMPs for agricultural practices. The first step is to modify equipment, such as fans and aeration equipment, by adjusting their direction as well as including mist to prevent PM10 from becoming airborne. The compost can be contained to prevent wind erosion (e.g. performed inside of a vessel, building, or under a roof, or covered with soil). The areas where greenwaste is loaded or unloaded should also remain covered to prevent wind erosion. Finally, bulking agents (material such as wood chips, and shredded landscape waste or other carbon-based material used to add structure (or bulk) to the compost pile) should be kept in consolidated piles to prevent exposure to precipitation, and covered.

Numerous BMPs have been created to minimize NH_3 emission from compost. An effective control method will likely require a combination of BMP techniques. However, the most common recommendation for reducing NH_3 emissions is addition of biochar or a similar NH_3-scavenging agent.

Result 7: Coarse estimates from a limited number of facility survey responses suggest that VOC, primary PM, and NH_3 emissions from large-scale bulk composting operations in Maricopa County are likely to represent a small fraction of the total emissions of these compounds in the county. The eight surveyed facilities likely include some of the largest operations in the county, but also include some small ones. If the eight surveyed facilities represent the range (large and small) of operations and, therefore, represent roughly 35% of the annual large-scale bulk composting throughput in Maricopa County, then we estimate that the annual VOC, PM10, and NH_3 emissions from all the large-scale bulk composting facilities would be 0.6%, 0.006%, and 4.4% of the total VOC, PM10, and NH_3 emissions, respectively, from all inventoried sources in Maricopa County (based on the 2014 Periodic Ozone Precursor and PM10 Emissions Inventories; MCAQD, 2016). High and low estimates were also calculated to present a range of possible emission rates since the survey response rate was low.

We compared our likely/expected estimates of VOC and NH_3 emissions to the 2014 EPA estimates of emissions from greenwaste composting in Maricopa County. Our estimates for composting VOC emissions was similar to that estimated by the EPA, but our NH_3 estimate is seven times higher than the EPA estimate. The primary reason for the difference in NH_3 estimates is the feedstock type: the EPA estimates are for greenwaste composting only and uses an EF of 0.66 lbs. NH_3/wet ton. Our estimates use the CARB (2015a) EFs for both greenwaste (EF of 0.78 lbs. NH_3/wet ton) and co-composting (EF of 2.93 lbs. NH_3/wet ton). If only the CARB (2015a) greenwaste composting EF is used, our estimated annual NH_3 emission from Maricopa County composting facilities would be 1.8% of the total NH_3 emissions from all 2014 inventoried sources, which is closer to the 0.6% estimate from the EPA.

Although we present a range, our estimates may not represent the true contribution of composting facilities to VOC, PM10, and NH_3 emissions in Maricopa County because the EFs were derived from studies in California under different climatic conditions and composting management practices; the reported survey data for stockpile duration, compost pile conditions, and number of drop points were incomplete; and the survey sample size may be too low.

1. Introduction

Waste minimization has become the focus for many municipal and state plans in recent years, as increasing consumption, overflowing landfills, and the impacts of climate change are now major concerns for the world (Singh et al., 2014). Many municipalities within Maricopa County are exploring composting as a method to divert organic material from landfills as part of their plans for waste management (e.g. Cities of Tempe and Phoenix). Composting is beneficial to communities because it reduces landfill inputs and methane emissions, and it reduces the need for fertilizers by enhancing and adding nutrients to the soil (Kumar et al., 2011). However, numerous gaseous compounds are emitted during the natural breakdown of organic materials in greenwaste and compost that can contribute to air pollution, including ozone precursors such as volatile organic compounds (VOCs); reactive oxides of nitrogen (NO_x), including nitric oxide (NO) and nitrogen dioxide (NO_2); particulate matter (primary PM), and PM precursors (also called secondary PM) such as ammonia (NH_3) and potentially oxides of sulfur (SO_x). Ozone, NO_2, sulfur dioxide (SO_2), and PM are regulated pollutants that must be controlled under the Clean Air Act to protect human health and welfare (United States Environmental Protection Agency [EPA], 2014).

In order to limit emissions of air pollutants and comply with the requirements of the Clean Air Act, state and local air pollution control agencies must explore ways to reduce emissions of criteria pollutants as part of the State Implementation Plan (SIP), the federally-enforceable plan for each State which identifies how that State will attain and/or maintain the primary and secondary National Ambient Air Quality Standards (NAAQS) (EPA, 2017a)

Since 1987, parts of Maricopa County have been in nonattainment for PM10, which is an area considered to have air quality worse than the NAAQS with respect to PM particles with an aerodynamic diameter less than or equal to 10 micrometers. Additionally, Maricopa County has been in nonattainment for ozone since 2008. Thus, the Maricopa County Air Quality Department (MCAQD) is interested in exploring the potential contributions of emerging activities that may impact regional air quality (Arizona Department of Air Quality [ADEQ], 2017).

Few studies to date have explored the impact of composting on ozone precursors, PM, and PM precursor emissions, and national data are limited. In 2014, the EPA estimated VOC and PM precursor emissions from greenwaste composting for all US counties (EPA, 2017b). However, these estimates were based on one emissions factor (EF) each for VOC and NH_3 that were developed from six studies at five locations within the South Coast Air Quality Management District (SCAQMD) in southern California

(California Air Resources Board [CARB], 2015a). At present, no studies have explored VOC, primary PM, or PM precursor emissions from composting facilities under the environmental conditions and potentially unique management practices of Arizona. As municipalities and private companies attempt to both develop their composting programs and adhere to air quality regulation, the MCAQD is interested in investigating the potential for large-scale composting to become a significant contributor to air pollution in Maricopa County.

2. Background

Composting is a naturally occurring, microbial process of aerobic biodegradation of organic waste material into a rich soil amendment known as compost. Composting has numerous economic and environmental benefits that make it an attractive solid waste solution. Composting can conserve valuable land space by keeping organic material out of landfills, minimize methane emissions, create healthy, usable soil, reduce the need for soil additives, such as fertilizers and pesticides, and increase soil water holding capacity, which reduces water usage and decreases nutrient related run-off (Kumar et al., 2011; Recycled Organics Unit, 2003). These soil enhancement benefits are especially important to the fertility of intensively farmed or degraded land in arid and semi-arid climates, such as in Maricopa County (Kumar et al., 2011). Currently numerous composting facilities exist in Maricopa County, and municipalities within the county hope to reap the benefits of composting. However, there are concerns regarding the potential for composting to contribute to air pollution. Thus, further investigation is needed on the air quality impacts of this process.

As a part of this report, MCAQD developed and implemented a composting facility survey to determine methods used and annual capacity of operations in the county. Prior to this survey, methods and materials used at composting operations in Maricopa County had largely remained unexamined. Results from the 2017 survey are described in detail in Section 4 of this report.

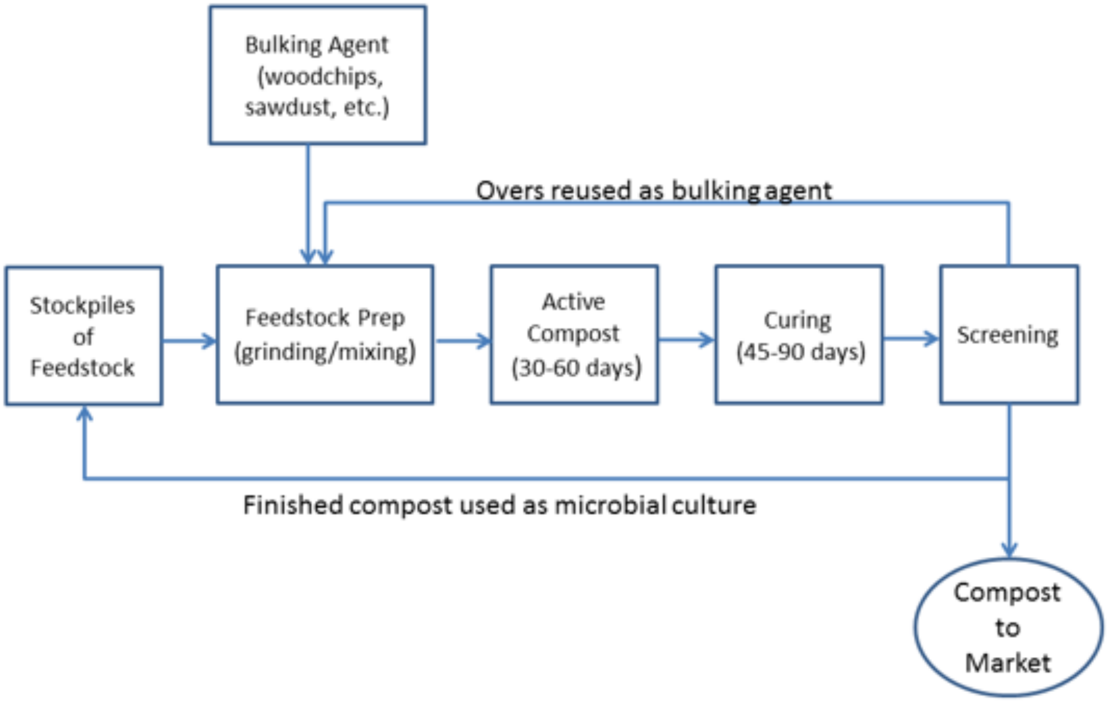
Materials Used in Composting

Roughly 61% of national municipal waste is composed of compostable materials (hereafter noted as ‘feedstocks’), 28% of which is yard and food waste, and 33% of which is paper and wood (EPA, 2016a). Common urban feedstocks include lawn clippings and prunings, tree trimmings, food scraps, farm waste and manure, biodegradable food packaging and processing wastes, and solid waste from sewage treatment plants (Kumar et al., 2011). All composting requires sufficient amounts and types of feedstocks, oxygen, moisture, and pore space for soil microorganisms to thrive (Platt et al., 2014).

Phases of Composting

At an industrial scale, the typical composting process is well defined (Figure 1). The incoming feedstock is dumped into piles, called stockpiles, where it can sit for a few hours to a few days or longer until the facility is ready to compost the material (Platt et al., 2014). Once the facility is ready to use the feedstock, it is ground, shredded and sometimes mixed with other feedstocks to create a uniform particle size. The feedstocks are then mixed with a bulking agent to allow for aeration and appropriate oxygen content within the pile, and “finished” compost is added to inoculate the pile with microbial cultures. These microorganisms are what initiate the composting process. The pile then enters an active composting phase, which can differ in length depending on the source material (type and volume), environmental conditions, and management practices. During active composting, microbial activity causes the internal temperature of the pile to rise high enough to kill pathogens, and the piles are turned or aerated in some way until organic matter decomposition is nearly complete. After the active phase, the compost enters a curing phase, in which more recalcitrant materials like wood are allowed to decay further, and the piles are turned less often. The temperature of the compost pile decreases and the rate of decomposition slows down significantly. Finally, the compost is screened for large, undecomposed material, known as “overs”, which are reused as bulking material. At the end of the process, the compost is considered “finished” and is distributed or sold.

Figure 1. The industrial composting process. Modified from Platt et al. (2014).



Methods of Composting

Composting methods in the United States vary considerably (Platt et al., 2014) but they can be roughly grouped into the categories of open vs. contained, passive aeration vs. active aeration, static turning vs. managed turning, and onsite operation vs. centralized operation (Table 1). Each of these composting methods have both advantages and disadvantages related to the area and time required, feedstock source, labor, and other management considerations (Table 2).

Table 1. Review of different composting methods used in the U.S (Platt et al., 2014).

Composting Method		Description
Enclosure	Open	Compost piles are located inside a building or enclosure.
	Contained	Compost piles are located outside in open-air.
Aeration	Passive	Passive aeration relies on natural airflow caused by chimneys of heated air (from microbial activity) that rise from the bottom of piles and are replaced with cool air from the surroundings.
	Active	Active aeration uses pipes or blowers to manage air flows throughout the compost pile.
Turning method	Static	Static piles are unturned or unmoved piles, which are usually used with active aeration methods (e.g. the aerated static pile method, ASP)
	Managed	Managed piles are manually turned and are often used with windrows, a passive aeration method.
Location of operations	Onsite	Compost is used wherever the feedstock is generated, such as an organic farm, and only includes one or a few feedstocks.
	Centralized	The composting operation serves as a centralized place for numerous feedstock sources (e.g. most municipal composting facilities are centralized).

Table 2. Advantages and disadvantages of different composting systems (Platt et al., 2014).

Advantages	Disadvantages
Static systems	
• Low capital and operating costs • Less equipment and staffing requirements • No electric power needed	• Large area required • Not suitable for putrescible materials • No means of controlling odors • Slow decomposition rate/ long process times

Turned Windrow Systems • Can handle putrescible feedstocks • Relatively low capital and operating costs • Relatively low technology requirements • No electric power needed • Extensive industry experience	• Large area required • More labor intensive • No means of controlling odors • Exposure to weather can be problematic
Passively Aerated Windrow Systems • Low capital and operating costs • Well-suited to small feedstock quantities • No electric power needed	• No means of controlling odors • Construction more complicated • Slow decomposition rate/long process times
Aerated Static Piles • Reduced space requirements • Negative aeration with biofiltration can help control odors • Smaller surface area reduces weather impacts • Significantly shorter composting times	• Slightly higher capital costs • Moisture loss is accelerated • Proper feedstock preparation and mixing needs • More operator skill needed • Three-phase electric supply usually needed
Bioreactor Systems • Low to moderate space requirements • High degree of odor control • Highly automated, so reduced labor costs • Small size allows for modular expansion • Can be located indoors or outdoors	• Often need to purchase carbon amendments • Shorter composting period, finishing needed • Not suitable for large-scale operations • Capital costs can be high
Tunnel Bioreactor Systems • High degree of odor control • Corrosive process exhaust air is routed outside of building, extending building life	• Cast-in-place concrete increases capital costs • Less opportunity for automation • Maybe designated as a “confined space” and thus need health and safety protocols
Agitated-Channel Bioreactor Systems • Usually enclosed in buildings, so high degree of odor control • Less space required than for windrow composting • Mechanical turning systems elevated so easier to maintain	• Medium-to-high capital costs • Limited flexibility in handling peaks in incoming materials • Lower indoor air quality from positive aeration • Building and facility footprint are long and narrow; may not fit all sites
Rotary Drum Bioreactor Systems • Body of drum can be located outdoors, typically only ends need to be covered • Effective mixing and agitation of feedstocks and amendments	• Higher mechanical complexity due to drive system and loading/unloading systems • Drums and drive systems need periodic realignment • Air injection systems prone to clogging • Short composting time; finishing needed

Emissions from Composting

During the natural breakdown of organic materials during composting, a variety of compounds can be released into the atmosphere such as carbon dioxide (CO_2), methane (CH_4), sulfur compounds, NO_x, NH_3, VOCs, and PM. A more complete list of individual VOCs emitted from greenwaste compost is presented in Appendix A. Because VOCs, NO_x, SO_x, and NH_3 are precursors to regulated pollutants, and PM is a regulated pollutant itself, the following paragraphs will focus on these emission types.

Volatile organic compounds are defined (per 40 CFR Part 51.100(s)) as any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participates in atmospheric photochemical reactions, except those designated by the EPA as having negligible photochemical reactivity. Thousands of compounds fall under the VOC category, some of which are harmless, such as the scent of lemons, while others can cause harm to air quality in urban regions (CalRecycle, 2015). VOCs are released during numerous natural and anthropogenic processes. During composting, VOCs are released from compost piles as microbes break down organic matter, and are also emitted indirectly through the combustion of fossil fuels.

NO_x emission sources are primarily anthropogenic in urban areas, but these gases can also be produced from soils, lightning, volcanoes, and natural fires (EPA, 1999). For composting operations as a whole, NO_x are primarily produced from combustion of fossil fuels (Komilis and Ham, 2004). However, during the composting process, nitric oxide (NO) is produced from microbial activity related to two stages of the soil nitrogen cycle, nitrification (aerobic oxidation of NH_4^+ to nitrite and nitrate) and denitrification (anaerobic reduction of oxidized nitrogen to nitrous oxide (N_2O) and N_2). Management activities that speed biological decomposition are likely to increase microbial emission of NO from soil (Hall et al., 1996), but to date no studies have quantified NO_x emissions from compost piles.

Ammonia is a colorless, pungent-smelling gas that poses a serious concern for the public and the environment as it impacts human health, soil acidification, water eutrophication, and formation of secondary PM (Palashikar et al., 2016). The buildup of NH_3 can accelerate the nitrification-denitrification processes and lead to the emission of NO and N_2O, a greenhouse gas (Palashikar et al., 2016). The primary source of ammonia emissions from composting operations is from the compost pile itself.

Particulate matter is a general term for the collection of chemical and physical substances suspended in air. PM can be either emitted directly from the composting process as dust from roads and black and/or elemental carbon from combustion sources, or formed secondarily from the chemical reactions of NO_x, SO_x, NH_3, VOCs, or other gases in the air (Natural Resources Conservation Service [NRCS], 2006).

Sulfur oxide refers to many types of sulfur and oxygen containing compounds, such as sulfur monoxide (SO), sulfur dioxide (SO_2), and sulfur trioxide (SO_3). The EPA's NAAQS for SO_2 are designed to protect against exposure to the entire group of sulfur oxides (SO_x). SO_2 is the component of greatest concern and is used as the indicator for the larger group of gaseous sulfur oxides (SO_x). Other gaseous SO_x (such as SO_3) are found in the atmosphere at concentrations much lower than SO_2 (EPA, 2017c). For composting operations, SO_x are primarily produced due to electricity consumption and therefore are mainly produced outside the boundaries of the composting facility itself (Komilis and Ham, 2004).

Air Quality in Maricopa County

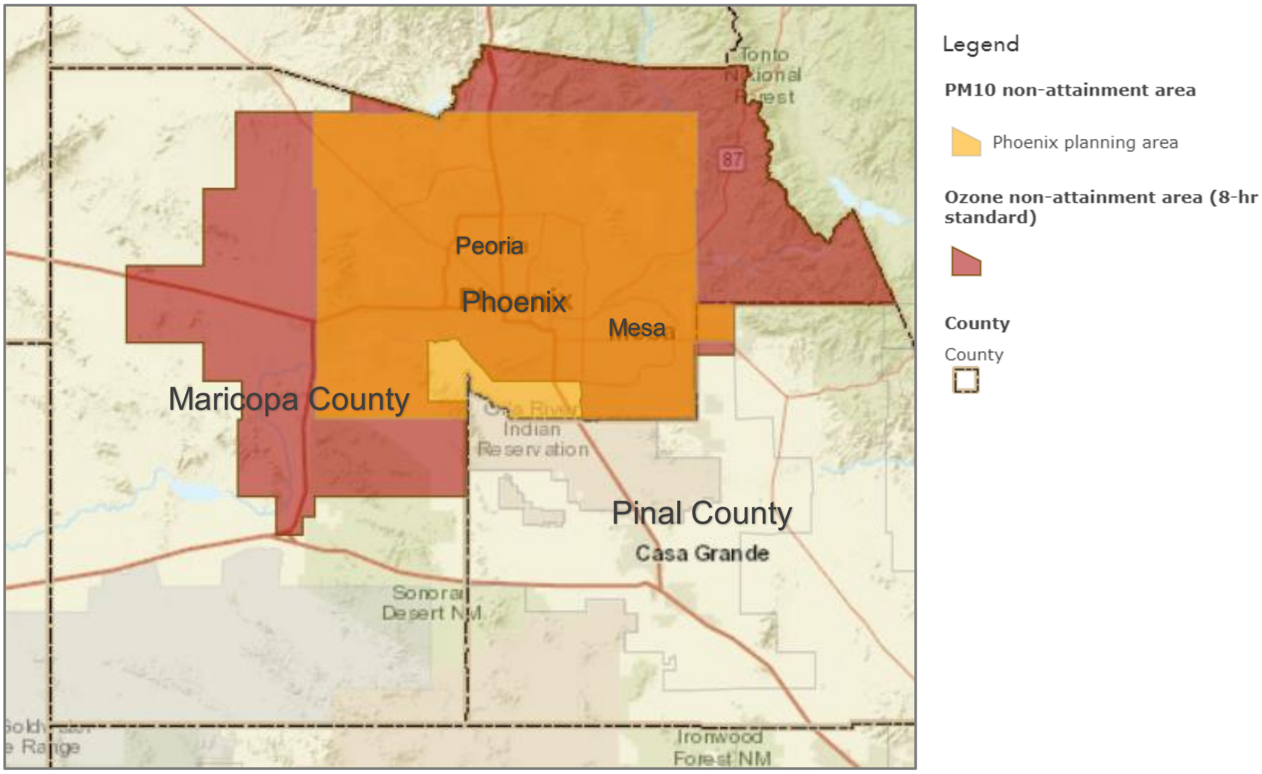
To date, the contribution of composting operations to ozone precursor, PM, or PM precursor emissions in Maricopa County is unknown. Several composting facilities are currently in operation or planned within Maricopa County that are directly connected to municipal waste diversion programs. At present, only PM10 emissions from travel on unpaved roads at these facilities are included in the Maricopa County Periodic Emissions Inventory conducted by MCAQD (MCAQD, 2016).

Maricopa County currently faces several air quality challenges associated with two nonattainment areas (**Error! Reference source not found.**2). These areas are defined as followed:

> **PM10 nonattainment area:** The area designated by EPA that exceeds the acceptable national standard for PM10 pollution levels.
>
> **8 Hour Ozone nonattainment area:** The area designated by EPA that exceeds the current acceptable national standard for ozone pollution levels.

The EPA also regulates emissions for PM2.5 (a subset of PM10 particles with diameters that are 2.5 micrometers and smaller), for which Maricopa County is in attainment (Maricopa County, 2017). On July 29, 2016, the EPA finalized requirements for implementing the NAAQS for PM2.5 in areas that are currently designated nonattainment for existing standards (EPA, 2016b). The final rule identifies SO_2, NO_x, VOC, and NH_3 as precursor compounds to PM2.5 that must be addressed in a state's attainment plan if the state is not currently in attainment. Thus, the goal of this report is to identify the factors that affect the type and rate of VOC, primary PM10, and PM precursor emissions, and to determine whether current composting EFs are relevant for Maricopa County.

Figure 2. Maricopa County PM10 and ozone (8-hour) NAAs (Maricopa County, 2017).



Few studies have been conducted to quantify ozone precursor, PM, or PM precursor emissions from the composting process. Of these, most have occurred in California, where air quality issues are severe. CARB estimates that Reactive Organic Gas emissions (ROGs; California's term for VOCs) from composting accounted for less than 1% of total ROG emissions from all sources (from a 2008 study cited in CARB, 2015a). However, even low emission rates can be concerning for areas that are in nonattainment for ozone, such as Maricopa County. Under the federal Clean Air Act, the EPA requires that local air quality districts must create and implement plans for cleaning up any pollutants that exceed federal standards (EPA, 2017a). While the majority of VOC and PM emissions in cities come from mobile sources, such as motor vehicles, local air districts are required to regulate emissions for area sources of air pollutants, such as from agricultural and industrial activities. This mandate has led MCAQD to consider air quality reduction plans from all sources, including those with potentially lower emission rates such as composting facilities.

In this report, we review the findings of existing studies to answer the following seven questions:

1. Research Question 1: How comprehensive is the existing literature on VOC, NOx, PM, SOx, and NH3 **emissions, and EFs from composting operations?**
2. **Research Question 2: How do VOC, NOx, PM, SOx, and NH3 emissions from composting operations contribute to air pollution?**
3. **Research Question 3: How do biophysical characteristics and management of compost piles (e.g. temperature, age, moisture, pile configuration and composition, other management practices, etc.) affect the rate of VOC, NOx, PM, SOx, and NH3 emissions from composting operations?**
4. **Research Question 4: What are recommended VOC, NOx, PM, SOx, and NH3 EFs from composting operations, and are existing EFs appropriate for Maricopa County's climate and composting methods?**
5. **Research Question 5: What is the recommended methodology for estimating compost-related VOC, PM, and NH3 emissions for composting operations?**
6. **Research Question 6: What are the best management practices (BMPs) for the reduction of compost-related VOC, NOx, PM, SOx, and NH3 emissions; and are these BMPs appropriate for Maricopa County's climate and composting methods?**

In addition, we synthesize data from a limited compost facility survey conducted in 2017 in Maricopa County to answer a seventh question:

7. **Research Question 7: What is the estimated contribution of VOC, NOx, PM, SOx, and NH3 from composting operations to annual emissions of these compounds in Maricopa County?**

3. Literature Review

Literature Review Methods

Existing literature was searched for studies on ozone precursor, PM, and PM precursor emissions from composting or greenwaste operations (combined hereafter as 'composting operations'), including those sources that developed or explored emissions factors (EFs) related to the underlying variables that drive emission rates. Searches were conducted using online databases, including Google, Google Scholar, Web of Science, and the BioCycle journal. A range of search terms was used to identify relevant white papers, reports or other published materials using the keywords *VOC,*

NO_x, nitrogen oxide(s), NO, nitric oxide, NO_2, nitrogen dioxide, SO_x, sulfur oxide(s), SO_2, sulfur dioxide, NH_3, ammonia, RO (reactive organic), particulate matter, or *PM* in combination with *composting, compost, emission(s)*, *EF(s), greenwaste(s) (with and without space), manure, decomposition, relative reactivity, direct or primary,* and *dust*. The search terms were used for all fields (title, abstract, keywords, and full text) and all result types were included. We then further searched for appropriate sources through the reference sections of relevant articles.

After the initial search, the results were narrowed by the following criteria:

- The findings were primary research from peer-reviewed journals or government reports, and
- The research methods are sufficiently explained, and
- The studies were on VOC, NO_x, PM, SO_x, or NH_3 emissions from composting operations, and/or
- The studies identified EFs for VOC, NO_x, PM, SO_x, or NH_3 from composting operations.

We did not include studies that did not report VOC, NO_x, PM, SO_x, or NH_3 emissions from composting operations, or studies that did not identify these different compound classes separately. Additionally, we omitted papers in which the research methods were vague or if significant advancements had been made in methods or technology that no longer make the study relevant, such as advancements in quantifying VOCs.

Research Question 1: How comprehensive is the existing literature on VOC, NO_x, PM, SO_x, and NH_3 emissions, and EFs from composting operations?

After implementing the above search criteria, 56 papers or reports related to compost VOC, NO_x, PM, SO_x, and NH_3 emissions, and EFs were identified (Table 3). Twelve of the 56 studies were conducted in Southern California, where nonattainment status is an extreme issue. In addition, California has one of the most robust composting systems in the country due to a state-wide focus on reducing waste in landfills, and it has a significant need for organic material for its agriculture sector (Kumar et al., 2011).

Nine reports listed EFs for VOCs and eight reports listed EFs for NH_3. Although composting activities have been identified as a source of primary PM emissions, only one study developed primary PM EFs for composting operations. No compost EFs were found for SO_x or NO_x; however, a study by Komilis and Ham (2004) reported SO_x and NO_x emissions from direct diesel combustion for municipal solid waste composting operations.

Table 3. Location and number of studies on VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations.

Emission Type	Number of Studies	Geographic Locations (Number of Studies)	Source
VOC	29*	California (12) Colorado (1), Greece (3), Spain (4)	Agapiou et al., 2016; Burger et al., 2015; CalRecycle, 2015, 2013; CARB, 2015a, 2015b; Card and Schmidt, 2008**; Carter, 2009; CIWMB, 2008, 2003; Delgado-Rodríguez et al., 2012, 2011; Eitzer, 1995; Green, 2010; Hentz Jr et al., 1996; Komilis et al., 2004; Komilis and Ham, 2004, 2000; Kumar et al., 2011; Maulini-Duran et al., 2014a, 2014b; Pagans et al., 2006; Scaglia et al., 2011; SCAQMD, 2013, 2011, SJVAPCD, 2010, 2006; Smet et al., 1999; Statheropoulos et al., 2005
NO_x	1*	N/A	Komilis and Ham, 2004
PM	1	California (1)	SJVAPCD, 2006
SO_x	3*	N/A	Komilis and Ham, 2004; Levis and Barlaz, 2011; Rosenfeld et al., 2004
NH_3	39*	Austria (1); California (8), China (1); Denmark (1), France (2); Germany (1), Japan (2), Spain (1), United Kingdom (1), USA (state not specified; 2)	Amlinger et al., 2008; Amon et al., 1998; Bautista et al., 2011; Beck-Friis et al., 2003, 2001; Cadena et al., 2009; CalRecycle, 2015, 2013; CARB, 2015a; Card and Schmidt, 2008; Chowdhury et al., 2014; CIWMB, 2003; de Guardia et al., 2010, 2008; Eklind et al., 2007; El Kader et al., 2007; Fukumoto et al., 2003; Hellebrand and Kalk, 2001; Jeong and Hwang, 2005; Jiang et al., 2011; Komilis and Ham, 2004, 2000; Li et al., 2013a; Malińska et al., 2014; Martins and Dewes, 1992; Maulini-Duran et al., 2014b; Osada et al., 2000; Paillat et al., 2005; Palashikar et al., 2016; Parkinson et al., 2004; Peigné and Girardin, 2004; Petersen et al., 1998; Roe et al., 2004; SCAQMD, 2013; Shen et al., 2011; SJVAPCD, 2010, 2006; Steiner et al., 2010; Zhao et al., 2008

* Includes studies conducted inside a laboratory or studies where no geographic location was listed.

Research Question 2: How do VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations contribute to air pollution?

Volatile Organic Compounds

Studies on VOC emissions from composting operations show that both the type of VOC and the rate of VOC emissions are important to quantify in order to determine their contributions to regional ozone formation. Some VOCs are more reactive in the ozone formation process than others, and EPA regulations allow emission of certain VOCs that have limited contributions to ozone formation. During early years of ozone mitigation, it was recognized that ethane did not contribute significantly to ozone formation (NRCS, 2006). From this knowledge, the EPA created two classifications for VOC reactivity, “reactive” and “nonreactive”, and used ethane as the dividing line between the two classes.

Due to California’s severe nonattainment areas and interest in VOCs, it has been a leading force in researching a reactivity scale to study the relative impacts of different VOCs on reactive ground-level ozone. California has been a catalyst for the continued research on air quality, which helps to explain the concentration of studies reviewed from the state.

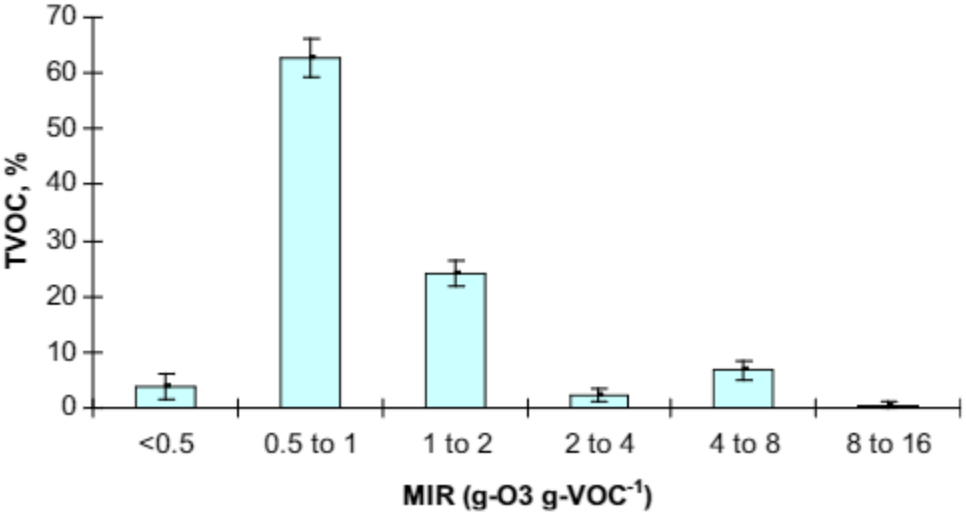
VOCs can significantly differ in their ozone-forming potential based on numerous factors, including how fast the VOC reacts, how quickly NO is converted to NO_2 by reacting with the VOC’s, the effect of VOC reactions on radical levels, the effects of reaction on NO_x levels, the availability of NO_x, the sensitivity of NO_x to radical levels, and the amount of time the VOCs have to react (Derwent, 2004). Determining the contribution to ozone formation by any individual VOC is therefore difficult to quantify because it is dependent on environmental conditions.

However, some studies have quantified the relative reactivity of individual VOCs (comparing one to another) as well as groups of VOCs. The most common index for these rankings is the Maximum Incremental Reactivity (MIR) Scale. This scale quantifies the relative reactivity of VOCs under the most sensitive conditions and highest NO_x levels, which is the most fitting model for areas with intense ozone formation conditions, such as Maricopa County (Derwent, 2004). The current accepted VOC relative reactivity rates can be found in a report titled, “Updated maximum Incremental Reactivity Scale and Hydrocarbon Bin Reactivities for Regulatory Applications Scales” (Carter, 2009).

Eitzer (1995) characterized VOC emissions from eight municipal solid waste composting facilities around the country and found that the primary VOCs emitted are terpenes, while incomplete composting resulted in alcohols, ketones, esters, and organic acids (Eitzer, 1995)

More recently, a comprehensive study by Kumar et al. (2011) found that greenwaste compost piles of different ages (freshly tipped to 2-3 weeks old) released >100 different types of VOCs most of which (66-85%) were a type of VOC that does not strongly contribute to ozone formation (e.g. alcohols; Appendices A and B). The remaining 15-34% of VOCs were composed of compounds with stronger ozone forming potential, including acids, biogenic hydrocarbons, alkenes, and carbonyl compounds (Appendix B). Overall, approximately 10% of the VOC types that were emitted from greenwaste piles had a medium to high potential for ozone formation (Figure 3).

Figure 3. Percent of total VOC emissions (TVOC) from composting operations, categorized by the Maximum Incremental Reactivity (MIR) scale (Kumar et al., 2011).



The type of VOC emissions from composting seems to be largely related to the type of feedstocks used. Komilis et al. (2004) found that mixed paper primarily produced alkylated benzenes, alcohols, and alkanes (all with low reactivity), while yard wastes produce terpenes (medium reactivity), alkylated benzenes (low reactivity), ketones and alkanes (both low reactivity). Food waste primarily produced sulfides (medium reactivity), acids, and alcohols (both with low reactivity), or highly reactive VOCs from meat and dairy products (Greenberg, 1981). Thus, food waste can vary from low to high reactivity (Agapiou et al., 2016).

The type of compost emissions is also influenced by the stage of the decomposition process (Delgado-Rodríguez et al., 2011). During the initial phase, composting releases aldehydes (medium reactivity), alcohols (low), carboxylic acids (low), esters (low), ketones (low), sulphides, and terpenes (medium). During the next thermophilic phase, VOC emissions are composed of ketones (low), organosulphur-compounds (low) and terpenes (medium). Finally, during the cooling phase, sulphides (low) and terpenes (medium) are emitted.

If compostable materials are not entering a composting facility, they would either decompose in a landfill or potentially be processed in waste treatment plant. Thus, it is important to understand the significance of the type and rate of VOC composting emissions in relation to these alternative processes. Traditional landfills produce reactive VOCs with high ozone-forming potential such as aromatic and halogenated compounds and furan (Scaglia et al., 2011). Composting lacks these highly reactive anthropogenic VOCs, which suggests that many highly reactive VOCs released from landfills do not originate from the organic fraction in waste (Statheropoulos et al., 2005). The separation between organic vs. other forms of waste therefore may allow for better management of highly reactive VOC emissions.

Another option other than composting is “managed decomposition” of waste, which means organic waste is allowed to decompose in the open after direct application to the land. This method is primarily used on farms as a way to conserve top soil or when composting isn’t available. One study found that ground greenwaste that was mixed into the soil had lower VOC emissions than when directly applied to the soil surface (Burger et al., 2015). Furthermore, greenwaste material directly applied to the land released fewer low-reactivity VOCs (methanol) and more medium-reactivity VOCs (monoterpenes), which represented roughly 50% of total VOC emissions. Because the breakdown of greenwaste material will always release VOCs, composting may actually reduce emissions of reactive VOCs compared to managed decomposition, where material is left to break down on the soil surface (United States Compost Council [USCC], 2012).

While some studies acknowledged that VOC emissions contribute to ozone formation, many studies did not quantify the relative reactivity of these compounds (Delgado-Rodríguez et al., 2012; Font et al., 2011; Maulini-Duran et al., 2014a; Pagans et al., 2006). In addition, VOC emissions have been classified in several different ways, such as the units of total VOCs (TVOC), the concentration of classes of VOCs, such as alcohols, or the concentrations of individual compounds, which makes it difficult to use the MIR scale on these studies. Further analysis of the ozone forming potential of composting VOC emissions will require additional research.

Nitrogen Oxides

A life-cycle based study on composting by Komilis and Ham (2004) reported that direct diesel combustion was responsible for the production of a relatively large percentage of the NO_x produced by composting operations; 37-49% for municipal solid waste composting operations, and 94% for yard waste composting operations. They also reported that the remaining percentage was from off-site emissions related to the operation. Although biogenic NO is likely emitted from compost or stockpiles during the composting process, no studies to date have quantified these emissions.

Particulate Matter

No studies have characterized direct PM emissions from composting facilities. For PM10, the SJVAPCD estimates PM10 emissions from composting facilities based on an

EF for crushed stone multiplied by the number of compost drop points (receiving, mixing, processing, transferring) per facility and annual throughput (San Joaquin Valley Air Pollution Control District [SJVAPCD], 2006).

Sulfur Oxides

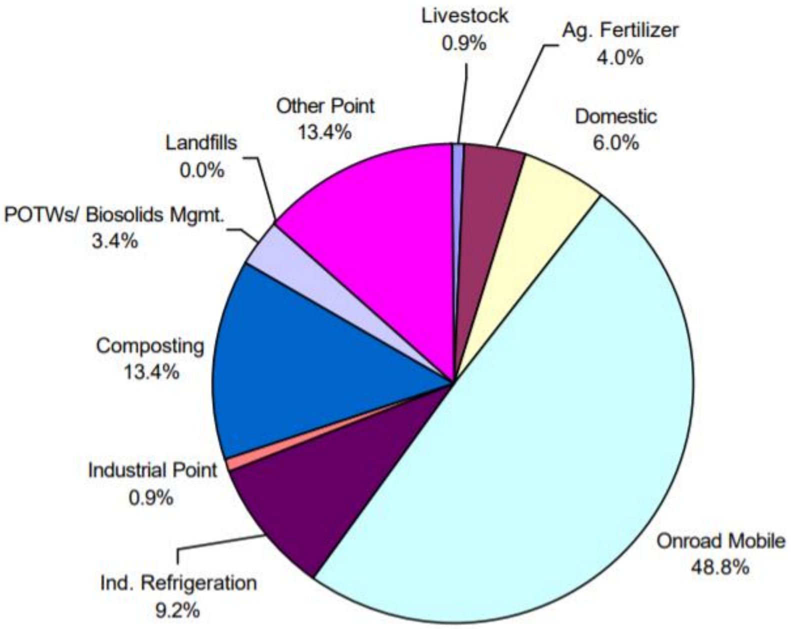
Life-cycle based studies on waste management indicate that SO_x emissions are primarily produced due to electricity consumption and therefore are mainly produced outside the boundaries of the composting facility itself; 54% for yard waste composting operations and 98-99% for municipal solid waste composting operations (Komilis and Ham, 2004). Within the facility, SO_x emissions are primarily produced from diesel combustion during the operation of vehicles and equipment (Komilis and Ham, 2004). Although biogenic SO_x is likely emitted from compost piles or stockpiles during the composting process, no studies to date have quantified these emissions. One study was found in which odorous sulfur compounds were measured (Rosenfeld et al., 2004); however, the study was unable to determine if or how much SO_2 contributed to these odorous emissions.

Ammonia

Ammonia is a colorless, pungent-smelling gas that, during composting, is generated from deprotonation of ammonium (NH_4^+), the product of aerobic microbial biodegradation of organic material. Ammonia emission poses a serious concern for the public and the environment as it impacts human health, soil acidification, water eutrophication, and formation of secondary PM (Palashikar et al., 2016). The buildup of ammonia can accelerate the nitrification-denitrification processes and lead to the formation of NO and N_2O, a greenhouse gas (Palashikar et al., 2016). Studies report a wide range of estimates for the percentage of total nitrogen lost as NH_3 during composting. However, despite this range, NH_3 often represents an important fraction of gas emissions during composting (Cadena et al., 2009; Komilis and Ham, 2000; Paillat et al., 2005; Peigné and Girardin, 2004).The volatilization of ammonia from any compost operation can be highly variable and can depend on the carbon-to-nitrogen (C:N) content of the source stock, temperature, pH, storage time, aeration, and pile configuration.

In 2016, the EPA National Emission Inventory estimate of total annual NH_3 emissions for the United States was 3,858,000 tons (EPA, 2016c). The dominant NH_3 source sectors at the national scale are livestock operations (70.9%) and agricultural fertilizer losses (14.3%), with composting contributing to less than 1% (Roe et al., 2004). However, urban and suburban areas are often underrepresented in national inventories and are dominated by different sources of NH_3 emissions (Roe et al., 2004). For example, Figure 4 provides a pie chart of ammonia source sector contributions to the New York City Metropolitan Area emission inventory, which is the only city identified in the literature search where the contribution of composting to NH_3 emissions in an urban area was quantified. At this scale, composting emissions contribute to 13.4% of the city's ammonia emissions inventory. Although the environmental and municipal conditions are different in Maricopa County, this study gives a coarse estimate of what might be expected for Maricopa County, which includes a large metropolitan area.

Figure 4. Source sector ammonia contributions in the New York Metropolitan Area (Roe et al., 2004).



Note: POTW refers to publicly-owned treatment works.

Research Question 3: How do biophysical characteristics and management of compost piles (e.g. temperature, age, moisture, pile configuration and composition, other management practices, etc.) affect the rate of VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations?

Based on the existing literature, the major factors that influence the type, timing, and rate of gaseous emissions from compost are feedstock type (or feedstock C:N ratio), stockpile age, compost pile age, configuration of compost piles, temperature, pH, moisture, and aeration. Here, we review the existing research on the impact of each factor on VOC, NO_x, PM, SO_x, and NH_3 emissions from composting operations.

Feedstock Type and C:N ratio

Feedstocks for composting operations vary (e.g. greenwaste, food waste, animal manure, and others) depending on the region and availability of feedstock sources. One way to evaluate the effects of feedstock on emission rates is through the ratio of carbon to nitrogen in the material (C:N ratio), which is largely determined by feedstock type and compost age. For example, the C:N of woody materials (leaves, brush, and wood) is ~60 on average, while the C:N of grassy materials is closer to 20 (California Integrated Waste Management Board [CIWMB], 2003). A report commissioned by the SCAQMD found a negative relationship between feedstock C:N ratio and VOC emission rates, where VOC emissions decreased by 34% to 80% as C:N ratio increased. Thus the control of feedstock blends is considered a feasible method for minimizing VOC emissions.

Despite the known importance of feedstock and C:N ratio on NH_3 emissions, the effects of these variables in the literature are mixed due to the combined effects of other controlling factors such as pH, moisture, and temperature. CIWMB and SCAQMD test programs showed that NH_3 emissions from biosolids or mixed waste composting processes (lower C:N ratio) were higher than green waste composting processes (higher C:N ratio) (Roe et al., 2004). De Guardia et al. (2010) found that the highest levels of NH_3 emissions were observed for pig slaughterhouse sludge, followed by food waste, green algae, separated pig solids, and then household waste. Komilis and Ham (2000) found food waste composting produced higher NH_3 emissions followed by yard wastes and then mixed paper. Paillat et al. (2005) reported from their investigations in livestock manure composting that the dynamics of NH_3, both in intensity of emissions and timing, varied depending on the mixture of slurry and manure.

Because SO_x emissions are primarily formed from direct diesel combustion, diesel pre-combustion, and electricity pre-combustion/combustion, feedstock type and C:N ratio are not directly related to SO_x emission rates from composting facilities. Although no studies have evaluated it, NO_x emissions from compost piles are likely to be related to C:N ratio of feedstocks, since higher N content of organic material leads to nitrification and denitrification, both of which produce NO (Hall et al., 1996). No studies have evaluated the effect of feedstock type on PM emissions from composting operations.

Stockpile and Compost Pile Age

The length of time that stockpiles sit at a facility, as well as the compost pile age, can affect the type and total gaseous emissions from the composting process.

VOCs and PM can be emitted during stockpiling, and a separate EF has been developed for this stage (CARB, 2015a). Once the feedstock has been moved to an active compost pile, VOC emission rates start to peak and then decrease during the composting process. In a laboratory study using mixed paper, yard, and food waste Komilis et al. (2004) and Pagans et al. (2006) found that the rate of VOC emission was highest upon the initiation of the experiment before biological decomposition had begun (Komilis et al., 2004). Kumar et al. (2011) found that the highest VOC emission rates were from younger composting windrows (3-6 days), compared to fresh tipping piles or older windrows (2-3 weeks). Similarly, the 2008 SJVAPCD Greenwaste Compost Report found the highest VOC emission rates early (3-8 days) in the composting process (Card and Schmidt, 2008). Another study by Peter Green at UC Davis quantified the ozone-forming potential of composting method and age of the compost pile (Green, 2010). This study found that older piles (~3 weeks) release more reactive VOCs, but at lower rates, compared to younger piles.

Compost pile age also affects NH_3 emission rate and timing, with the majority of NH_3 emissions occurring within the early stages of composting. For example, Paillat et al. (2005) reported peak NH_3 emission in the early stage of composting of livestock manure. El Kader et al. (2007) also observed most ammonia emissions occurring in the first days and the highest rates during the first 1-2 weeks of composting with manure, which is similar to reports by Amon et al. (1998), Fukumoto et al. (2003), Osada et al. (2000), Parkinson et al. (2004), and Petersen et al. (1998). Li et al. (2013) found that approximately 70% of the ammonia emissions occurred within 96-144 hours of the thermophilic stage in laboratory experiments with municipal solid waste.

Stockpile and compost pile age will likely not have a significant effect on SO_x or PM emission rates, but will likely affect NO_x emissions due to changes in rates of biological nitrification and denitrification processes during compost decomposition.

Configuration of Compost Piles

Several types of compost pile configurations are used throughout the country (see Methods of Composting section above). In the arid US Southwest, windrow and aerated static piles (ASP) are common (Platt et al., 2014). Emission fluxes are calculated as mass of gas per unit of area per unit of time (e.g. 1 lb. VOC/1000 sq. ft./hour). Thus, the volume-to-surface area ratio of compost piles at a facility significantly affects total annual emissions. SJVAPCD (2010) reported that if all other factors remain the same (moisture, temperature, aeration, C:N ratio, etc.), a shorter windrow (less deep) of the same length as deeper windrow would have a higher surface area relative to its volume, and would thus emit more VOCs over the year. Similarly, for NH_3, Roe et al. (2004)

reported that compost piles with a higher surface area yielded higher emission rates of NH_3 because they allow for greater air infiltration.

As above, compost pile configuration will likely not have a significant effect on SO_x and PM emission rates, but will likely affect NO_x emissions due to changes in rates of biological nitrification and denitrification processes during compost decomposition.

Temperature and pH

Four studies have reported the relevance of internal pile temperature on VOC emission rates (Agapiou et al., 2016; Delgado-Rodríguez et al., 2011; Hentz Jr et al., 1996; Komilis et al., 2004). During the compost process, internal temperatures follow three typical phases: a short initial mesophilic phase (rising to 45° C/113°F), a thermophilic phase (above 45° C/113°F), and a second mesophilic phase (decreasing from 45° C/113°F). Delgado-Rodríguez et al. (2011) reported high VOC emission rates during the initial mesophilic and the thermophilic phase, followed by a progressive decrease in the second mesophilic phase. These findings are similar to Komilis et al. (2004), which found high VOC emissions during the transition from the mesophilic to thermophilic stages; and Agapiou et al. (2016) which found that VOC emissions increased with higher internal pile temperatures and later decreased over time. In an aerated static pile of biosolids, Hentz Jr. et al. (1996) found a positive relationship between headspace VOC concentration and internal temperature (Hentz Jr. et al., 1996).

Numerous studies have also shown that NH_3 emission is positively correlated to the internal temperature of the composting material (Amlinger et al., 2008; Eklind et al., 2007; Fukumoto et al., 2003; Hellebrand and Kalk, 2001; Pagans et al., 2006; Peigné and Girardin, 2004). Specifically, Amlinger et al. (2008) found that concentrations of NH_3 are highest at temperatures around 40-50°C/104-122°F for biowaste, greenwaste, and sewage sludge. Similarly, Eklind et al. (2007) observed that ammonia emissions at 67°C/153°F were more than double those at lower temperatures and they were lowest at 40°C/104°F in source-separated household waste composting. Additionally, Fukumoto et al. (2003) and Zhao et al. (2008) noted that compost NH_3 emissions in their experiments were influenced by ambient temperatures, although external temperature effects were not the main focus of their studies. Zhao et al. (2008) observed that NH_3 emissions increased during the daytime and fell at night, and that diurnal variations were stronger in the summer and weaker in the winter. Chamber experiments conducted by Fukumoto et al. (2008) also observed similar fluctuations, with increased emissions occurring when chamber temperatures were higher.

Studies specific to the effects of high external temperature on gaseous emission rates similar to what Maricopa County experiences during the summer (38-48°/100-118°F), were not found during this literature search. However, A. Agapiou (personal communication, December 24, 2017) provided this:

> *"According to my research knowledge, since compost is affected by pile temperature, aeration and moisture, external temperature may not direct(ly) affect the compost procedure, but it will affect the moisture content and the aeration rate and both parameters impact pile temperature. High external temperature is favored to lower internal humidity and may extend and retain the time of the process. Certainly, it will not affect directly the microbes work; however it offers the basis to shift towards degradation, decomposition and drying of organic content*."

Due to the region's intense summer heat and projected future temperature increases, ambient temperature may be an important factor related to compost VOC and NH_3 emission rates in Maricopa County, particularly if internal temperature, moisture, and pile maturity are not monitored or regulated.

Because gaseous NH_3 is a product of NH_4^+ deprotonation, compost pH is strongly related to NH_3 emissions when the concentration of compost N is high. Beck-Friis et al. (2001), Martins and Dewes (1992), and Peigné and Girardin (2004) reported that a high pH value (pH>8) promoted NH_3 emissions in livestock manure composting. Beck-Friis et al. (2001), experimenting with household waste in compost reactors, noted that when the thermophilic phase started and the pH increased to about 9, the microbial activity and NH_3 emissions simultaneously increased and the temperature increased above 45°C/113°F.

Compost pile temperature and pH will likely not have a significant effect on SO_x and PM emission rates, but these factors are likely to significantly affect NO_x emissions. In particular, NO_x emissions from soil are strongly controlled by temperature (Hall et al., 1996), and they may also be influenced by changes in pH to the extent that compost acidity or alkalinity alters rates of biological nitrification and denitrification processes during compost decomposition.

Moisture and Aeration

Another management practice that varies across facilities is aeration method. Aeration rates affect microbial activity and temperature, and thus affect substrate (e.g. compost) degradation rate (Agapiou et al., 2016). For example, in one compost facility, fall/winter (October-February) VOC emissions were lower from static piles compared to turned (managed) windrows, possibly due to a quick release of VOCs during managed aeration (CIWMB, 2003).

In a laboratory comparison of aeration rate, feedstock C:N ratio, and pile moisture on VOC emission rates, Delgado-Rodríguez et al. (2011) found that aeration rate was the most important variable. Higher aeration rates (0.30 L_{air} kg^{-1} min^{-1}) led to higher VOC emissions compared to a lower aeration rates (0.05 L_{air} kg^{-1} min^{-1}). A follow up study identified that the ideal aeration rate to minimize VOC emissions but maximize aerobicity was 0.175 L_{air} kg^{-1} min^{-1} (Delgado-Rodriguez et al., 2012). Moisture content had variable effects on VOC emission depending on the VOC type, and Delgado-Rodríguez et al. (2011) concluded that a medium moisture value (55%) was ideal for controlling emissions. Together, aeration, moisture and feedstock C:N ratio also influence pile temperature, complicating the ability to quantify independent effects of variables on emission rates.

Aeration has also been shown to effect emission rates of NH_3 from compost piles. Osada et al. (2000) found that as the aeration rate rose, the level of NH_3 emissions increased; however, when the aeration rate was too high (about 100 L_{air} m^{-3} min^{-1}), the moisture content of the compost mixture dropped too low for microorganisms to grow. Jiang et al. (2011) also observed that higher aeration rate increased NH_3 losses, as did de Guardia et al. (2008). Similarly, Beck-Friis et al. (2003) observed that at lower oxygen concentrations, rates of NH_3 emissions are also reduced. De Guardia et al. (2010) had similar findings but noted that the increase in emissions with aeration was significant for food waste, pig slaughterhouse sludge, and green algae, but almost negligible for household waste.

The effects of moisture on NH_3 emissions is less clear. Jiang et al. (2011) reported that moisture does not influence emissions significantly. Contrary to this finding, El Kader et al. (2007) observed a reduction in NH_3 emissions by 30-70% with a reduction of free air space by 20–60%, either by compacting or adding water (or both). Further research is needed to tease apart the effects of moisture on NH_3 emissions from other management factors.

The effect of moisture on facility SO_2 emissions was noted by Levis and Barlaz (2011) who modeled four types of compost - windrows, ASP, gore cover system, and in-vessel systems. They found that that for aerated static piles, increasing moisture content decreases SO_2 emissions because the reduced amount of dry mass reduces the necessary odor control and forced aeration electricity use.

Compost pile moisture and aeration are likely to significantly affect NO_x emissions. In particular, NO_x emissions from soil are strongly controlled by water and oxygen availability (Hall et al., 1996), as both modulate biological rates of nitrification and denitrification.

PM emissions can be significantly reduced by the addition of water to compost piles to prevent or reduce dust plumes.

Research Question 4: What are recommended VOC, NO_x, PM, SO_x, and NH_3 EFs from composting operations, and are existing EFs appropriate for Maricopa County's climate and composting methods?

Volatile Organic Compounds

Currently, California is the only state that has developed composting EFs for VOCs. The most recent, comprehensive review of composting VOC emissions is the CARB Emissions Inventory Methodology for Composting Facilities (CARB, 2015a). The CARB (2015a) report uses the underlying emissions source test data used in SJVAPCD (2010) and SCAQMD (2013/2015) to recommend EFs for composting and co-composting for the state as a whole (Table 4). The estimates presented by CARB (2015a) are the most recent, inclusive, and geographically pertinent EFs for estimating VOC emissions in Maricopa County.

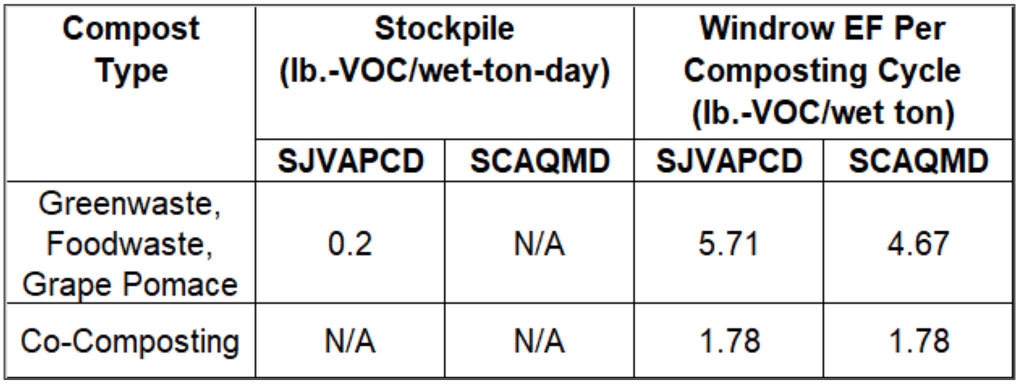
Table 4. CARB (2015a) recommended VOC EFs for composting.

Pollutant	Stockpile (lbs./wet ton-day)	Composting Process (lbs./wet ton)	Co-composting Process (lbs./wet ton)
VOC	0.20	3.58	1.78

Note: Stockpile and Composting Process columns consider greenwaste and food waste, while the Co-composting column considers greenwaste mixed with animal manure, biosolids, or poultry litter.

SJVAPCD and SCAQMD composting and co-composting EFs are presented in Table 5 for comparison to the CARB (2015a) state-wide recommended EFs. Table 5 estimates were created by SJVAPCD (2010) and SCAQMD (2013) based on studies conducted within their districts. The approximately 1 lb./wet ton difference between the SJVAPCD (2010) VOC EF and the SCAQMD (2013, 2015) VOC EF for greenwaste, foodwaste, and grape pomace is because SJVAPCD chose not to include two source tests because they believed that the facilities were small and did not reflect the size of facilities in their district (CARB, 2015a). The CARB (2015a) recommended co-composting EF for VOCs is the same as the EF used by SCAQMD and SJVAPCD. However, the CARB (2015a) recommended composting EF for VOCs is less than that used by SCAQMD and SJVAPCD because the CARB (2015a) estimate is an average of nine studies in the state, whereas SCAQMD (2013/2015) and SJVAPCD (2010) estimates are averages of six and four studies, respectively.

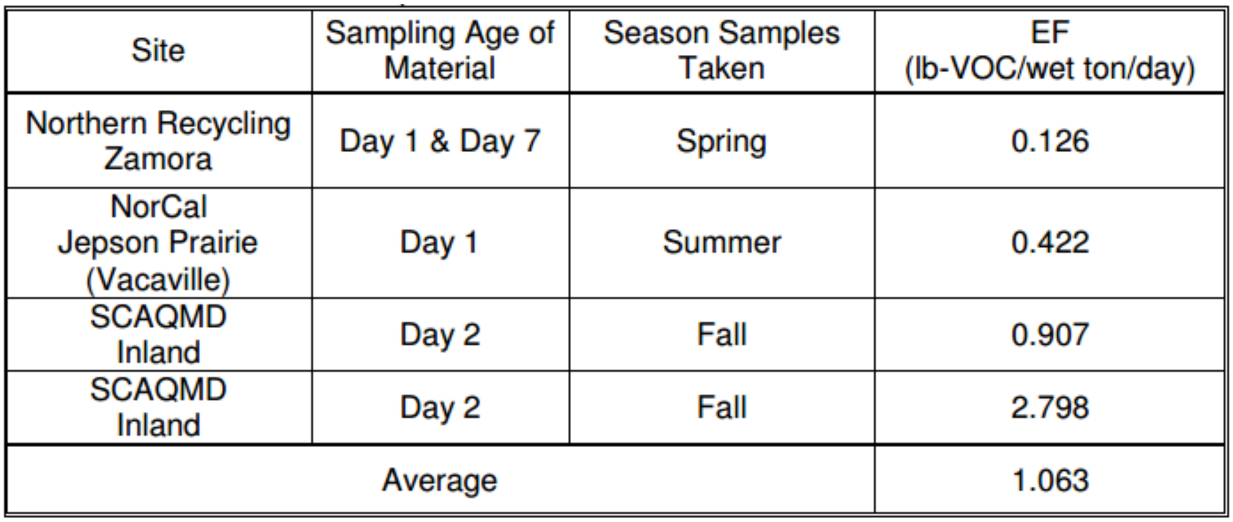
Table 5. Summary of composting VOC EFs approved by SJVAPCD & SCAQMD (CARB, 2015a).



Compost Type	Stockpile (lb.-VOC/wet-ton-day)		Windrow EF Per Composting Cycle (lb.-VOC/wet ton)	
	SJVAPCD	**SCAQMD**	**SJVAPCD**	**SCAQMD**
Greenwaste, Foodwaste, Grape Pomace	0.2	N/A	5.71	4.67
Co-Composting	N/A	N/A	1.78	1.78

The SJVAPCD (2010) report identifies several major factors that affect compost VOC emission rates and thus the EFs, including oxygen (aeration), moisture, and seasonal temperature, temperature within the pile, nutrient levels (C:N ratio), feedstock variability and pH (SJVAPCD, 2010). Additionally, the SJVAPCD (2010) report recommends an EF of 1.063 lb.-VOC/wet ton for greenwaste stockpiles based on field tests at several facilities (Table 6) (SJVAPCD, 2010). Although the reasoning for the change in EFs is not clear, a more recent review by CARB recommends a state-wide stockpile EFs of 0.20 lbs./wet ton-day for greenwaste and food waste, which is reflected in the general stockpile EF in Table 4 **Error! Reference source not found.**(CARB, 2015a).

Table 6. Greenwaste stockpile VOC EF (SJVAPCD, 2010).



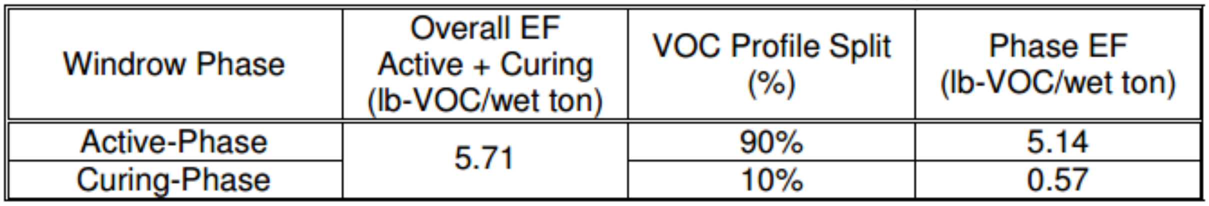
Site	Sampling Age of Material	Season Samples Taken	EF (lb-VOC/wet ton/day)
Northern Recycling Zamora	Day 1 & Day 7	Spring	0.126
NorCal Jepson Prairie (Vacaville)	Day 1	Summer	0.422
SCAQMD Inland	Day 2	Fall	0.907
SCAQMD Inland	Day 2	Fall	2.798
Average			1.063

In 2012, the Colorado Air Pollution Control Division (COAPCD) conducted a review of VOC emissions from composting operations (Burger et al., 2015). Outside of California, the COAPCD is the only known air quality agency considering VOC EFs for composting at this time. They concluded that the greenwaste windrow EF was most appropriate for their facilities, 5.71 lb.-VOC/wet ton (Table 5). However, the COAPCD determined that the recommended stockpile EF of 1.063 lb-VOC/wet ton was not appropriate for this reason:

> *“The Division does not recommend the use of the SJVAPCD Greenwaste Stockpile VOC emission factor at this time. The San Joaquin Valley’s climate is different than Colorado’s and it is not clear how the climate differences (e.g. moisture, temperature) would alter VOC emissions from an unmaintained stockpile. However, the Division believes that the climate differences should not have a significant impact on the VOC emission factor for the compost windrows since the compost operation is managed to control important parameters (e.g. moisture, nutrients, temperature) regardless of location.”*

One final study on compost pile age from SJVAPCD (2010) identifies separate VOC EFs for active and curing phases of composting VOC (Table 7) (SJVAPCD, 2010). The EFs appear to reflect the current data on VOC emission variability over the stockpile and compost pile lifecycles (see above section on Stockpile and Compost Pile Age).

Table 7. Greenwaste windrow VOC EF active-phase vs. curing phase (SJVAPCD, 2010).



Windrow Phase	Overall EF Active + Curing (lb-VOC/wet ton)	VOC Profile Split (%)	Phase EF (lb-VOC/wet ton)
Active-Phase	5.71	90%	5.14
Curing-Phase		10%	0.57

The EPA estimates for county-level VOC emissions from greenwaste composting uses the SCAQMD (2013) EFs. The EPA estimates are calculated by multiplying the total amount of greenwaste recovered for composting per year (0.35 lbs. per person per day of greenwaste multiplied by the population in each county in 2014 from the U.S. Census Bureau) by 4.67 lb.-VOC/wet ton (EPA, 2017b). The EPA does not provide estimates for county-level VOC emissions from co-composting.

Nitrogen Oxides

No EFs were found during the literature search for NO or NO_2 emissions from composting.

Particulate Matter

Currently, there are no known PM10 EFs developed specifically for composting. The SJVAPCD thus proposed to use the EF for crushed stone, which is a conservative estimate for primary PM, see Table 8 and Appendix C (EPA, 2004; SJVAPCD, 2006). While crushed stone is a very different material than compost, it goes through a similar process when handled: the material is received, stored, and mixed; it is then left out in piles, screened and then is transferred. Because of the similar processing and handling, comparable EFs were created for each step in the composting process. The SJVAPCD uses separate EFs for uncontrolled emissions and controlled emissions, which is when water sprays are used for dust control.

The SJVAPCD estimates there are nine drop points on average at a facility, including 5 drop points for material receiving, storage, and mixing; 2 drop points during open windrow active and curing phase composting; and 2 drop points for finished compost storage and loadout operations (Table 8).

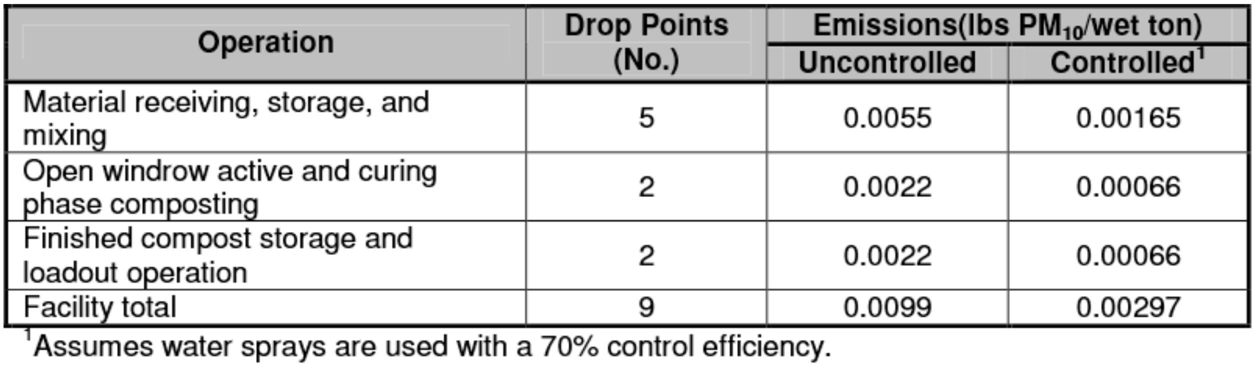
The SJVAPCD has developed PM EFs from uncontrolled and controlled composting operations, based on EFs for crushed stone (SJVAPCD, 2006).

PMEF (uncontrolled) = 0.0011 lb.-PM10/wet ton

If water sprays are used for dust control, then a control efficiency of 70% is assumed. The controlled EF is:

PMEF (controlled) = 0.0011 lb.-PM10/wet ton x (1-0.70) =0.00033 lb.-PM10/wet ton

Table 8. Summary of composting operation PM10 emissions (SJVAPCD, 2006).



Operation	Drop Points (No.)	Emissions(lbs PM_{10}/wet ton)	
		Uncontrolled	Controlled[1]
Material receiving, storage, and mixing	5	0.0055	0.00165
Open windrow active and curing phase composting	2	0.0022	0.00066
Finished compost storage and loadout operation	2	0.0022	0.00066
Facility total	9	0.0099	0.00297

[1] Assumes water sprays are used with a 70% control efficiency.

Sulfur Oxides

No EFs were found during the literature search for SO_x emissions.

Ammonia

EFs for NH_3 were reported in studies by Amlinger et al. (2008), Amon et al. (1998), Andersen et al. (2010), Cadena et al. (2009), CARB (2015a), Maulini-Duran et al. (2014b), SCAQMD (2013), SCAQMD (2015), SJVAPCD (2010), and Zhao et al. (2008). The estimates presented by CARB (2015a) are the most recent, inclusive, and geographically pertinent EFs for estimating NH_3 emissions in Maricopa County. CARB (2015a) recommended EFs for NH_3 for greenwaste and foodwaste, and for greenwaste mixed with animal manure, biosolids, or poultry litter (co-composting) are 0.78 lbs./wet ton and 2.93 lbs./wet ton, respectively (Table 9). The CARB (2015a) report does not list an EF for NH_3 for stockpiles.

Table 9. CARB (2015a) recommended NH_3 EFs for composting.

Pollutant	Stockpile (lbs./wet ton-day)	Composting Process (lbs./wet ton)	Co-composting Process (lbs./wet ton)
NH_3	N/A	0.78	2.93

Note: Stockpile and Composting Process columns consider greenwaste and food waste, while the Co-composting column considers greenwaste mixed with animal manure, biosolids, or poultry litter.

The co-composting EFs used by CARB (2015a) are also used by SCAQMD and SJVAPCD. The composting EF used by SCAQMD (2013/2015) for NH_3 is 0.66 lb./wet ton for uncontrolled greenwaste composting and 0.57 lb./wet ton for controlled (assumes 20% control applied to the active phase only) greenwaste composting, which is less than the CARB (2015a) recommended EF for composting. The CARB (2015a) estimate differs from the SCAQMD (2015) estimate because the CARB (2015a) estimate contains data from nine emissions studies in the state of California, whereas the SCAQMD (2015) contains estimates only from within the district (six total). CARB (2015a) uses the same composting EF as SJVAPCD (2010).

The EPA estimates for county-level NH_3 emissions from greenwaste composting uses the SCAQMD (2013) EF. The EPA estimates are calculated by multiplying the total amount of greenwaste recovered for composting per year (0.35 lbs. per person per day of greenwaste multiplied by the population in each county in 2014 from the U.S. Census Bureau) by 0.66 lb.-NH_3/wet ton (EPA, 2017b). The EPA does not provide estimates for county-level NH_3 emissions from co-composting.

Research Question 5: What is the recommended methodology for estimating compost-related VOC, PM, and NH_3 emissions for composting operations?

Volatile Organic Compounds and Ammonia

California and Colorado are the only states that have recognized VOC and NH_3 EFs for composting (and Colorado uses the EFs created in California). Therefore, the methodology reviewed in this section is entirely from the state of California.

CARB (2015a) identifies two methods for estimating VOC and NH_3 emission rates from composting facilities: (1) using facility specific data and on-site emissions tests to develop local EFs, or (2) using EFs from emission tests at other facilities with facility-specific parameters. If EFs are used from other facilities, local data are required in order to calculate facility-specific emissions. The required local data include:

- **Facility throughput (wet tons):** Annual amount of organics processed at the facility, excluding screen waste that does not go through the composting process.
- **Feedstock composition (greenwaste, food waste, co-composting):** The mix of feedstocks used in the compost by percentage.
- **Control technology efficiency (e.g. ASP, biofilter):** The emission control technologies used to determine emission reduction efficiency (Table 10).
- **Average stockpile time:** The amount of time incoming organics are stockpiled before incorporation in to the facility.

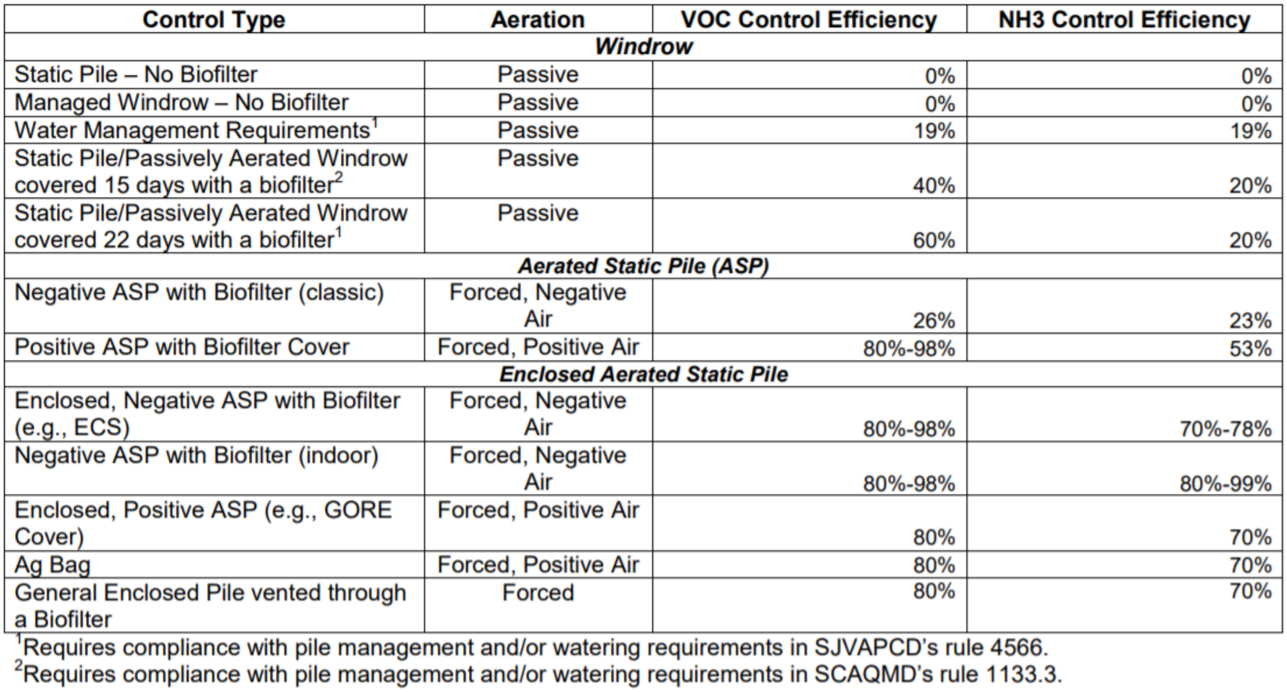
These data are then input into the following equation to calculate total emissions from a facility:

Total annual VOC emissions = (CPEF x (1-CE) x TP) + (SEF x SD x TP);
Total annual NH_3 emissions = (CPEF x (1-CE) x TP)

Where

- CPEF= Composting Process EFs (lbs. VOC or NH_3/wet ton)
- SEF= Stockpile EFs (lbs./wet ton-day)
- SD=Average number of days material is stockpiled (days)
- CE=Control Efficiency (percentage; Table 10)
- TP=Total annual facility throughput (wet tons)

Table 10. Control techniques and CEs for composting (CARB, 2015a).



Control Type	Aeration	VOC Control Efficiency	NH3 Control Efficiency
Windrow			
Static Pile – No Biofilter	Passive	0%	0%
Managed Windrow – No Biofilter	Passive	0%	0%
Water Management Requirements[1]	Passive	19%	19%
Static Pile/Passively Aerated Windrow covered 15 days with a biofilter[2]	Passive	40%	20%
Static Pile/Passively Aerated Windrow covered 22 days with a biofilter[1]	Passive	60%	20%
Aerated Static Pile (ASP)			
Negative ASP with Biofilter (classic)	Forced, Negative Air	26%	23%
Positive ASP with Biofilter Cover	Forced, Positive Air	80%-98%	53%
Enclosed Aerated Static Pile			
Enclosed, Negative ASP with Biofilter (e.g., ECS)	Forced, Negative Air	80%-98%	70%-78%
Negative ASP with Biofilter (indoor)	Forced, Negative Air	80%-98%	80%-99%
Enclosed, Positive ASP (e.g., GORE Cover)	Forced, Positive Air	80%	70%
Ag Bag	Forced, Positive Air	80%	70%
General Enclosed Pile vented through a Biofilter	Forced	80%	70%

[1] Requires compliance with pile management and/or watering requirements in SJVAPCD's rule 4566.
[2] Requires compliance with pile management and/or watering requirements in SCAQMD's rule 1133.3.

For example, for a facility that composts 85,000 wet tons of greenwaste and manure feedstock per year in average-depth windrows with no control technologies, with an average stockpiling time of 3 days, the values for each of the equation variables would be:

CPEF= Composting Process EFs (lbs./wet ton) = 1.78
SEF= Stockpile EFs (lbs./wet ton/day) = 0.20
SD=Average number of days material is stockpiled (days) = 3
CE=Control Efficiency (percentage) = 0
TP=Total annual facility throughput (wet tons) = 85,000 wet tons

Total annual VOC emissions (lbs.) = (1.78 x (1-0) x 85,000 wet tons) + (0.20 x 3 x 85,000 wet tons) = 151,300 lbs. + 51,000 lbs. = 202,300 lbs. VOC per year.

Particulate Matter

The SJVAPCD has developed PM EFs from uncontrolled and controlled composting operations, based on EFs for crushed stone (SJVAPCD, 2006).

PMEF (uncontrolled) = 0.0011 lb.-PM10/wet ton

If water sprays are used for dust control, then a control efficiency of 70% is assumed. The controlled EF is:

PMEF (controlled) = 0.0011 lb.-PM10/wet ton x (1-0.70) =0.00033 lb.-PM10/wet ton

Total annual PM emissions are then calculated as

Total annual PM emissions (lbs.) = (PMEF (controlled or uncontrolled) x TP x # Drop Points)

Where

- PMEF (controlled or uncontrolled) = PM EFs for controlled or uncontrolled
- operations (lbs./wet ton)
  TP = Total annual facility throughput (wet tons)
- # Drop Points = Number of points where compost was moved or dropped (e.g. material receiving, storage and mixing, during open windrow active and curing phase composting, compost screening, or finished compost storage and loadout operations).

For example, for a facility that processes 1 wet ton of compost per year with no control technologies, the annual PM emissions (lbs.) would be:

Total annual PM emissions (lbs.) = 0.0011 lb.-PM10/wet ton x 1 wet ton x 9 drop points = 0.0099 lbs. PM per year.

If a facility that used water to control dust, the annual PM emissions (lbs.) would be:

Total annual PM emissions (lbs.) = 0.00033 lb.-PM10/wet ton x 1 wet ton x 9 drop points = 0.00297 lbs. PM per year.

Research Question 6: What are the best management practices (BMPs) for the reduction of compost-related VOC, NO_x, PM, SO_x, and NH_3 emissions; and are these BMPs appropriate for Maricopa County's climate and composting methods?

Volatile Organic Compounds

Numerous BMPs have been developed to reduce VOC and PM from composting operations (Appendix D). One of the more effective techniques for VOC reduction reviewed is the use of aerated static piles (ASP) with a forced air ventilation system, capped with a layer of cured compost (Positive ASP with a biofilter cover). This technique uses large static piles instead of rows, which are placed over a network of pipes that supply air and is capped with a 4-6 inch layer of finished compost, which is sometimes called a 'compost blanket'. ASP systems can also be also fitted with other BMP technologies to improve VOC emission capture efficiency by sucking the air into a ventilation system. Some of these additional control systems are called Gore cover, Engineered Compost System (ECS), or AgBag.

In one study, CalRecycle and SJVAPCD used an extended aerated static pile (eASP) compost system design. The eASP uses deeper and wider windrows than the typical configuration, and windrows are placed on aerated tubing and chipped material and then capped with a one-foot-thick layer of finished compost as a biofilter (CalRecycle, 2013). This system resulted in a 99% reduction in non-methane, non-ethane VOCs, (Table 11).

Table 11. Results of eASP study (pounds of pollutant per wet ton) (CARB, 2015a).

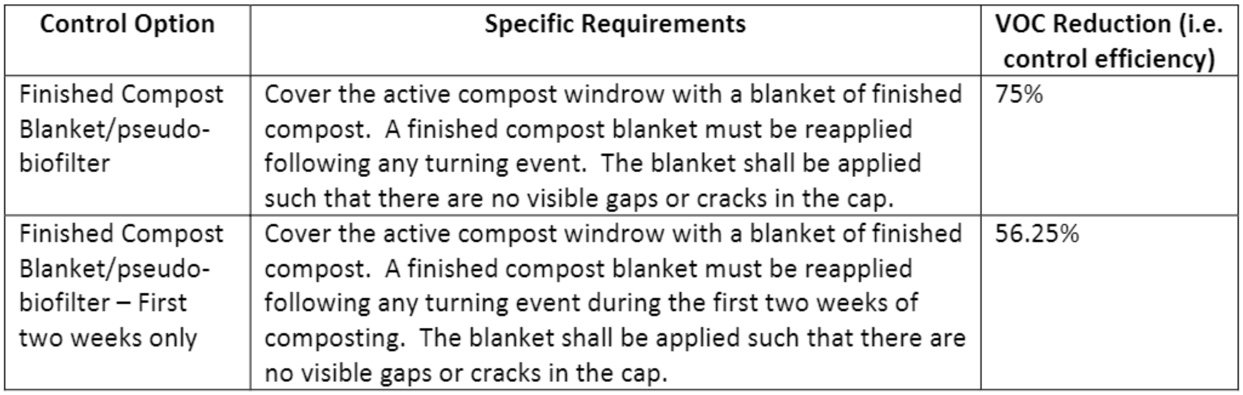
		NH3	
	VOC	Field	Lab
Prototype ASP (22 Days)	0.099	0.017	0.007
Baseline Windrow (22 Days)	8.604	0.099	0.014
% Reduction from Baseline	**-98.80%**	**-83.20%**	**-53.30%**

Biofilter caps allow microbes in the finished compost cap to consume VOC emissions (using the carbon as an energy source) before they are emitted to the atmosphere. In another study, biofilter VOC emissions were significantly reduced over the first two weeks of composting (Green, 2010). Some biofilters are created using the leftovers, or "overs", from compost, which are the large particles that won't break down during composting and are screened out before it is sold. The use of this material is beneficial because it does not cost extra or deter from selling compost, and the bulk material can be mixed into the compost pile after peak emissions are minimized to help aerate the pile. Even if the overs are only applied during the first two weeks of composting, a 56% control efficiency is expected (CARB, 2015a). Laboratory studies on biofilters for VOC emissions support these findings (Pagans et al., 2006).

One final BMP that can reduce VOC emissions from composting is the operation of composting processes indoors or in a fully enclosed system (CARB, 2015a). Moving composting inside or within an enclosed system allows for air capture and filtration from all composting emissions, resulting in reductions as high as 80%. The use of indoor facilities may also help to address the increase in VOC emissions rates from higher temperatures in Maricopa County.

In Colorado, the COAPCD uses BMP recommendations from the SJVMCD (Table 12; Burger et al., 2015). At the time of this study, no other BMPs in Colorado were used.

Table 12. BMP for VOC emission reduction for Colorado (Burger et al., 2015)



Control Option	Specific Requirements	VOC Reduction (i.e. control efficiency)
Finished Compost Blanket/pseudo-biofilter	Cover the active compost windrow with a blanket of finished compost. A finished compost blanket must be reapplied following any turning event. The blanket shall be applied such that there are no visible gaps or cracks in the cap.	75%
Finished Compost Blanket/pseudo-biofilter – First two weeks only	Cover the active compost windrow with a blanket of finished compost. A finished compost blanket must be reapplied following any turning event during the first two weeks of composting. The blanket shall be applied such that there are no visible gaps or cracks in the cap.	56.25%

Particulate Matter

Few agricultural PM BMPs are applicable to reducing composting PM emissions (ADEQ, 2008). Facilities can adjust fans and aeration equipment direction as well as utilize a mist system to prevent PM10 from becoming airborne. Alternatively, compost piles can be created inside of a vessel or a building, performed under a roof, or covered with soil to prevent wind erosion. The areas where greenwaste is loaded and unloaded could also remain covered to prevent wind erosion. Additionally, bulking agents could be kept in consolidated piles and/or covered to prevent wind exposure (ADEQ, 2008).

Sulfur Oxides

Two studies provided recommendations for reducing SO_x emissions from composting operations. Levis and Barlaz (2011) recommended increasing moisture content in piles to reduce SO_2 emissions from electricity use for odor control. Rosenfeld et al. (2004) reported that biofiltration reduced the concentration of odorous compounds of sulfur by 100% in compost piles; however, the study was unable to specify if or how much SO_2 may have contributed to odorous emissions.

Ammonia

Multiple studies provided recommendations for reducing NH_3 emissions through a variety of management techniques, including managing C:N ratio, aeration rate, temperature, and adding biochar or a similar NH_3-scavenging agent. Amlinger et al. (2008) recommended a C:N ratio >25 to minimize NH_3 emissions; however, they note that a C:N ratio >35 may limit proper decomposition and humification processes. Li et al. (2013) suggested that the addition of a 7:3 mixture of sucrose and straw powder (a degradable carbon source) would be suitable for reducing ammonia emissions. They predicted that the decomposition of carbon compounds would provide an energy source for NH_3 assimilating bacteria.

In addition to managing the C:N ratio, Amlinger et al. (2008) also recommended maintaining proper pore space and aeration, advising that bulking material should constitute 40-60% of the mix by volume. Shen et al. (2011) recommended decreasing aeration rate to decrease NH_3 emissions; however, the lowest aeration rate of 0.01 m^3 min^{-1} m^{-3}, did not reach the thermophilic phase and achieve compost maturity. The eASP study by CalRecycle and SJVAPCD, previously mentioned in the BMP section for VOCs, found that using an eASP resulted in a 83.2% reduction in NH_3 emissions in field tests and 53.3% reduction in NH3 emissions in laboratory tests (Table 11) (CARB, 2015a).

Two studies provided specific recommendations for reducing NH_3 emissions through temperature control. Eklind et al. (2007) recommended controlling the biowaste composting process at about 55°C/131°F in the initial, high rate stage and then reducing the temperature after. Beck-Friis et al. (2001) recommended treating compost gas in a cooling and moisture-trapping system, although this method can be costly and may be unfeasible for many operations.

The most common recommendation for reducing NH_3 emissions was through the addition of biochar or a similar NH_3-scavenging agent. Chowdhury et al. (2014) recommended the inclusion of barley straw and biochar at a ratio of 3:1 to reduce NH_3 emissions. Steiner et al. (2010) recommended biochar for composting N-rich materials, reporting that NH_3 emissions from poultry litter were reduced by up to 64% if mixed with biochar, and total gaseous N losses were reduced by up to 52%. Malińska et al. (2014) also reported that the addition of biochar significantly reduced volatilization of NH_3

during the first week of the process. Bautista et al. (2011) recommended the addition of alum or Zeolite to reduce NH_3 emissions.

4. Survey of Composting Operations in Maricopa County

In May 2017, the MCAQD conducted a survey to evaluate composting practices among composting operations in the county. Twenty facilities were asked to participate in the survey, which was estimated to represent approximately 90% of the large-scale bulk composting facilities in Maricopa County. Eight facilities responded. Surveys were received from Orchard Community Learning Center, Mountain States Wholesale Nursery (MSWN), GroWell, Duncan Family Farms, Diversified Organics, Prema, the City of Tempe, and the City of Phoenix. A summary of results from the survey is shown in Appendix E and copies of the eight survey responses are included in Appendix F.

Feedstock type and throughput

Feedstock from five of the eight facilities included animal manure (MSWN, Duncan Family Farms, Diversified Organics, City of Tempe, and City of Phoenix), and two used exclusively greenwaste (GroWell and Prema). One facility (City of Phoenix) indicated that their feedstock composition changes monthly. Annual feedstock throughput at each facility ranged from 468 wet tons per year (Orchard Community Learning Center) to 85,000 wet tons per year (Prema).

Compost pile management

Pile configuration ranged widely, from long windrows between 170-320 ft. in length and 3-25 ft. in height, to more symmetrical shapes (e.g. 8 ft. wide x 15 ft. long x 6 ft. high). Piles at all facilities were located outside and uncovered, except for Diversified Organics which used a composting blanket on one of their outdoor piles for a specific type of compost and the City of Phoenix which uses biochar to cover their initial pile. Seven of the eight facilities used the turned windrow method, with aeration rates ranging from two turns per day to one turn every couple of weeks. One facility (GroWell) used an unspecified anaerobic method of composting that is not discussed in this review.

Compost pile conditions

Only one of the facilities (Duncan Family Farms) reported complete data on the duration, C:N ratio, moisture, and internal temperature of piles in all phases of the composting process (stockpile, active, and curing piles). When asked about the duration of active composting, responses ranged from 21 days to 2 years. When reported, internal pile temperatures ranged from ambient (which would vary seasonally) to 88°C/190°F.

Research Question 7: What is the estimated contribution of VOC, NO_x, PM, SO_x, and NH_3 from composting operations to annual emissions of these compounds in Maricopa County?

The number of large-scale bulk composting facilities in Maricopa County is estimated to be 25. Twenty facilities were asked to participate in the survey, which was estimated to represent approximately 90% of the large-scale bulk composting facilities in Maricopa County. Eight facilities responded. We used the CARB (2015a) and SJVAPCD (2006) recommended EFs and equations for VOC, PM10, and NH_3 emissions for composting to estimate emissions from the eight survey responses. Then, using several coarse assumptions, we estimated the contribution of large-scale bulk composting facilities to the annual VOC, PM10, and NH_3 inventories of Maricopa County (Tables 13, 14, 15). We calculated high, low, and likely estimates of emission contributions based on the eight survey responses representing 15%, 55%, and 35%, respectively, of the annual large-scale bulk composting throughput for the county.

EFs used in the Maricopa County estimate

- VOC Composting EF (greenwaste and food waste only): 3.58 lbs. VOC/wet ton
- VOC Co-composting EF (greenwaste, poultry and other animal manure, and biosolids): 1.78 lbs. VOC/wet ton
- VOC Stockpile EF: 0.2 lbs. VOC/wet ton
- PM EF (uncontrolled): 0.0011 lb.-PM10/wet ton
- PM EF (controlled): 0.0011 lb.-PM10/wet ton x (1-0.70)
- NH_3 Composting EF (greenwaste and food waste only): 0.78 lbs. NH_3/wet ton
- NH_3 Co-composting EF (greenwaste, poultry and other animal manure, and biosolids): 2.93 lbs. NH_3/wet ton

Equations used in the Maricopa County estimate

1. Total annual VOC emissions (lbs.) = (CPEF x (1-CE) x TP) + (SEF x SD x TP)

CPEF= Composting Process EFs (lbs./wet ton)
SEF= Stockpile EFs (lbs./wet ton/day)
SD=Average number of days material is stockpiled (days), as reported or fourteen days if unreported, per CARB (2015a)
CE=Control Efficiency (percentage)
TP=Total annual facility throughput (wet tons)

2. Total annual PM emissions (lbs.) = (PMEF [controlled or uncontrolled] x TP x # Drop Points)

PMEF (controlled or uncontrolled) = PM EFs for controlled or uncontrolled operations (lbs./wet ton)
TP=Total annual facility throughput (wet tons)
# Drop Points = Number of points where compost was moved or dropped (e.g. material receiving, storage and mixing, during open windrow active and curing phase composting, compost screening, or finished compost storage and loadout operations).

3. Total annual NH_3 emissions (lbs.) = (CPEF x (1-CE) x TP)

CPEF= Composting Process EFs (lbs./wet ton)
CE=Control Efficiency (percentage)
TP=Total annual facility throughput (wet tons)

Results

Since the twenty facilities selected for the survey are estimated to represent approximately 90% of the large-scale bulk composting facilities in Maricopa County, three estimates (likely, low, and high) of annual VOC, PM10, and NH_3 emissions from composting operations were made based on the eight survey responses received (Tables 13, 14, and 15).

If the eight surveyed facilities represent the range (large and small) of operations and, therefore, represent roughly 35% of the annual large-scale bulk composting throughput in Maricopa County, then we estimate that the annual VOC, PM10, and NH_3 emissions from all the large-scale bulk composting facilities would be 0.6%, 0.006%, and 4.4% of the total VOC, PM10, and NH_3 emissions, respectively, from all inventoried sources in Maricopa County (based on the 2014 Periodic Ozone Precursor and PM10 Emissions Inventories; MCAQD, 2016) (Tables 13, 14, and 15).

Alternatively, if the eight facility responses actually represent a larger portion of the large-scale bulk composting throughput, say roughly 55%, then we estimate the annual VOC, PM10, and NH_3 emissions from all large-scale bulk composting facilities in the county to be 0.4%, 0.004%, and 2.8% of the total VOC, PM10, and NH_3 emissions, respectively, from all inventoried sources in Maricopa County.

Finally, if the eight surveyed facilities actually represent a smaller portion of the large-scale bulk composting throughput, say roughly 15%, then we estimate the annual VOC, PM10, and NH_3 emissions from all large-scale bulk composting facilities in the county to be 1.4%, 0.013%, and 10.3% of the total VOC, PM10, and NH_3 emissions, respectively, from all inventoried sources in Maricopa County.

We compared our likely/expected estimates of VOC and NH_3 emissions to the 2014 EPA estimates of emissions from greenwaste composting in Maricopa County, which was calculated by multiplying the total amount of greenwaste recovered for composting per year (0.35 lbs. per person per day of greenwaste multiplied by the population in each county in 2014 from the U.S. Census Bureau) by EFs from SCAQMD (2013) (EPA, 2017). Using this formula, the EPA estimates that composting contributes to 0.2% and 0.6% of the total VOC and NH_3 emissions, respectively, from all inventoried sources in Maricopa County (EPA, 2017). Our likely/expected estimate for composting VOC emissions was similar to that estimated by the EPA, but our NH_3 estimate is seven times higher than the EPA estimate. The primary reason for the difference in NH_3 estimates is the feedstock type: the EPA estimates are for greenwaste composting only and uses an EF of 0.66 lbs. NH_3/wet ton. Our estimates use the CARB (2015a) EFs for both greenwaste (EF of 0.78 lbs. NH_3/wet ton) and co-composting (EF of 2.93 lbs. NH_3/wet ton). If only the CARB (2015a) greenwaste composting EF is used and we revised our NH_3 EF to 0.78 lbs. NH_3/wet ton, our estimated annual NH_3 emission from Maricopa County composting facilities would be 1.8% of the total NH_3 emissions from all 2014 inventoried sources, which is closer to the 0.6% estimate from the EPA.

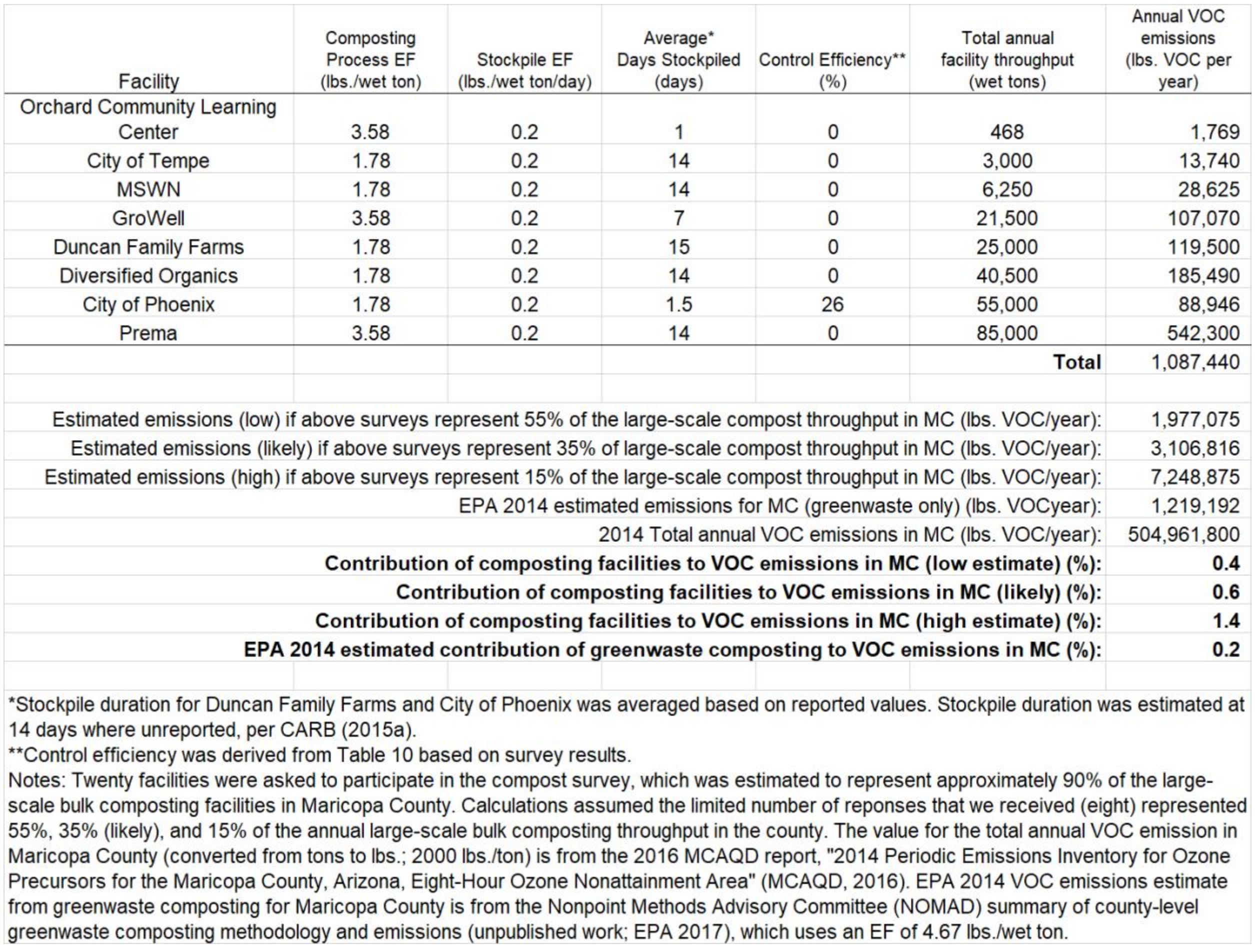
Our VOC estimates are similar to estimates from the CARB Compost Emissions Work Group, which reported that composting facilities contribute <1% of the total reactive organic gas emissions in California (CARB, 2015b).

Although we present a range, our estimates may not represent the true contribution of composting facilities to VOC, PM10, and NH_3 emissions in Maricopa County because the EFs were derived from studies in California under different climatic conditions and composting management practices; the reported survey data for stockpile duration, compost pile conditions, and number of drop points were incomplete; and the survey sample size may be too low.

On-site studies that capture a range of management styles and seasonal effects in Maricopa County, particularly the effects of high summer temperatures on emission rates, will help refine county-wide emission estimates. If future on-site studies are to be conducted, we recommend that they are designed similar to the studies in California, which use EPA standard operating procedures to determine the effects of various environmental factors (e.g. ambient temperature) and management practices (e.g. feedstock type and pile configuration) on compost VOC and NH_3 emissions estimation (for example, see Schmidt et al., 2005 and CIWMB, 2003). These studies quantify VOC and NH_3 emissions using isolation flux chambers (16 inch diameter, 30 liters) placed on piles within the compost facility at different times (e.g. times of day, seasons, stages of the composting process), at various locations (e.g. pile apex or side), and representing various management practices (e.g. turning method, pile configuration, feedstock type, moisture levels) (Figure 5).

Figure 5. Photo of flux chamber set up used for compost pile VOC and NH_3 emission estimation (CIMWB, 2003).

Table 13. Estimated contribution of large-scale bulk composting operations to the annual VOC inventory in Maricopa County (MC).



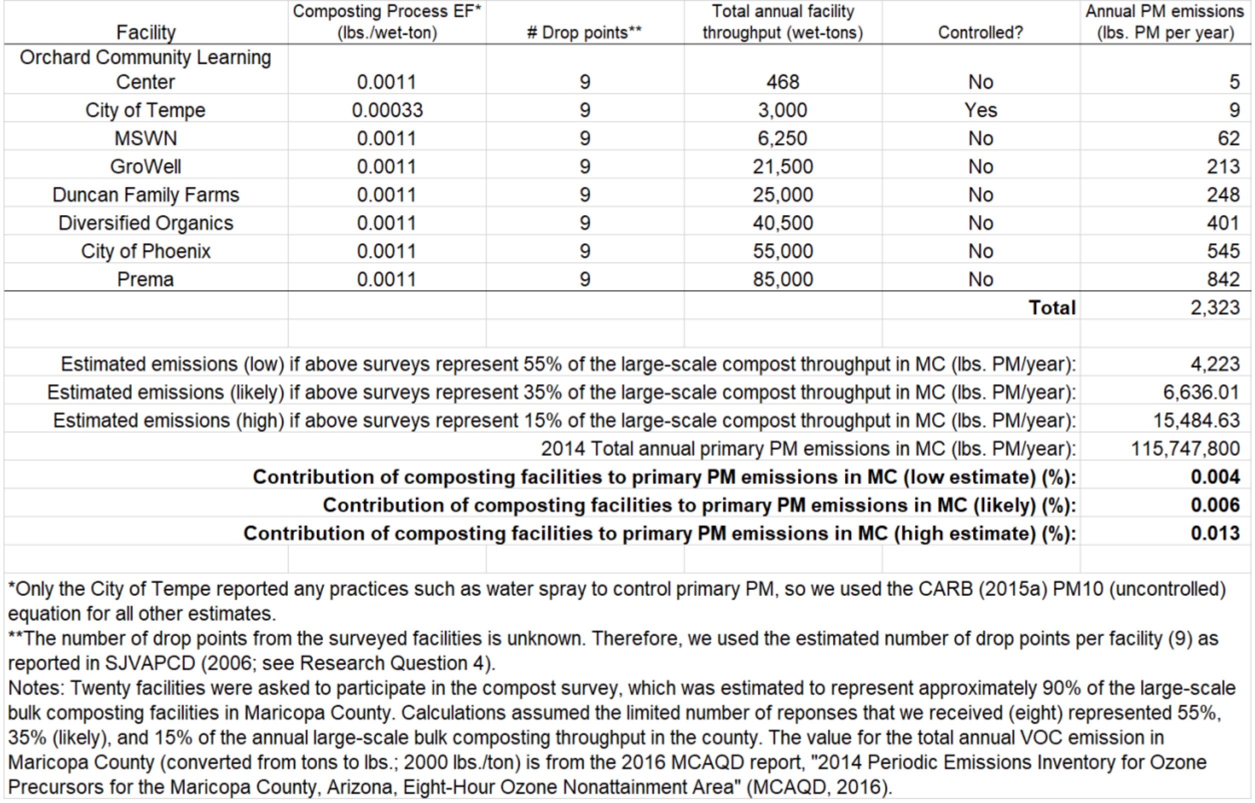
Facility	Composting Process EF (lbs./wet ton)	Stockpile EF (lbs./wet ton/day)	Average* Days Stockpiled (days)	Control Efficiency** (%)	Total annual facility throughput (wet tons)	Annual VOC emissions (lbs. VOC per year)
Orchard Community Learning Center	3.58	0.2	1	0	468	1,769
City of Tempe	1.78	0.2	14	0	3,000	13,740
MSWN	1.78	0.2	14	0	6,250	28,625
GroWell	3.58	0.2	7	0	21,500	107,070
Duncan Family Farms	1.78	0.2	15	0	25,000	119,500
Diversified Organics	1.78	0.2	14	0	40,500	185,490
City of Phoenix	1.78	0.2	1.5	26	55,000	88,946
Prema	3.58	0.2	14	0	85,000	542,300
					Total	1,087,440
Estimated emissions (low) if above surveys represent 55% of the large-scale compost throughput in MC (lbs. VOC/year):						1,977,075
Estimated emissions (likely) if above surveys represent 35% of large-scale compost throughput in MC (lbs. VOC/year):						3,106,816
Estimated emissions (high) if above surveys represent 15% of the large-scale compost throughput in MC (lbs. VOC/year):						7,248,875
EPA 2014 estimated emissions for MC (greenwaste only) (lbs. VOCyear):						1,219,192
2014 Total annual VOC emissions in MC (lbs. VOC/year):						504,961,800
Contribution of composting facilities to VOC emissions in MC (low estimate) (%):						**0.4**
Contribution of composting facilities to VOC emissions in MC (likely) (%):						**0.6**
Contribution of composting facilities to VOC emissions in MC (high estimate) (%):						**1.4**
EPA 2014 estimated contribution of greenwaste composting to VOC emissions in MC (%):						**0.2**

*Stockpile duration for Duncan Family Farms and City of Phoenix was averaged based on reported values. Stockpile duration was estimated at 14 days where unreported, per CARB (2015a).

**Control efficiency was derived from Table 10 based on survey results.

Notes: Twenty facilities were asked to participate in the compost survey, which was estimated to represent approximately 90% of the large-scale bulk composting facilities in Maricopa County. Calculations assumed the limited number of reponses that we received (eight) represented 55%, 35% (likely), and 15% of the annual large-scale bulk composting throughput in the county. The value for the total annual VOC emission in Maricopa County (converted from tons to lbs.; 2000 lbs./ton) is from the 2016 MCAQD report, "2014 Periodic Emissions Inventory for Ozone Precursors for the Maricopa County, Arizona, Eight-Hour Ozone Nonattainment Area" (MCAQD, 2016). EPA 2014 VOC emissions estimate from greenwaste composting for Maricopa County is from the Nonpoint Methods Advisory Committee (NOMAD) summary of county-level greenwaste composting methodology and emissions (unpublished work; EPA 2017), which uses an EF of 4.67 lbs./wet ton.

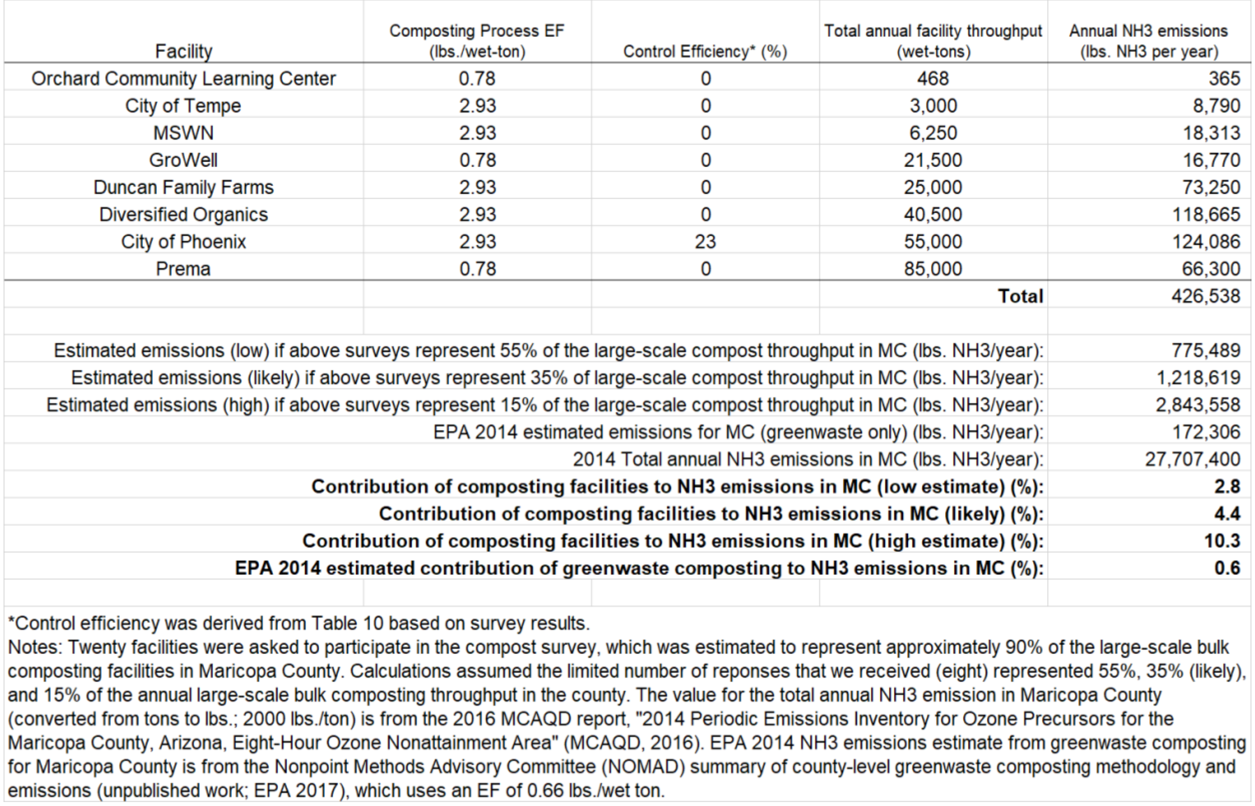
Table 14. Estimated contribution of large-scale bulk composting operations to the annual PM10 inventory in Maricopa County (MC).



Facility	Composting Process EF* (lbs./wet-ton)	# Drop points**	Total annual facility throughput (wet-tons)	Controlled?	Annual PM emissions (lbs. PM per year)
Orchard Community Learning Center	0.0011	9	468	No	5
City of Tempe	0.00033	9	3,000	Yes	9
MSWN	0.0011	9	6,250	No	62
GroWell	0.0011	9	21,500	No	213
Duncan Family Farms	0.0011	9	25,000	No	248
Diversified Organics	0.0011	9	40,500	No	401
City of Phoenix	0.0011	9	55,000	No	545
Prema	0.0011	9	85,000	No	842
				Total	2,323
Estimated emissions (low) if above surveys represent 55% of the large-scale compost throughput in MC (lbs. PM/year):					4,223
Estimated emissions (likely) if above surveys represent 35% of the large-scale compost throughput in MC (lbs. PM/year):					6,636.01
Estimated emissions (high) if above surveys represent 15% of the large-scale compost throughput in MC (lbs. PM/year):					15,484.63
2014 Total annual primary PM emissions in MC (lbs. PM/year):					115,747,800
Contribution of composting facilities to primary PM emissions in MC (low estimate) (%):					**0.004**
Contribution of composting facilities to primary PM emissions in MC (likely) (%):					**0.006**
Contribution of composting facilities to primary PM emissions in MC (high estimate) (%):					**0.013**

*Only the City of Tempe reported any practices such as water spray to control primary PM, so we used the CARB (2015a) PM10 (uncontrolled) equation for all other estimates.
**The number of drop points from the surveyed facilities is unknown. Therefore, we used the estimated number of drop points per facility (9) as reported in SJVAPCD (2006; see Research Question 4).
Notes: Twenty facilities were asked to participate in the compost survey, which was estimated to represent approximately 90% of the large-scale bulk composting facilities in Maricopa County. Calculations assumed the limited number of reponses that we received (eight) represented 55%, 35% (likely), and 15% of the annual large-scale bulk composting throughput in the county. The value for the total annual VOC emission in Maricopa County (converted from tons to lbs.; 2000 lbs./ton) is from the 2016 MCAQD report, "2014 Periodic Emissions Inventory for Ozone Precursors for the Maricopa County, Arizona, Eight-Hour Ozone Nonattainment Area" (MCAQD, 2016).

Table 15. Estimated contribution of large-scale bulk composting operations to the annual NH_3 inventory in Maricopa County (MC).



Facility	Composting Process EF (lbs./wet-ton)	Control Efficiency* (%)	Total annual facility throughput (wet-tons)	Annual NH3 emissions (lbs. NH3 per year)
Orchard Community Learning Center	0.78	0	468	365
City of Tempe	2.93	0	3,000	8,790
MSWN	2.93	0	6,250	18,313
GroWell	0.78	0	21,500	16,770
Duncan Family Farms	2.93	0	25,000	73,250
Diversified Organics	2.93	0	40,500	118,665
City of Phoenix	2.93	23	55,000	124,086
Prema	0.78	0	85,000	66,300
			Total	426,538
Estimated emissions (low) if above surveys represent 55% of the large-scale compost throughput in MC (lbs. NH3/year):				775,489
Estimated emissions (likely) if above surveys represent 35% of large-scale compost throughput in MC (lbs. NH3/year):				1,218,619
Estimated emissions (high) if above surveys represent 15% of the large-scale compost throughput in MC (lbs. NH3/year):				2,843,558
EPA 2014 estimated emissions for MC (greenwaste only) (lbs. NH3/year):				172,306
2014 Total annual NH3 emissions in MC (lbs. NH3/year):				27,707,400
Contribution of composting facilities to NH3 emissions in MC (low estimate) (%):				**2.8**
Contribution of composting facilities to NH3 emissions in MC (likely) (%):				**4.4**
Contribution of composting facilities to NH3 emissions in MC (high estimate) (%):				**10.3**
EPA 2014 estimated contribution of greenwaste composting to NH3 emissions in MC (%):				**0.6**

*Control efficiency was derived from Table 10 based on survey results.
Notes: Twenty facilities were asked to participate in the compost survey, which was estimated to represent approximately 90% of the large-scale bulk composting facilities in Maricopa County. Calculations assumed the limited number of reponses that we received (eight) represented 55%, 35% (likely), and 15% of the annual large-scale bulk composting throughput in the county. The value for the total annual NH3 emission in Maricopa County (converted from tons to lbs.; 2000 lbs./ton) is from the 2016 MCAQD report, "2014 Periodic Emissions Inventory for Ozone Precursors for the Maricopa County, Arizona, Eight-Hour Ozone Nonattainment Area" (MCAQD, 2016). EPA 2014 NH3 emissions estimate from greenwaste composting for Maricopa County is from the Nonpoint Methods Advisory Committee (NOMAD) summary of county-level greenwaste composting methodology and emissions (unpublished work; EPA 2017), which uses an EF of 0.66 lbs./wet ton.

5. Conclusions

- Few field studies have been conducted on the types and rates VOC emissions from composting operations. All of the compost VOC EFs have been developed from field studies in California.

- No EFs have been developed for primary PM emissions from composting operations. The PM EFs in use were developed for crushed stone, which is compositionally different than organic material.

- Eight studies reported EFs for NH_3 emissions, three of which were from California.

- No EFs have been developed for NO_x or SO_x emissions from compost piles. Contributions to NO_x and SO_x emissions inventories from composting operations are primarily from direct diesel combustion, diesel precombustion, and electricity precombustion/combustion. Although biogenic NO compounds are likely emitted from compost or stockpiles during the composting process, no studies to date have quantified these emissions.

- A range of environmental and management variables affect the type and rate of VOC, PM10, and NH_3 emissions from the composting process. Some of these factors, such as temperature, may influence composting VOC and NH_3 emissions in Maricopa County. On-site studies of emission rates within Maricopa County are needed to verify the importance of these factors. Studies that incorporate the range of management practices and environmental conditions will be particularly valuable in refining county-wide emission estimates.

- California has developed a suite of BMP practices and technologies that have been shown to significantly reduce composting emissions. Emission control recommendations were also identified in many of the papers found during the literature search.

- Coarse estimates of composting VOC, PM, and NH_3 emissions can be calculated for Maricopa County using equations and emission factors developed from CARB (2015a) and SJVAPCD (2006) with local facility data on seasonal feedstock composition, stockpile duration, use of control technology, and total annual facility throughput.

- In May 2017, the MCAQD asked twenty facilities, representing approximately 90% of the large-scale bulk composting facilities in Maricopa County, to participate in a survey, and eight facilities responded. Survey results revealed a wide range of feedstocks, management practices, and annual throughput.

- If the eight surveyed facilities represent the range (large and small) of operations and, therefore, represent roughly 35% of the annual large-scale bulk composting throughput in Maricopa County, then we estimate that the annual VOC, PM10, and NH_3 emissions from all the large-scale bulk composting facilities would be 0.6%, 0.006%, and 4.4% of the total VOC, PM10, and NH_3 emissions, respectively, from all inventoried sources in Maricopa County (based on the 2014 Periodic Ozone Precursor and PM10 Emissions Inventories; MCAQD, 2016). The small fractional contribution of composting VOC emissions is similar to estimates reported for California.

- Low and high estimates of annual VOC, PM10, and NH_3 emissions from the facility survey were also calculated. If the eight facility responses actually represent a larger portion of the large-scale bulk composting throughput, say roughly 55%, then we estimate the annual VOC, PM10, and NH3 emissions from all large-scale bulk composting facilities in the county to be 0.4%, 0.004%, and 2.8% of the total VOC, PM10, and NH3 emissions, respectively, from all inventoried sources in Maricopa County. If the eight surveyed facilities actually represent a smaller portion of the large-scale bulk composting throughput, say only 15%, then we estimate the annual VOC, PM10, and NH3 emissions from all large-scale bulk composting facilities in the county to be 1.4%, 0.013%, and 10.3% of the total VOC, PM10, and NH3 emissions, respectively, from all inventoried sources in Maricopa County.

- The 2014 EPA estimate of emissions from greenwaste composting in Maricopa County (based on per capita greenwaste recovery, population size, and EFs developed by SCAQMD) for VOC and NH_3 are 0.2% and 0.6%, respectively. Our likely/expected estimate for composting VOC emissions was similar to that estimated by the EPA, but our NH_3 estimate is seven times higher than the EPA estimate. The primary reason for the difference in NH_3 estimates is the feedstock type: the EPA estimates are for greenwaste composting only. Our estimates use the CARB (2015a) EFs for both greenwaste and co-composting. If only the CARB (2015a) greenwaste composting EF is used, our estimated annual NH_3 emission from Maricopa County composting facilities would be 1.8% of the total NH_3 emissions from all 2014 inventoried sources, which is closer to the 0.6% estimate from the EPA.

- Although we present a range of estimated emission rates from large-scale bulk composting operations, these estimates may not represent the true contribution of composting facilities to VOC, PM10, and NH_3 emissions in Maricopa County because the EFs were derived from studies in California under different climatic conditions and composting management practices; the reported survey data for stockpile duration, compost pile conditions, and number of drop points were incomplete; and the survey sample size may be too low.

- On-site studies that capture a range of management styles and seasonal effects in Maricopa County, particularly the effects of high summer temperatures on emission rates, will help refine county-wide emission estimates. If future on-site studies are to be conducted, we recommend that they are designed similar to the studies in California, which use EPA standard operating procedures to determine the effects of various environmental factors (e.g. ambient temperature) and management practices (e.g. feedstock type and pile configuration) on compost VOC and NH_3 emissions estimation.

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Appendix A: List of VOCs Emitted from Greenwaste Compost Operations

List of compounds found in the air emissions from greenwaste compost operations (Kumar et al., 2011)

Propane
Pentane isomers
3 Methyl hexane
Dimethyl hexane isomers
Trimethyl hexane isomers
Epoxy cyclooctane
Others ≥ C7 straight and cyclic Hydrocarbons
Propene
2 Methyl 1-propene
n-Butene & isomers
2 Methyl1,3-butadiene(Isoprene)
2 Methyl 3-butene 2-ol
2 Methyl 1,3 pentadiene
2,4-Heptadienal
Acetyl cyclomethylpentene
2 Ethyl 3-hexen 1-ol
Methyl hexyne
Methyl cycloheptene
Acetyl methylcyclohexene
Other alkenes
Benzene
Toluene
Xylene isomers
Styrene
C-3 Benzene isomers
C-4 Benzene isomers
Isopropenyl toluene
4 Methyl benzenemethanol
Naphthalene
Dichlorobenzene isomers
Trichlorobenzene isomers
α-Pinene
β-Pinene

2 Pinen-3-one
Thujen-2-one (Umbellulone)
Verbenone
trans-Verbenol
Linalool
Eucalyptol
Terpineol
Borneol
Allylanisole
Safrol (1,3-Benzodioxole, 5-(2-propenyl))
Formaldehyde
Acetaldehyde
Propionaldehyde
Crotonaldehyde (2-Butenal)
Butyraldehyde
Isovaleraldhyde
Valeraldehyde
2 Methyl pentenal
Hexanal
Hexenal
Heptanal
Heptenal
Octanal
Nonanal
Decanal
Dimethyl octenal
Benzaldehyde
Furan
3 Methyl furan
2 Methyl furan
2,5 Dimethyl furan
2 Ethyl 5-methyl furan
2 Butyl furan

Acetone[a]
2 Butanone
2 Pentanone
3 Pentanone
3,3 Dimethyl 2-butanone
Methyl isobutyl ketone (MIBK)
3 Pentene 2-one
3 Methyl 2-pentanone
2 Hexanone
Methyl hexanone isomers
Octanone
Nonanone
2 Butanedione (Diacetyl)
1 Hydroxy 2-propanone
3 Hydroxy 2-butanone
Methyl phenylethanone
[a]Methyl acetate
Ethyl acetate
Propyl acetate
Isoamyl acetate
Methyl butylacetate
Bornyl acetate
Methyl isobutanoate
Methyl butanoate
Methyl isopentanoate
Ethyl butanoate
Methyl pentanoate
Propyl butanoate
Methyl hexanoate
Butyl butanoate
Isomer of butylbutanoate
Heptyl hexanoate
Other esters

4 Carene	2 Pentyl furan	Acetic acid
3 Carene	Methyl hexanone isomers	Propionic acid
Camphene	Methanol	Methyl propionic acid
Terpinene	Ethanol	Butanoic acid
Terpinolene	2 Propanol	Methyl butanoic acid
Limonene	1 Propanol	Pentanoic acid
Adamantane	2 Butanol	Hexanoic acid
α-Phellandrene	1 Butanol	Acetyl benzoic acid
β-Phellandrene	2 Methyl 1-butanol & isomer	Dimethyl disulfide
l-Fenchone	Pentanol	Methylthymyl ether
Copaene	Hexanol	Dichlorodifluoro methane[b]
Camphor	2,3 Butanediol	Chloro difluoro methane[b]
cis-Linalool oxide	Pentanol	Trichloromonofluoromethane[b]
trans-Linalool oxide	Hexanol	
	2,3 Butanediol	
a	Exempted from federal ROG list	
b	Exempted from federal and California ROG list	

Appendix B: Relative Reactivity of Compost Pile VOCs

Relative Reactivity of Compost Pile VOCs (Kumar et al., 2011)

Relative reactivity (g-O3g-VOC^{-1}) and percent of weighted average compost pile emissions. [% VOC units are (mg m^{-2} min^{-1} compound)/(mg m^{-2} min^{-1} TVOC)*100].

VOCs	MIR[a]	EBIR[b]	% VOC	SD[c]	Cumulative %
Isopropyl alcohol	0.61	0.25	42.31	2.74	42.31
Ethyl alcohol	1.53	0.59	18.16	3.49	60.47
Methyl alcohol	0.67	0.19	12.79	1.36	73.26
Acetic acid	0.68	0.21	5.94	0.39	79.2
Limonene	4.55	0.96	2.27	1.01	81.47
α-Pinene	4.51	0.89	1.36	0.4	82.83
Butanoic acid	1.82	0.56	1.35	0.8	84.18
Camphor	0.49	0.13	1.18	0.81	85.36
Methylthymyl ether	N.A.	N.A.	0.73	0.63	86.09
Bornyl acetate	N.A.	N.A.	0.63	0.11	86.72
Pinene Isomers	3.52	0.79	0.6	0.18	87.32
Eucalyptol	N.A.	N.A.	0.58	0.24	87.9
Propionic acid	1.22	0.35	0.53	0.14	88.43
Naphthalene	3.34	0.49	0.5	0.51	88.93
Acetone	0.36	0.09	0.47	0.51	89.4
3 Hydroxy 2-butanone (Acetoin)	N.A.	N.A.	0.43	1.71	89.83
2 Methyl 1-Propene	6.29	1.18	0.41	0.44	90.24
2 Butanol	2.4	0.75	0.39	0.37	90.63
Hexanoic acid	N.A.	N.A.	0.39	0.25	91.02
Terpineol	4.63	0.89	0.35	0.26	91.37
Heptyl hexanoate	N.A.	N.A.	0.31	0.49	91.68
3 Methyl butanoic acid	4.23	0.96	0.28	0.13	91.96
Methyl propionic acid	1.2	0.39	0.26	0.13	92.22
Methyl cycloheptene	N.A.	N.A.	0.24	0.15	92.46
Camphene	4.51	0.89	0.24	0.07	92.7
1 Methyl<comma> 3-1-methyl ethyl benzene	5.49	0.89	0.23	0.23	92.93
Pentanoic acid	N.A.	N.A.	0.23	0.18	93.16
Propene	11.66	2.73	0.22	0.22	93.38
Thujen-2one (Umbellulone)	N.A.	N.A.	0.22	0.17	93.6
Undecane	0.61	0.16	0.2	0.17	93.8
2 Butene	14.24	3.08	0.17	0.15	93.97
Isovaleraldhyde	4.97	1.23	0.15	0.13	94.12
Acetaldehyde	6.54	1.61	0.14	0.08	94.26
Methyl butylacetate	1.09	0.4	0.14	0.74	94.4
Others >80			5.6		100

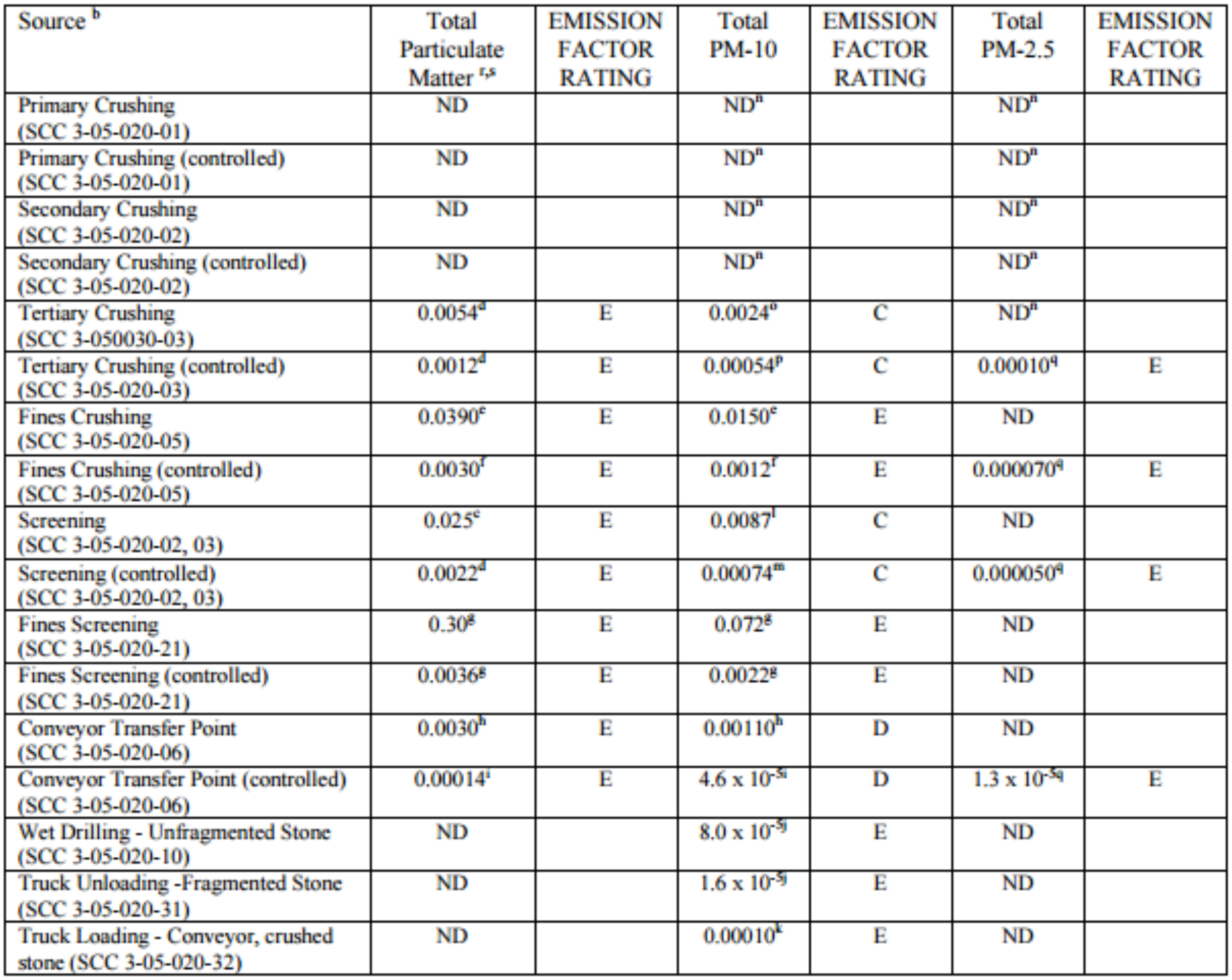
[a] MIR, Maximum Incremental Reactivity.

[b] EBIR, Equal Benefit Incremental Reactivity, N.A.: not available

[c] Standard deviation (%) represents the variability between the 3 sample types' mean.

Appendix C: EFs for Crushed Stone Processing Operations (lbs./ton)

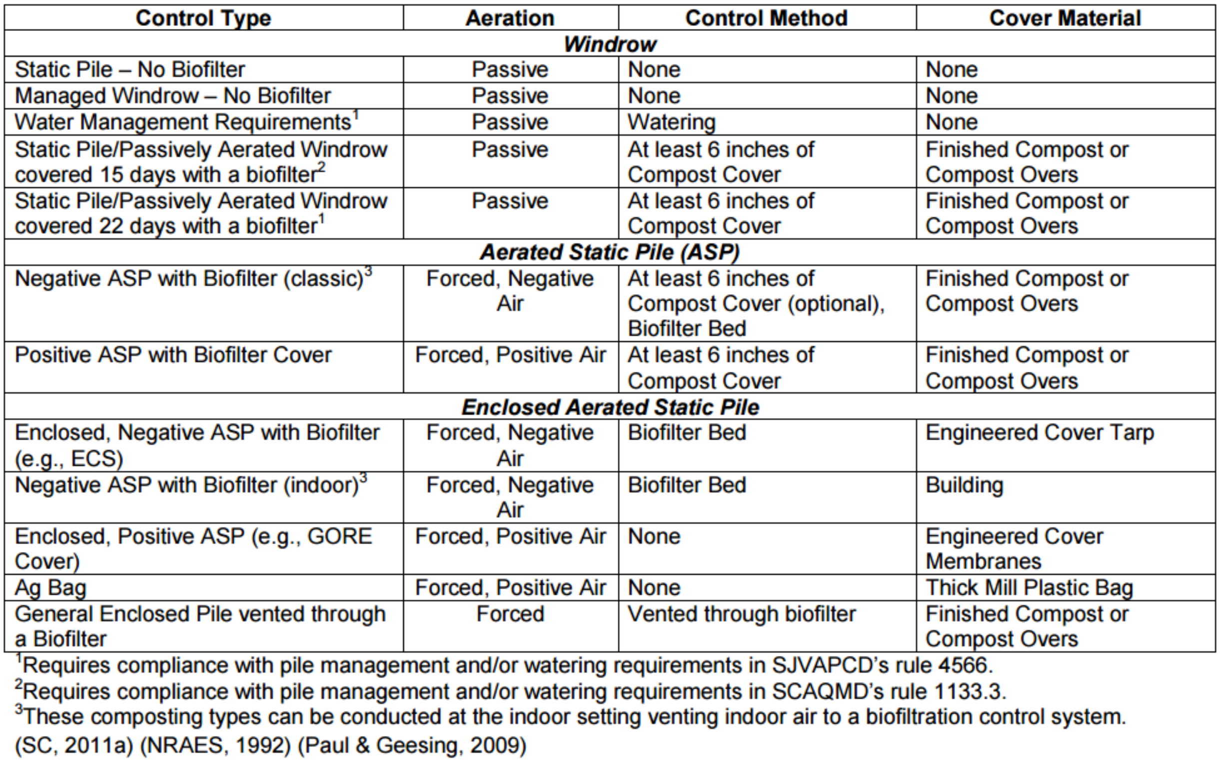
Emission factors for crushed stone processing operations (EPA, 2004).



Source [b]	Total Particulate Matter [r,s]	EMISSION FACTOR RATING	Total PM-10	EMISSION FACTOR RATING	Total PM-2.5	EMISSION FACTOR RATING
Primary Crushing (SCC 3-05-020-01)	ND		ND[n]		ND[n]	
Primary Crushing (controlled) (SCC 3-05-020-01)	ND		ND[n]		ND[n]	
Secondary Crushing (SCC 3-05-020-02)	ND		ND[n]		ND[n]	
Secondary Crushing (controlled) (SCC 3-05-020-02)	ND		ND[n]		ND[n]	
Tertiary Crushing (SCC 3-050030-03)	0.0054[d]	E	0.0024[o]	C	ND[n]	
Tertiary Crushing (controlled) (SCC 3-05-020-03)	0.0012[d]	E	0.00054[p]	C	0.00010[q]	E
Fines Crushing (SCC 3-05-020-05)	0.0390[e]	E	0.0150[e]	E	ND	
Fines Crushing (controlled) (SCC 3-05-020-05)	0.0030[f]	E	0.0012[f]	E	0.000070[q]	E
Screening (SCC 3-05-020-02, 03)	0.025[c]	E	0.0087[l]	C	ND	
Screening (controlled) (SCC 3-05-020-02, 03)	0.0022[d]	E	0.00074[m]	C	0.000050[q]	E
Fines Screening (SCC 3-05-020-21)	0.30[g]	E	0.072[g]	E	ND	
Fines Screening (controlled) (SCC 3-05-020-21)	0.0036[g]	E	0.0022[g]	E	ND	
Conveyor Transfer Point (SCC 3-05-020-06)	0.0030[h]	E	0.00110[h]	D	ND	
Conveyor Transfer Point (controlled) (SCC 3-05-020-06)	0.00014[i]	E	4.6 x 10^{-5}[i]	D	1.3 x 10^{-5}[q]	E
Wet Drilling - Unfragmented Stone (SCC 3-05-020-10)	ND		8.0 x 10^{-5}[j]	E	ND	
Truck Unloading -Fragmented Stone (SCC 3-05-020-31)	ND		1.6 x 10^{-5}[j]	E	ND	
Truck Loading - Conveyor, crushed stone (SCC 3-05-020-32)	ND		0.00010[k]	E	ND	

Appendix D: Compost Control Techniques

Control Techniques for Composting Operations (From Table II-4, CARB, 2015a)



Control Type	Aeration	Control Method	Cover Material
Windrow			
Static Pile – No Biofilter	Passive	None	None
Managed Windrow – No Biofilter	Passive	None	None
Water Management Requirements[1]	Passive	Watering	None
Static Pile/Passively Aerated Windrow covered 15 days with a biofilter[2]	Passive	At least 6 inches of Compost Cover	Finished Compost or Compost Overs
Static Pile/Passively Aerated Windrow covered 22 days with a biofilter[1]	Passive	At least 6 inches of Compost Cover	Finished Compost or Compost Overs
Aerated Static Pile (ASP)			
Negative ASP with Biofilter (classic)[3]	Forced, Negative Air	At least 6 inches of Compost Cover (optional), Biofilter Bed	Finished Compost or Compost Overs
Positive ASP with Biofilter Cover	Forced, Positive Air	At least 6 inches of Compost Cover	Finished Compost or Compost Overs
Enclosed Aerated Static Pile			
Enclosed, Negative ASP with Biofilter (e.g., ECS)	Forced, Negative Air	Biofilter Bed	Engineered Cover Tarp
Negative ASP with Biofilter (indoor)[3]	Forced, Negative Air	Biofilter Bed	Building
Enclosed, Positive ASP (e.g., GORE Cover)	Forced, Positive Air	None	Engineered Cover Membranes
Ag Bag	Forced, Positive Air	None	Thick Mill Plastic Bag
General Enclosed Pile vented through a Biofilter	Forced	Vented through biofilter	Finished Compost or Compost Overs

[1] Requires compliance with pile management and/or watering requirements in SJVAPCD's rule 4566.

[2] Requires compliance with pile management and/or watering requirements in SCAQMD's rule 1133.3.

[3] These composting types can be conducted at the indoor setting venting indoor air to a biofiltration control system.

(SC, 2011a) (NRAES, 1992) (Paul & Geesing, 2009)

Appendix E: Summary of May 2017 Survey Results from Composting Operations in Maricopa County

		Facility name							
		Orchard Community Learning Center	City of Tempe	Mountain States Wholesale Nursery	GroWell	Duncan Family Farms	Diversified Organics	City of Phoenix	Prema
Feedstock mix (%)	Greenwaste	50	85	10	100	35	0.5	0-100	100
	Limited food waste	40	0	0	0	5	0	Combined 0-25, not to exceed 25	0
	All food waste	10	0	0	0	0	0		0
	Manure	0	10	90	0	60	99.5	0-100, typically 5	0
	Other	0	5	0	0	0	0	0-5	0
Feedstock mix category		Co-composting	Composting	Co-composting	Composting	Co-composting	Co-composting	Co-composting	Composting
Does feedstock mix change by month?		No	No	No	No	No	No	Yes	No
Annual feedstock throughput (wet tons)		468	3,000*	6,250	21,500	25,000	40,500	55,000 (phase I; current) 110,000 (phase II)	85,000
Compost pile configuration (ft)	Width	8	18	200	150	15	12	170	25
	Length	15	170	300	250	250	320	185	200
	Height	6	8	12	25	8-9	3	7.5	20
Pile location		Outside covered and uncovered	Outside uncovered	Outside uncovered	Outside uncovered	Outside uncovered	Outside uncovered	Outside uncovered (initial stage covered with biochar)	Outside uncovered
Pile aeration method		Mechanical turning with loader	Active aeration; turned windrow	Turned windrow	Anaerobic 7-8 months	Turned windrow	Turned windrow	Negative forced aeration, Positive forced aeration, Turned windrow	Turned windrow
Rate of aeration		Turned 3 times per week	Turned once per week	1 pile turn/day	NA	1-2 pile turns/day	7 pile turns/90 days	Aerated at 2-5 cfm/yd^3, Turned once every 2-4 days	Turned after every grind/screen (initial, 20 d, 45 d, 70 d)
Duration (days)	Stockpile	1	not answered	Unknown	7	1-30	Unknown	1-2	Unknown
	Active pile	90-120	not answered	730	240	30-90	40	21-28	45-70
	Curing pile	5-30	not answered	730	0	90-240	40	23-32	Unknown
C:N ratio	Stockpile	Unknown	Unknown	Unknown	Unknown	30:1	Unknown	Unknown	Unknown
	Active pile	Unknown	18:1	Unknown	Unknown	15:1	12:1	Unknown	Unknown
	Curing pile	8:1	22:1	Unknown	25:1 finished	10:1-12:1	16:1	Unknown	Unknown
Moisture content (%)	Stockpile	Unknown	Unknown	Unknown	Unknown	40	Unknown	25	Unknown
	Active pile	Unknown	Unknown	Unknown	Unknown	20	45	48-65	7-11
	Curing pile	Unknown	Unknown	Unknown	Unknown	10-20	35	40-48	7-11
Internal pile temperature (°F)	Stockpile	Unknown	90	Unknown	Ambient	120	Unknown	Ambient	Unknown
	Active pile	130-160	140-160	Unknown	150-165	150	150-155	125-145	160-190
	Curing pile	90-110	120-130	Unknown	Unknown	110-130	140	Ambient to 150	120-125
Notes or additional control techniques		No manure or yard waste used. Will be converting to active aeration by turned windrow.	Pile watered twice per week. *Estimated from RISN (2006) report	Facility described "visible steam" when asked about composting duration, C:N ratio, moisture content, and pile temperautre.	Piles managed in 3-50 ft wide cells. Rotation between active, feedstock, and finished compost.	Feedstock is consistent blend of dairy, horse manure, and greenwaste composed of ground trees and limited produce processing waste.	Compost blanket on one pile for special compost.	Turned Aerated Pile Technology (TAP) with constant aeration with reversing airflow every 1-2 hours. Negative aeration airflow is through a biofilter. Initial pile covered with biochar to reduce odor.	