Compost Demonstration Project,
Sacramento, California

Using High-Carbon Wood Ash to Control Odor at a Green Materials Composting Facility

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Executive Summary

A pilot study on the feasibility of using high carbon wood ash to control composting odor emissions was conducted August 2001 at a green material composting facility (Lionudakis Wood and Green Waste Recycling in Sacramento, California). The study's treatments consisted of adding 0 percent, 12.5 percent, and 25 percent high-carbon wood ash by volume to green-material compost feedstock in three separate windrows. Odor emissions (as perceived by human odor panels) and chemical odorant emissions were measured from each of the three windrows on days 1 and 7 of composting. The physical and chemical properties of wood ash and compost were also evaluated.

High-carbon wood ash was examined for its ability to control green material compost odors because it has been shown to be effective in reducing odor emissions from related waste streams such as biosolids and municipal wastewater effluent (Rosenfeld and Henry, 2000). The high-carbon wood ash used in this experiment was produced via combustion of whole tree chips at a Covanta Energy facility in Susanville, California. The wood ash has properties similar to activated carbon with an active surface area of 105 square meters (m^2) per gram on a dry-weight basis.

An odor panel consisting of seven trained individuals evaluated odor produced during composting on days 1 and 7. While the 12.5 percent treatment reduced odor emissions by 73 percent and 25 percent on days 1 and 7, respectively, the 25 percent treatment reduced odor emissions by 88 percent and 89 percent on days 1 and 7, respectively. The 25 percent treatment provided longer periods for active adsorption of odorants and hence greater reduction in odor emissions.

Intensities of odorant emissions were estimated for each treatment using the U.S. Environmental Protection Agency's (USEPA) SCREEN3 model (USEPA, 1995a, 1995b). The model predicts the concentration of pollutants at an array of distances, and it assumes stable nighttime conditions when air currents move parallel to the surface of the earth and can be detected by humans. The lowest reported human detection limits (Ruth, 1986) for odorants were then used to predict the "worst case scenario" odor traveling distance for each treatment.

The treatment with the highest percentage of wood ash generally resulted in fewer detected emissions than the other treatments. In addition, for a given treatment, emissions generally decreased over time. Emissions from the control compost treatment (0 percent wood ash) included formic acid, acetic acid, propionic acid, isobutyl and butyl acid, isovaleric acid, valeric acid, acetaldehyde, and propionaldehyde. Emissions from the 12.5 percent ash treatment included acetaldehyde, ammonia, and ethyl mercaptan. Emissions from the 25 percent ash treatment included acetaldehyde and ammonia. The "Findings" section of this report presents information on detected emissions in greater detail.

In contrast to the reductions exhibited for most compounds, ammonia emissions increased in the 12.5 percent and 25 percent wood ash treatments on both days 1 and 7, compared to the control treatment. This is believed to be a result of the strongly alkaline pH (10.3) of the wood ash at the time of addition. It is possible that reducing the pH of the wood ash, for example, by exposing it to water and carbon dioxide from the atmosphere could result in more control of ammonia emissions.

The odorant emission data suggest that the higher percentage wood ash treatment results in the most effective control of most compost odors and that wood ash provides effective treatment of volatile fatty acids and some aldehydes and ketones. The 25 percent wood ash treatment resulted in more effective treatment of odors for a longer time period than the 12.5 percent treatment. Based on these results, it is assumed that additional odor control for the 25 percent treatment would have been achieved further into the composting process beyond day 7.

Introduction

Odor emissions from compost facilities have become a priority concern for facility operators, engineers, urban planners, and citizens living near facilities. Odor complaints can shut down compost facilities and prevent the expansion of existing facilities. Compost odors are generated throughout the composting process, with the highest emission rates noted early in composting and then again during pile turning or agitation. Moiser et al. (1977) found that aldehydes, alcohols, ketones, volatile fatty acids, terpenes, nitrogen, and sulfur compounds are associated with compost odors. Ruth (1996) quantified the odor thresholds and established irritant levels for a number of compounds found during the composting process (Table 1).

The physio-chemical adsorption (adhesion of molecules to a surface) of odorants using activated carbon is a very successful approach for odor control (Huang, 1994). However, the cost of activated carbon is often prohibitively expensive to use in municipal composting. Wood ash incorporation has been reported to reduce odor emissions from biosolids composting (Carpenter and Beecher, 1997; Rosenfeld and Henry, 2000), and may be a promising, less costly alternative to activated carbon for odor control. Wood ash is a byproduct of cogeneration facilities and the pulp and paper industry and has been found to have properties similar to activated carbon (Rosenfeld and Henry, 2001). The similarity is thought to result from incomplete combustion of wood residual at temperatures greater than700°C. Approximately 358,720 tons of high-carbon ash is produced in California every year (Trott, 2001).

The study had five aims:

1. Determine if high-carbon wood ash can control compost odor under field conditions.
2. Investigate difficulties of incorporating wood ash into compost under field conditions.
3. Determine the effect of wood ash on specified compost product quality criteria.
4. Estimate the traveling distance of odor emissions from a hypothetical site using a dispersion model.
5. Analyze the cost of odor control using wood ash versus other methods.

Materials and Methods

Materials and Methods

Green material from the City of Sacramento was used in this experiment, and the material consisted of ground wood chips, foliage, and grass. High-carbon wood ash was produced at the Covanta Energy wood boiler cogeneration facility in Susanville, California. Feedstock material was whole tree chips incinerated at approximately 1200°C. Three windrows were constructed at Lionudakis Wood and Green Waste Recycling in Sacramento California. The windrow dimensions were 15 meters (m) long, 6 m wide at the base, and 3 m high (photographs 1 and 2). Compost and wood ash were mixed using a front-end loader, adding 25 percent and 12.5 percent wood ash by volume to compost.

Compost and Wood Ash Chemical and Physical Analysis

Two surface area measurements of ash were conducted using the BET (Brunauer-Emmett-Teller) method and a FlowSorb 2300 surface area analyzer (Micrometrics, Norcross, Georgia). Approximately 2 milligrams of dried and crushed material were placed in a U-shaped plexiglass tube submerged in liquid nitrogen. Using a mixture of helium (inert) and nitrogen (sorbate) gases, adsorption of nitrogen was measured using a thermal conductivity meter.

Compost and ash samples were analyzed for product quality criteria, including pH, electrical conductivity, base cations, carbon, nitrogen, cation exchange capacity (CEC), and percent organic matter. Saturated pastes of compost and wood ash were prepared for analyses of pH and electrical conductivity measurements using distilled water and subsequent vacuum extraction of the liquid phase for the determination (U.S. Salinity Laboratory Staff, 1954). Compost and ash were quantified using the saturated paste and pH meter (U.S. Salinity Laboratory Staff, 1954). Electrical conductivity was quantified by measuring the amount of soluble salts in the saturation paste extract using a conductivity meter (Rhoades 1982).

Amounts of base cations (calcium, magnesium, potassium, and sodium) were measured. Amounts of soluble calcium and magnesium in the saturated paste extract were determined by inductively coupled plasmic atomic emission spectrometry (Lanyon and Heald, 1982; Soltanpour et al., 1982). Amounts of soluble potassium and sodium in the saturated paste extract were determined by emission spectrometry (Lanyon and Heald, 1982; Knedesen et al., 1982). Total nitrogen and total carbon were quantified using the combustion gas analyzer method (Pella 1990a, 1990b). CEC was determined by the acetate saturation and calcium replacement (Janitzky, 1986). Organic matter was determined by potassium dichromate reduction of organic carbon and subsequent spectrophotometric measurement (modified Walkley-Black) (Nelson and Sommers, 1982.)

Odorant and Odor Sampling

On days 1 and 7 after construction of the windrows, emissions from windrows were sampled for sulfur compounds, ammonia, ketones and aldehydes, volatile fatty acids, and dilutions-to-threshold. Gaseous emissions from surface migration were collected from isolated surface areas with enclosure devices called “emission isolation flux chambers.” Each flux chamber encompasses a fixed surface area and is designed to isolate the surface from phenomena that can alter emissions such as wind, other meteorological conditions, or properties of the waste itself. The flux chambers used in the program were polyethylene chambers 0.5 m long x 0.35 m wide and 0.5 m high. A dry-sweep gas (ultra-high nitrogen) was introduced to the flux chamber at a fixed controlled rate (5 liters per minute) as a carrier, where it mixed with the contaminants from the surface migration.

During the monitoring, one flux chamber was placed on each of the three windrows and located at one location on day 1 and another on day 7.

The flux chamber was sunk into the compost to a depth of 2.5 centimeters (cm) to create a seal between the chamber and the surface of the windrow. The flux chamber and sweep air system are designed so that the contents are well-mixed and no stratification exists. A probe was located in the flux chamber to extract a gaseous sample for subsequent analysis. The probe was designed to collect a sample composite at various altitudes within the flux chamber. Sampling was conducted at a rate less than or equal to the sweep air rate. The remainder of the flux chamber contents were allowed to vent through a small opening located on the top of the chamber.

Odor Analysis

Odor samples were collected using a low-flow sampling pump and five-liter Tedlar bags (SKC, Fullerton, California), an 18.5-liter bucket, and vinyl tubing. Tedlar bags filled with odor samples were shipped overnight to Odor Science and Engineering, Inc (Bloomfield, Connecticut). Odor concentration was defined as the point of dilution with odor-free air at which 50 percent of an odor panel detected the odor. The odor panel consisted of seven trained individuals. This point represents the odor threshold and is expressed in terms of “dilution-to-threshold” (D/T). Odor concentration was determined by means of forced air dynamic dilution olfactometry, where odorous air is bled into clean ultra-pure air until the panelist can just detect the odor. The members of the panel were screened for their olfactory sensitivity and their ability to match odor intensities.

The olfactometer and the odor presentation procedure met the recommendations of the American Society of Testing and Materials (ASTM) Standard Practice for Determination of Odor and Taste Thresholds by a Forced-Choice Ascending Concentration Series of Limits (ASTM E679-91).

Ammonia Sampling

The sampling train for ammonia consisted of two midget impingers (glass vials designed to absorb the ammonia as it is bubbled through a solution), each filled with 15 milliliters (mL) of 0.1 mole (M) sulfuric acid. The impinger was connected to the vacuum side of a leak-free sample pump and a calibrated rotameter. The samples were collected for two hours at a sampling rate of 1 liter per minute. An additional sample was collected from the exhaust side of the blower feeding the untreated gas to the primary biofilter to determine the ammonia concentration prior to treatment at the biofilter. Samples were analyzed for ammonia using ion chromatography (Dionex 2020) according to EPA Method 206.

Carboxylic Acids Analysis

Carboxylic acids in air samples were quantified using Occupational Safety and Health Administration (OSHA) Method 28. The sampling train consisted of two midget impingers, each filled with 15mL of a carbonate-bicarbonate solution. The impingers were connected to the vacuum side of a leak-free sample pump and a calibrated rotameter. The samples were collected for 50 minutes at a sampling rate of 2 liters per minute. The samples were analyzed by high performance liquid ion exclusion chromatography coupled with an ultraviolet detector (HPLC-UV). Acid concentrations in the flux chamber were determined using the carboxylic acid content collected in the impingers along with the sampling rate and net elapsed sampling time. The ultraviolet detector was set at 210 micrometers to record the corresponding ultraviolet absorption.

Sulfur Analysis

An integrated gas sample, EPA Method 18, was collected during each sampling run from the flux chamber sample line using the vacuum side of a leak-free sample pump and calibrated rotameter. The samples were collected in 10-liter Tedlar bags at a rate of approximately 1 liter per minute for five minutes. The Tedlar bags were enclosed in lead-free sample chambers for protection against contamination and photoreactivity. Due to the reactivity of the sulfur compounds, chemical analyses were performed within 24 hours.

Total sulfides were analyzed using a Hewlett Packard 5890 gas chromatograph, a flame photometric detector, and a DB-1 column. Sulfides scanned include the following:

Hydrogen sulfide
Carbonyl sulfide
Sulfur dioxide
Methyl mercaptan
Ethyl mercaptan
Propyl mercaptan
Carbon disulfide
Methyl sulfide
Dimethyl disulfide
Allyl sulfide
Propyl sulfide
Butyl sulfide
Isopropyl sulfide
T-butyl mercaptan
Ethyl methyl sulfide
Thiophene
Isobutyl mercaptan
Diethyl sulfide
N-butyl mercaptan
Allyl mercaptan
3-methylthiophene
Tetrahydrothiophene
2-ethylthiophene
2,5-dimethylthiophene
Diethyl sulfide

Dimethyl disulfide and sulfur dioxide (or carbonyl sulfide) were identified using gas chromatography/mass spectrometry. Gas samples were collected in Tedlar bags before and after passing through the biofilter.

Ketones Analyses

Ketones in air samples were quantified using EPA Method 11A. The samples were collected using DNPH-coated silica gel cartridges (SKC, San Jose, California) at a sampling rate of 1 liter per minute for 10 minutes. Ketones were eluted from the cartridges with carbonyl-free acetonitrile. The samples were chromatographically separated using a C_{18} reversed phase column and analyzed by high-performance liquid chromatography—ultraviolet (HPLC-UV) at 360 nanometers.

Odorant Dispersion Estimates

Odor traveling distances for odorant emissions were estimated for each treatment using the EPA's SCREEN3 model. The model predicts the concentration of pollutants at an array of distances using a time-weighted 1-hour average during all meteorological conditions. Assumptions used to run the SCREEN3 include:

- Composting area—1 hectare
- Wind speed—1 meter per second
- Application elevation—0 meters
- Ambient temperature—21°C
- Receptor height—1.5 meters
- Moderately stable atmospheric conditions

Stable conditions were assumed because odor complaints occur most frequently at dusk or dawn, when air moves parallel to the earth's surface when heat from the sun is not present. Actual emissions data from the compost and compost/ash treatments were input into the model. The lowest reported human detection limits for odorants then were used to predict the "worst case scenario" odor traveling distance for each treatment (Ruth, 1986).

Statistical Data Analyses

Mean emission rates were calculated for chemical odorants using two data points each from the 25 percent ash treatment, the 12.5 percent ash treatment, and the control treatment on days 1 and 7. Pearson correlation coefficients and p-values were determined for all possible variables and pairs.

Findings

Effects On Compost Characteristics

Selected chemical and physical properties of the untreated compost, wood ash-compost mixtures, and wood ash collected on day 7 of composting are shown in Table 1. Results in Table 1 indicate that wood ash has little effect on compost quality from an agronomic perspective. However, more study needs to be done with compost containing wood ash relative to seed germination assays, growth studies, and nutrient release characteristics.

The wood ash was strongly alkaline, with a mean pH of 10.3. The alkalinity of wood ash results from the combustion of wood. The combustion process forms carbonate, bicarbonate, and hydroxide. The relative proportion of these compounds varies with combustion temperature. Carbonates and bicarbonates predominate when wood is combusted below 500°C (Etiegni and Campbell, 1990), whereas oxides become more prevalent when combustion temperatures exceed 850°C (Brady and Weil, 1996). Because wood ash feedstock used in this experiment was combusted above1200°C, it is likely that, as reported by Misra et al. (1993), much of the calcium in ash was initially in the form of calcium oxide (CaO).

It is important to consider that the high pH of wood ash could be reduced to a pH of 8.6 by allowing the wood ash to be exposed to water and carbon dioxide from the atmosphere, which dissolves into solution, forming calcium carbonate (Rosenfeld et al., 1998). We speculate that reducing the pH of the wood ash would control ammonia emissions.

The wood ash was found to have a surface area of 105 square meters per gram. This is a large surface area, considering that commercial activated carbon often has a surface area of approximately 500 square meters per gram. The surface area of wood ash can vary from between 5 to more than 105 square meters per gram and is directly proportional to carbon content in ash and incineration temperature (Rosenfeld and Henry, 2000).

The compost treated with 12.5 percent and 25 percent wood ash by volume slightly increased the pH and electrical conductivity of the compost. Important agronomic parameters such as total nitrogen (N) and carbon (C), organic matter content, CEC, and soluble micronutrients were not affected by the addition of wood ash (Table 1).

Odorant Emission and Reduction

The chemical and physical properties of odorants typically associated with compost are presented in Table 2. This information demonstrates that a wide array of odor compounds may be emitted from the composting process. These compounds include those derived from nitrogen, sulfur, volatile fatty acids, and ketones and aldehydes.

Mean emission rates for each chemical odorant are presented in Table 3 and are summarized below.

Emissions from the control compost treatment included formic acid, acetic acid, propionic acid, isobutyl and butyl acid, isovaleric acid, valeric acid, acetaldehyde, and propionaldehyde. Below are the values (number of times) at which these compounds are estimated to be greater than the lowest human detection limit on days 1 and 7:

	Day 1	**Day 7**
Formic acid	9	0.4
Acetic acid	3.5	0
Propionic acid	3.4	0.1
Isobutyl and butyl acid	450	45
Isovaleric acid	110	0
Valeric acid	240	490
Acetaldehyde	14,000	680
Propionaldehyde	7.7	0.6

Emissions from the 12.5 percent ash treatment included acetaldehyde, ammonia, and ethyl mercaptan. Below are the values (number of times) at which these compounds are estimated to be greater than the lowest human detection limit on days 1 and 7:

	Day 1	**Day 7**
Acetaldehyde	386	160
Ammonia	4	1
Ethyl mercaptan	6	0

Emissions from the 25 percent ash treatment included acetaldehyde and ammonia. Below are the values (number of times) at which these compounds are estimated to be greater than the lowest human detection limit on days 1 and 7 (other compounds not listed were below the instrument or human detection levels):

	Day 1	**Day 7**
Acetaldehyde	100	470
Ammonia	2	0.3

All compounds not listed in the 25 percent ash treatment group were below analytical or human detection limits. Reductions in emission rates from the wood ash treatment were noted for all volatile fatty acids and most ketones and aldehydes.

The 12.5 percent wood ash treatment reduced acetaldehyde, propionaldehyde, crotonaldehyde, and butanaldehyde emissions, but not as sharply as the 25 percent wood ash treatment did. In some instances, the formaldehyde, acetone, methyl ethyl ketone, and valeraldehyde emission rates were higher with the wood ash-amended treatments, but these compounds were not attributed to objectionable odors as measured by the odor panel.

Mean dilution-to-threshold values for the windrow with 25 percent wood ash treatment were reduced by 88 percent and 89 percent on days 1 and 7, respectively, compared to the control treatment (Table 3). Similarly, the windrow with 12.5 percent wood ash treatment reduced the mean dilution-to-threshold values by 73 percent and 25 percent on days 1 and 7, respectively, compared to the control treatment (Table 3). These data suggest that wood ash can reduce odor emissions from green material compost facilities. The 25 percent wood ash treatment provided longer periods for active adsorption of odorants and hence greater reduction in odor emissions.

The odor panels used for dilution-to-threshold olfactometry also provided qualitative descriptors of compost odor (Table 4). The term “medicinal” was used for all treatments during day 1, while some individuals noted a “burnt wood” odor in the wood ash treatments. For the control windrow, panelists noted a “moldy” and “mildew” odor that was not detected in the windrows with wood ash treatments. Medicinal is indicative of ammonia, while moldy and mildew odors are often associated with incomplete decomposition or anaerobic conditions.

Ammonia (NH_3) emission rates were generally found to be higher in the compost treated with wood ash (Table 3). This effect likely occurred because the wood ash had a strongly alkaline pH. Under high pH conditions, ammonium (NH_4^+) ions in the compost are continually converted into NH_3, which can be an odorant depending on concentration.[1]

Sulfur emissions were detected in only one of the treatments on day 1. Ethyl mercaptan was detected on day 1 at a low emission rate in the 12.5 percent ash treatment; no ethyl mercaptan was detected in the 25 percent treatment. The results suggest that sulfur emissions from this particular green material feedstock were not important in generating odor that could affect composting operations.

Odorant Dispersion Estimates

The maximum concentrations of individual odorants from a 1-hectare compost facility are presented in Table 5. Traveling distances from the control compost treatment exceed 10,000 meters from the facility for acetaldehyde, valeric acid, and isobutyl and butyl acids (Table 5). The excessive estimated traveling distance for these compounds results from selection of conservative (lowest reported) human detection limits (Ruth, 1986). Compounds without a noted distance were non-detect or below human detection limit. The model suggests that the highest wood ash application rate can dramatically reduce the traveling distance of compost odor.

Correlation Analyses

Mean emission rates were calculated for each chemical odorant using two data points from each of the three treatments, one data point for day 1 and one for day 7. Table 6 presents Pearson correlation coefficients for dilutions-to-threshold compared to odorant emission rates. Increasing dilutions-to-threshold were found to be statistically correlated to formic acid, acetic acid, propionic acid, isobutyl and butyl acid, isovaleric acid, isocaprinic acid, caprinic acid, acetaldehyde, propionaldehyde, crotonaldehyde, butanaldehyde and valeraldehyde. These compounds fall primarily into either the aldehyde or volatile fatty acid groups of chemicals. Hence, aldehydes and volatile fatty acids appear to be the major odorants responsible for odor emissions at this green waste composting facility.

Cost Analysis and Wood Ash Handling

Wood ash can be provided free of cost (except for hauling costs) from several cogeneration and paper facilities throughout California (Table 7).

Wood ash was found to be easy to handle, did not create dust, and blended quickly into the compost with a front-end loader, although it could be better incorporated with a scarab. The incorporation of ash requires little time and effort. It is simplest when the ash is simply laid on top of windrows and then incorporated later during normal turning.

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[1] Using the Henderson-Hasselbach equation for the ionization of NH_3, where pH = 9.25 + log (ammonia/ammonium [NH_3/NH_4^+]) (Oxtoby et al., 1996), one can predict that the percentages of potentially volatile NH_3 are approximately 10 and 50 at pH 8 and 9 (Henry, 1989). Hence, as NH_3 volatilized, new NH_4^+ ions were continually deprotonated. Henry's law states that NH_3 is in equilibrium between liquid and gas phases, and the rate at which NH_3 volatilizes from a liquid into the air depends on the partial pressure of the liquid phase versus that of the gas phase. As NH_3 molecules in gas phase were volatilized and carried off, the partial pressure of NH_3 gas near the compost decreased and new NH_4^+ ions was formed and converted at pH 7.7-10.3 in the windrows to NH_3 molecules and continued to volatilize from the compost pile.

The hauling of wood ash typically costs between $1.25 and $1.35 per mile for a 24-ton load (Trott, 2001). These economics can be improved if “back hauling” is incorporated into a program, for example by trucking wood fuel back to a cogeneration facility after transporting the ash.

Assuming a 50,000-ton-per-year facility incorporating 25 percent wood ash (12,500 tons) and a hauling distance of 50 miles, the annual cost for ash transportation would be approximately $34,000, using the hauling figures cited above. However, this cost can be offset by the additional revenue from the 12,500 additional tons of compost (increased volume resulting from incorporation of wood ash, as wood ash increases the amount of compost, thus increasing the tonnage of marketable material).

Incorporation of wood ash is a passive odor control method that requires no blowers or additional engineering associated with other odor control technologies. Alternative odor control approaches can be expensive and energy-intensive, requiring high operations and maintenance costs. For instance, enclosed facilities or operations using an in-vessel composting system with biofilters can cost from tens of thousands to millions of dollars. Biofilters need to be replaced frequently and often have sizing problems. Perimeter misting systems can cost from tens to hundreds of thousands of dollars and are often ineffective.

Conclusions

As stated previously in this report, high-carbon wood ash was examined for its ability to control green material compost odors because it has been shown to be effective in reducing odor emissions from related waste streams such as biosolids and municipal wastewater effluent. The high-carbon wood ash has properties similar to activated carbon and has an active surface area of 105 square meters per gram on a dry weight basis.

Dilutions-to-threshold as determined using an odor panel indicated that aldehydes and volatile fatty acids appeared to be the major odorants responsible for odor emissions at the project site.

Wood ash added at 12.5 percent and 25 percent by volume increased ammonia emissions on days 1 and 7, compared to the control treatment. This is believed to be the result of the strongly alkaline pH of the wood ash at the time of addition (10.3). It is likely that reducing the pH of the wood ash will result in lower ammonia emissions.

Only one sulfur compound was detected during the study, and odor panelists did not notice a sulfur odor, suggesting that the green material feedstock did not contain concentrations of sulfur compounds capable of producing objectionable odors early in the composting process.

The 25 percent wood ash treatment resulted in more effective treatment of odors for a longer time period than the 12.5 percent treatment. For the 25 percent treatment, it is likely that additional odor control could be achieved even further into the composting process beyond day 7.

Following are conclusions from the study regarding the use of high-carbon wood ash as an odor control treatment in composting:

- It was easy to incorporate.
- It did not alter compost quality.
- It can increase compost quantity and be a cost-effective odor control technology.
- It is an economically viable odor control strategy when compared to in-vessel composting, enclosed facilities, misting, aeration, and biofiltration.
- It was found to have little effect on compost quality from an agronomic perspective. However, more study needs to be done with compost containing wood ash relative to seed germination assays, growth studies, and nutrient release characteristics.

In summary, this study shows that high-carbon wood ash can reduce odor and odorant emissions at compost facilities. (The 25 percent wood ash treatment provided odor control for most components on days 1 and 7 of composting, while the 12.5 percent wood ash treatment was effective for most components on day 1.) Hence high-carbon wood ash could be an effective management tool to help reduce odor complaints.

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Appendix A: Abbreviations

BDT	Bone-dry ton
BET	Brunauer-Emmett-Teller
D/T	Dilution-to-threshold
Ca	Calcium
CaO	Calcium oxide
$CaCO_3$	Calcium carbonate
CEC	Cation exchange capacity
cm	Centimeter
CO_2	Carbon dioxide
g	Gram
K	Potassium
HPLC	High performance liquid chromatography
L	Liter
M	Mole
m^2	Square meter
m^3	Cubic meter
mEq	Milliequivalent (one-thousandth of the equivalent weight of an element or compound)
Mg	Magnesium
Mmho	Micro-mho (a measure of electrical conductivity equal to the reciprocal of the ohm)
MW	Megawatt
Na	Sodium
NH_3/NH_4^+	Ammonia/Ammonium
OSHA	Occupational Safety and Health Administration
pH	Measure of acidity and basicity
ppb	Parts per billion
SP	Solubility
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
µg	Micrograms

Appendix B: Tables

Table 1: Chemical and Physical Properties of Wood Ash and Compost Used in This Study

Treatment	pH	Electrical Conductivity (Mmhos/cm)	Ca (SP*) (mEq/L)	Mg (SP*) (mEq/L)	Na (SP*) (mEq/L)	K (SP*) (ppm	Percent Total Nitrogen	Percent Total Carbon	Cation Exchange Capacity (mEq/100g)	Percent Organic Matter	Surface Area (m^2/gram)
Compost with no ash	6.6	9.2	13.0	15.7	6.1	1715	1.3	31.5	50.9	24.6	NA
Compost with 12.5% ash by volume	7.9	11.9	10.7	13.9	10.5	2345	1.0	27.8	50.5	24.6	NA
Compost with 25% ash by volume	7.7	10.8	12.9	15.4	8.6	1970	1.0	28.6	50.2	24.6	NA
100% wood ash	10.3	29.0	2.7	0.2	28	6810	0.1	15.6	34.0	6.2	105

* SP=Solubility

Notes:
Ash was supplied by Covanta Energy in Susanville, California.
Compost was supplied by Lionudakis Wood and Green Waste Recycling in Sacramento, California.

Table 2: Chemical Properties of Odorants Associated With Compost (Ruth, 1986)

Analyte	Formula	Odor	Human Detection Limit (µg/m^3)	Human Detection Limit (ppb)	Analytical Detection Limit	[Boiling] Point (°C)	Molecular Weight
Volatile Fatty Acids							
Formic acid	$HCOOH$	biting	45	24	32 ppb	101	46
Acetic acid	CH_3COOH	vinegar	2500	1019	24 ppb	118	60
Propionic acid	$C_3H_6O_2$	rancid, pungent	84	28	20 ppb	141	74
Isobutyl and butyl acid	$C_4H_8O_2$	rancid	1.0	0.3	17 ppb	164	88
Isovaleric acid	$C_5H_{10}O_2$	unpleasant	2.6	0.6	15 ppb	177	102
Valeric acid	$C_5H_{10}O_2$	unpleasant	2.6	0.6	15 ppb	187	102
Isocaprionic acid	$C_6H_{12}O_2$	unpleasant	11951	2521	13 ppb	202	116
Caprionic acid	$C_6H_{12}O_2$	unpleasant	11951	2521	13 ppb	202	116
Aldehydes and Ketones							
Formaldahyde	CH_2O	unpleasant	1470	1199	4.9 ppb	-20	30
Acetaldehyde	C_2H_4O	green sweet	0.2	0.1	2.2 ppb	21	44
Acetone	C_3H_6O	sweet, minty	47466	20692	2.5 ppb	56	58
Acreolin	C_3H_6O	burnt, sweet	52	22.8	0.87 ppb	56	56
Propionaldehyde	C_3H_6O	sweet, ester	22	11	2.5 ppb	68	49
Crotonaldehyde	C_4H_6O	pungent, suffocating	105	37	1.4 ppb	102	70
Methyl ethyl ketone	C_4H_8O	sweet, minty	737.0	250.4	1.4 ppb	80	72
Butanaldehyde	C_4H_8O	sweet	28000	9514	1.4 ppb	76	72
Valeraldehyde	$C_5H_{10}O$	pungent	98	28	1.9 ppb	103	86
Nitrogen Compounds							
Ammonia	NH_3	pungent	26.6	38	1 µg/m^3	-33.4	17
Sulfur Compounds							
Ethyl mercaptan	C_2H_6S	rotten cabbage	0.032	0.01	100 ppb	35	62
Hydrogen sulfide	H_2S	rotten eggs	0.7	0.5	100 ppb	-60.7	34.1
Carbon disulfide	CS_2	disagree, sweet	24.0	7.7	100 ppb	46.3	76.1
Dimethyl sulfide	$CH_3\text{-}S\text{-}CH_3$	rotten cabbage	2.5	1.0	100 ppb	37.3	62.1
Dimethyl disulfide	$(CH_3)_2S_2$	rotten cabbage	0.1	0.026	100 ppb	109.7	94.2

Analyte	Formula	Odor	Human Detection Limit (µg/m^3)	Human Detection Limit (ppb)	Analytical Detection Limit	[Boiling] Point (°C)	Molecular Weight
Dimethyl trisulfide	$(CH_3)_2S_3$	rotten cabbage	6.2	1.2	100 ppb	165	126
Methyl mercaptan	$(CH_3)SH$	rotten cabbage	0.04	0.02	100 ppb	6.2	48.1
Allyl mercaptan	$CH_2=CH-CH_2-SH$	garlic coffee	0.2	0.1	100 ppb	NA	74.2
Propyl mercaptan	$CH_3-CH_2-CH_2-SH$	unpleasant	0.2	0.1	100 ppb	NA	76.2
Amyl mercaptan	$CH_3-(CH_2)_3-CH_2-SH$	putrid	0.1	0.02	100 ppb	NA	104
Benzyl mercaptan	$C_6H_5CH_2-SH$	unpleasant	1.6	0.3	100 ppb	NA	124
Sulfur dioxide	SO_2	irritating	1175	449	100 ppb	NA	64.1
Carbon oxysulfide	COS	pungent	NA	NA	100 ppb	-50.2	60.1

Table 3: Mean Odorant Emission Rates And Odorant Emission Reduction From Green Waste Compost and Wood Ash Treatments

							Reduction Compared To Control			
	Day 1			**Day 7**			**Day 1**		**Day 7**	
	25% Ash	**12.5% Ash**	**Control**	**25% Ash**	**12.5% Ash**	**Control**	**25% Ash**	**12.5% Ash**	**25% Ash**	**12.5% Ash**
	(μg/m^2 sec^{-1})									
Volatile Fatty Acids										
Formic acid	0.84	1.1	11	ND	ND	0.51	92.4%	90.2%	88.8%	88.8%
Acetic acid	ND*	0.78	241	0.42	0.71	2.60	100.0%	99.7%	83.7%	72.6%
Propionic acid	ND	ND	7.8	ND	ND	0.33	99.3%	99.3%	82.5%	82.5%
Isobutyl and butyl acid	ND	ND	12.2	0.60	0.57	1.23	99.5%	99.5%	51.0%	53.6%
Isovaleric acid	ND	ND	7.86	ND	ND	ND	99.2%	99.2%	0.0%	0.0%
Valeric acid	ND	ND	17.1	ND	0.70	34.8	99.7%	99.7%	99.8%	98.0%
Isocaprinic acid	ND	ND	23.9	ND	ND	ND	99.8%	99.8%	0.0%	0.0%
Caprinic acid	ND	ND	18.31	1.93	1.06	5.88	99.7%	99.7%	67.1%	82.0%
Aldehydes and Ketones										
Formaldahyde	0.55	0.97	0.35	0.50	0.33	0.63	-58.3%	-176.7%	20.4%	48.1%
Acetaldehyde	0.56	2.11	75.98	2.57	0.87	3.75	99.3%	97.2%	31.4%	76.7%
Acetone	5.24	10.71	0.50	17.83	13.36	6.46	-955%	-2055%	-176%	-107%
Acreolin	ND	ND	ND	ND	ND	ND	0.0%	0.0%	0.0%	0.0%
Propionaldehyde	0.04	0.19	4.64	0.24	0.06	0.33	99.0%	95.9%	28.9%	81.9%
Crotonaldehyde	ND	ND	0.75	ND	ND	0.44	97.5%	97.5%	95.6%	95.6%
Methyl ethyl ketone	0.76	2.47	1.19	2.49	5.97	3.76	36.5%	-107.1%	33.7%	-59.0%
Butanaldehyde	0.18	0.59	39.62	0.91	0.23	1.04	99.6%	98.5%	12.2%	78.2%
Valeraldehyde	0.09	0.27	1.19	0.28	0.04	0.18	92.3%	77.3%	-51.4%	76.1%
Nitrogen Compounds										
Ammonia	1.29	2.87	0.01	0.23	0.72	0.41	-9100%	-20300%	44.8%	-74.8%
Sulfur Compounds										
Ethyl mercaptan	ND	0.01	ND	ND	ND	ND	NA	NA	NA	NA
Hydrogen sulfide	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA

							Reduction Compared To Control			
	Day 1			**Day 7**			**Day 1**		**Day 7**	
	25% Ash	**12.5% Ash**	**Control**	**25% Ash**	**12.5% Ash**	**Control**	**25% Ash**	**12.5% Ash**	**25% Ash**	**12.5% Ash**
	(µg/m^2 sec^{-1})									
Carbon disulfide	ND*	ND	ND	ND	ND	ND	NA	NA	NA	NA
Dimethyl sulfide	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Dimethyl disulfide	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Dimethyl trisulfide	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Methyl mercaptan	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Allyl mercaptan	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Propyl mercaptan	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Amyl mercaptan	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Benzyl mercaptan	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Sulfur dioxide	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Carbon oxysulfide	ND	ND	ND	ND	ND	ND	NA	NA	NA	NA
Dilution-to-threshold values	**872**	**1972**	**7337**	**331**	**2255**	**3009**	**88.1%**	**73.1%**	**89.0%**	**25.1%**

*ND = non-detect

Table 4: Mean Dilution-To-Threshold Values and Qualitative Descriptors of Odor Character

Day	Treatment	Mean D/T*	Descriptors
1	**25% Wood Ash**	872	Medicinal, sweet, molasses, camphor, menthol, eucalyptus, cedar, peppery, pesticide, rotten fish, petroleum, burnt wood, charred wood, smoky.
	12.5% Wood Ash	1,972	Medicinal, menthol, eucalyptus, camphor, cedar, peppery, spicy, sour garbage, rotting fruit, fermented fruit, dirty socks, mushrooms, wet cardboard, pesticide, charred wood.
	Control	7,337	Medicinal, menthol, cleaning fluid, detergent, alcohol, sweet, garbage, fermented fruit, damp, moldy, wet tobacco, burnt chocolate.
2	**25% Wood Ash**	331	Menthol, disinfectant, camphor, eucalyptus, spicy, cedar wood, pine, pine sap, grassy, turpentine, varnish, rotten fruit, insecticide.
	12.5% Wood Ash	2,255	Eucalyptus, pine, antiseptic, cinnamon, resin, varnish, turpentine.
	Control	3,009	Menthol, medicinal, camphor, eucalyptus, pine, antiseptic, varnish, turpentine, spicy, resin, mildew, rotten.

* D/T = dilution-to-threshold

Table 5: Odorant Concentration Divided By Lowest Reported Human Detection Limit

Figures in parentheses are mean estimated odor traveling distance in meters from 1-hectare area source during stable conditions.

	Day 1			Day 7		
Analyte	**25% Ash Addition**	**12.5% Ash Addition**	**Control Compost Treatment**	**25% Ash Addition**	**12.5% Ash Addition**	**Control Compost Treatment**
Volatile Fatty Acids						
Formic acid	0.7	0.9	9.0 (1200)	ND	ND	0.4
Acetic acid	ND*	0.0	3.5 (500)	0.0	0.0	0.0
Propionic acid	ND	ND	3.4 (500)	ND	ND	0.1
Isobutyl & Butyl acid	ND	ND	447 (>10,000)	22 (2400)	21 (2300)	45 (4000)
Isovaleric acid	ND	ND	111 (8000)	ND	ND	ND
Valeric acid	ND	ND	240 (>10,000)	ND	9.9 (1,300)	490 (>10,000)
Isocaprionic acid	ND	ND	0.1	ND	ND	ND
Caprionic acid	ND	ND	0.1	0.01	0.00	0.02
Aldehydes and Ketones						
Formaldahyde	0.01	0.02	0.01	0.01	0.01	0.02
Acetaldehyde	102 (7,500)	386 (>10,000)	14,000 (>10,000)	471 (>10,000)	160 (>10,000)	686 (>10,000)
Acetone	0.0	0.0	0.0	0.0	0.0	0.0
Acreolin	ND	ND	ND	ND	ND	ND
Propionaldehyde	0.1	0.3	7.7	0.4	0.1	0.6
Crotonaldehyde	ND	ND	0.3	ND	ND	0.2
Methyl ethyl ketone	0.04	0.1	0.1	0.1	0.3	0.2
Butanaldehyde	0.00	0.00	0.1	0.00	0.00	0.00
Valeraldehyde	0.03	0.1	0.4	0.10	0.02	0.1
Nitrogen Compounds						
Ammonia	2 (200)	4 (500)	0.0	0.3	1.0 (100)	0.6

	Day 1			Day 7		
Analyte	**25% Ash Addition**	**12.5% Ash Addition**	**Control Compost Treatment**	**25% Ash Addition**	**12.5% Ash Addition**	**Control Compost Treatment**
Sulfur Compounds						
Ethyl mercaptan	ND	11.4 (1500)	ND	ND	ND	ND
Hydrogen sulfide	ND	ND	ND	ND	ND	ND
Carbon disulfide	ND	ND	ND	ND	ND	ND
Dimethyl sulfide	ND	ND	ND	ND	ND	ND
Dimethyl disulfide	ND	ND	ND	ND	ND	ND
Dimethyl trisulfide	ND	ND	ND	ND	ND	ND
Methyl mercaptan	ND	ND	ND	ND	ND	ND
Allyl mercaptan	ND	ND	ND	ND	ND	ND
Propyl mercaptan	ND	ND	ND	ND	ND	ND
Amyl mercaptan	ND	ND	ND	ND	ND	ND
Benzyl mercaptan	ND	ND	ND	ND	ND	ND
Sulfur dioxide	ND	ND	ND	ND	ND	ND
Carbon oxysulfide	ND	ND	ND	ND	ND	ND

*ND = non-detect

Note: Estimates are based on SCREEN3 (USEPA, 1995).

Table 6: Correlation Coefficients for Odor Units Relative To Odorant Concentrations

	Odor Units	*Formic acid*	*Acetic acid*	*Propionic acid*	*Isobutyl & Butyl acid*	*Isovaleric acid*	*Valeric acid*	*Isocaprinic acid*	*Caprinic acid*	*Formaldahyde*	*Acetaldehyde*	*Acetone*	*Propionaldyhyde*	*Crotonaldyhyde*	*Methyl ethyl ketone*	*Butanaldyhyde*	*Valeraldehyde*	*Ammonia*
Odor Units	-																	
Formic acid	0.92*	-																
Acetic acid	0.93*	0.99*	-															
Propionic acid	0.93*	0.99*	1.00*	-														
Isobutyl & Butyl acid	0.94*	0.98*	1.00*	1.00*	-													
Isovaleric acid	0.92*	0.99*	1.00*	1.00*	1.00*	-												
Valeric acid	0.52	0.28	0.29	0.32	0.36	0.28	-											
Isocaprinic acid	0.92*	0.99*	1.00*	1.00*	1.00*	1.00*	0.28	-										
Caprinic acid	0.94*	0.94*	0.95*	0.96*	0.98*	0.95*	0.55	0.95*	-									
Formaldahyde	-0.34	-0.35	-0.43	-0.43	-0.46	-0.43	-0.06	-0.43	-0.44	-								
Acetaldehyde	0.93*	0.99*	1.00*	1.00*	1.00*	1.00*	0.31	1.00*	0.96*	-0.42	-							
Acetone	-0.74	-0.72	-0.67	-0.69	-0.67	-0.67	-0.52	-0.67	-0.68	0.11	-0.67	-						
Propionaldehyde	0.93*	0.99*	1.00*	1.00*	1.00*	1.00*	0.32	1.00*	0.96*	-0.41	1.00*	-0.67	-					
Crotonaldehyde	0.92*	0.83*	0.84*	0.86*	0.88*	0.84*	0.76*	0.84*	0.96*	-0.32	0.85*	-0.75*	0.86*	-				
Methyl ethyl ketone	-0.16	-0.46	-0.41	-0.40	-0.36	-0.41	0.07	-0.41	-0.30	-0.19	-0.41	0.50	-0.41	-0.25	-			
Butanaldehyde	0.92*	0.99*	1.00*	1.00*	1.00*	1.00*	0.30	1.00*	0.96*	-0.42	1.00*	-0.67	1.00	0.85*	-0.41	-		
Valeraldehyde	0.88*	0.97*	0.97*	0.97*	0.97*	0.97*	0.28	0.97*	0.94*	-0.29	0.98*	-0.59	0.98*	0.82*	-0.48	0.98*	-	
Ammonia	-0.36	-0.35	-0.43	-0.44	-0.49	-0.42	-0.44	-0.42	-0.57	0.84*	-0.43	0.12	-0.44	-0.54	-0.08	-0.43	-0.37	-
Ethyl Mercaptan	-0.13	-0.13	-0.20	-0.21	-0.25	-0.20	-0.30	-0.20	-0.31	0.87*	-0.20	0.13	-0.19	-0.30	-0.08	-0.20	-0.08	0.91*

* $p < 0.05$

Table 7: Biomass-to-Energy Facilities Producing Wood Ash in California (Trott, 2001)

Name	Size (MW*)	Combustion Technology	Biomass Used (BDTs** [thousands])	Estimated Ash Production (tons)	County	City
Wheelabrator—Martell	18	Grate	120	9,600	Amador	Martell
Pacific Oroville Power	18	Grate	140	11,200	Butte	Oroville
Wadham Energy	26.5	Grate	200	16,000	Colusa	Williams
Mendota Biomass	25	Fluid Bed	190	9,500	Fresno	Mendota
Rio Bravo—Fresno	25	Fluid Bed	190	9,500	Fresno	Fresno
Pacific Lumber	23	Grate	250	20,000	Humboldt	Scotia
Fairhaven Power	17.5	Grate	108	8,640	Humboldt	Fairhaven
Primary Power	15	Grate	120	9,600	Imperial	Brawley
Delano Energy	50	Fluid Bed	350	17,500	Kern	Delano
Dinuba Energy	12	Grate	110	8,800	Kings	Dinuba
Sierra Forest Products	9.5	Grate	90	7,200	Kings	Terra Bella
SPI—Susanville	13	Grate	100	8,000	Lassen	Susanville
Mount Lassen Power	11.5	Grate	100	8,000	Lassen	Westwood
Honey Lake Power	30	Grate	250	20,000	Lassen	Wendel
GP—Fort Bragg	15	Grate	120	9,600	Mendocino	Fort Bragg
Soledad Energy	12	Fluid Bed	100	5,000	Monterey	Soledad
Rio Bravo Rocklin	25	Fluid Bed	180	9,000	Placer	Rocklin
SPI—Lincoln	8	Grate	100	8,000	Placer	Lincoln
SPI—Quincy	25	Grate	180	14,400	Plumas	Quincy
Collins Pine	12	Grate	70	5,600	Plumas	Chester
Colmac Energy	47	Fluid Bed	340	17,000	Riverside	Mecca
Tracy Biomass	20	Grate	150	12,000	San Joaquin	Tracy
Diamond Walnut	4.5	Grate	33	2,640	San Joaquin	Stockton
Big Valley Lumber	7.5	Grate	50	4,000	Shasta	Bieber
SPI—Burney	17	Grate	140	11,200	Shasta	Burney
Burney Mountain Power	10	Grate	100	8,000	Shasta	Burney
Burney Forest Power	31	Grate	240	19,200	Shasta	Burney
Wheelabrator—Shasta	50	Grate	350	28,000	Shasta	Anderson
Wheelabrator—Hudson	6	Grate	63	5,040	Shasta	Redding
SPI—Anderson	4	Grate	50	4,000	Shasta	Anderson
SPI—Loyalton	17	Grate	140	11,200	Sierra	Loyalton

Name	**Size (MW*)**	**Combustion Technology**	**Biomass Used (BDTs** [thousands])**	**Estimated Ash Production (tons)**	**County**	**City**
Roseburg Forest Products	3	Grate	20	1,600	Siskiyou	Weed
Pacific-Ultrapower Chinese Station	22	Fluid Bed	150	7,500	Tuolumne	Jamestown
SPI—Standard	3	Grate	40	3,200	Tuolumne	Sonora
Woodland Biomass	25	Fluid Bed	180	9,000	Yolo	Woodland
Total				**358,720**		

* MW=megawatt

** BDT=bone-dry ton

Appendix C: Photographs

Photograph 1: Wood ash being incorporated into compost at Lionudakis Wood and Green Waste Recycling in Sacramento.

Photograph 2: Three pilot study compost piles with flux chambers during sampling. The pile in the front contained 25 percent wood ash, the middle pile contained 12.5 percent wood ash, and the farthest pile contained no wood ash.