Evaluation of Odor Characteristics of Heat-Dried Biosolids Product

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ABSTRACT: Because it produces an exceptional quality pellet product, heat drying of wastewater solids from municipal wastewater treatment plants is becoming more prevalent as biosolids management regulations become more restrictive. The product from heat drying is sometimes odorous as dry or wetted pellets. The odors, although not regulated, can be important for marketability and public acceptance of the product. The reasons for the odors are usually a result of upstream processing and management of wastewater solids prior to drying. The goals of this study were to determine odor characteristics and to compare the odors produced by evaluating odors from four types of heat-dried biosolids products: all undigested; primary digested–waste activated sludge (WAS) undigested; all digested; and WAS lime stabilized pellets. The results are described in this paper. *Water Environ. Res.,* **75,** 523 (2003).

KEYWORDS: heat drying, odors, pellets, biosolids.

Introduction

Material derived from heat drying of wastewater solids can typically meet the stringent U.S. requirements to produce an exceptional quality product (U.S. EPA, 1993). Regulations dictate the rules governing land application of the pellets, and the product quality dictates the ability and desire to use the material. The eventual marketability of the final dried material depends on product quality. One criterion that describes the product quality is the odor characteristics of the heat-dried pellets. Depending on the upstream processes, the product from heat drying can be odorous as dry or wetted (i.e., moisture added during handling or after application) pellets. The odors, although not regulated, can be important for marketability and public acceptance of the product. Upstream treatment process parameters and product management prior to drying can affect product odor quality. There are many uncertainties about the odor potential for various types of heat-dried materials. To maintain a viable program, the least odorous product should be produced.

Biosolids management at the Blue Plains Advanced Wastewater Treatment Plant (AWWTP), Washington, D.C., as described in the facility plan includes anaerobic digestion of all solids produced at the plant with an option to heat dry the digested material should that be necessary or cost-effective in the future. The intent of anaerobic digestion of the wastewater solids is to achieve a process that will sustain the land application program by producing a low odor product. However, this alone may not be enough as the future of the land application program becomes more uncertain because of increasing pathogen-related regulatory restrictions and bans by counties in Virginia, leading to a need to produce a Class A product (U.S. EPA, 1993). In the absence of a proven, reliable, large-scale method of producing Class A material from digesters, Blue Plains AWWTP must investigate other methods. While investigating Class A digestion processes, plant management is considering heat drying as a potential solution for future implementation as it produces a Class A product that is successfully marketed throughout the United States. The intent of the Blue Plains biosolids management plan is to create a diverse biosolids program, with multiple options for marketing dried product while continuing with the existing beneficial land application option. As long as land application remains viable, Blue Plains AWWTP intends to continue this practice. Any future drying plans will be flexible enough to expand if land application becomes infeasible.

The specific objectives of this study were to determine the effect of upstream solids processing on odors from a heat-dried product, evaluate the odor characteristics from wetted products, evaluate the effect of storage time on odors produced from wetted products, and determine the effect of soil inoculation on odors produced from wetted products. Soil inoculation was intended to simulate an ‘‘application event’’, where microorganisms are able to react with the wetted product.

The primary goals of the Blue Plains AWWTP were to determine odor characteristics from different types of heat-dried pellets and to relate these odors to the odor produced from undigested and digested, oven-dried, heat-dried product. Comparing odors to these benchmarks would assist in determining the validity of the current program to digest wastewater solids prior to the future option of heat drying the digested product.

Methodology

Approach. Heat-dried pellets from four plants with upstream processing were evaluated, including wastewater solids that were (1) all undigested (primary and waste activated sludge [WAS] undigested); (2) primary digested–WAS undigested (Milorganite); (3) all digested (primary and WAS digested); and (4) WAS lime stabilized (no primary sludge). In addition to these samples, a primary undigested (primary sludge only) sample and a second all-digested (primary and WAS digested) sample were analyzed to further elucidate and confirm the types of odor compounds generated for these pellet types.

Additionally, digested dewatered biosolids and undigested dewatered blend (primary and WAS) solids were collected from the Blue Plains AWWTP, oven-dried overnight at 105 °C, and run through a grinder to simulate heat-dried products from this plant. The odors from these products were compared to the ‘‘benchmark’’ products from the other plants.

The heat-dried product can become wetted when exposed to rain or through the accumulation of moisture during storage, transportation, or application. These wetted samples can become

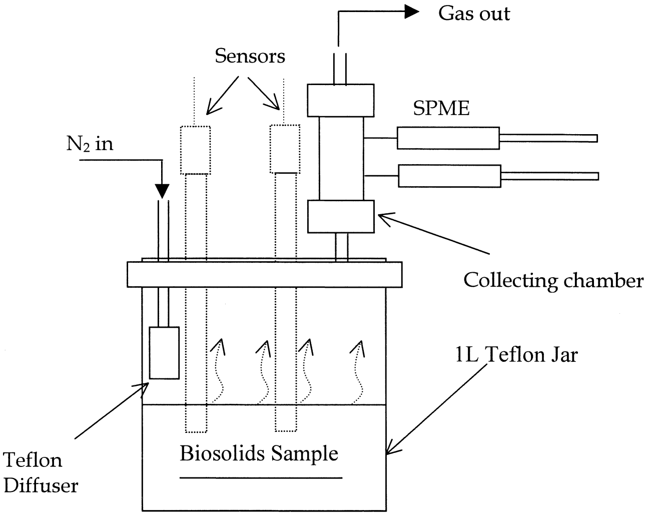

Figure 1—Schematic diagram of experimental setup for sample analysis.

odorous after short periods (less than 24 hours) of storage. The odors from wetted pellets can intensify when microorganisms are present. Therefore, the samples were analyzed under the following circumstances: (1) dry pellets (as obtained from the source); (2) wetted pellets with 33% moisture added (6-hour sample); (3) wetted pellets with 33% moisture added (24-hour sample); and (4) wetted pellets with 33% moisture added and amended with commercial potting soil (33% additional soil) and stored anaerobically for 24 hours.

Storage times of 6 and 24 hours were selected as representative waiting time periods for transport and full-scale land application of pellets subsequent to accidental wetting or rainfall. Storage times greater than 24 hours are indeed possible and should be considered in any future evaluations.

In addition to 33% moisture addition to dry pellets, 25% moisture addition was also evaluated after 24 hours of storage to determine the effect of moisture addition. Addition of 25 and 33% moisture was considered sufficient to encourage microbial or enzymatic activity.

Experimental Conditions and Constraints. Specific field conditions will produce site-specific odors. These field conditions that produce a mass flow of odor compounds combined with ambient site-specific conditions (weather, topography, and distance) will result in odors at a receptor site. All of these conditions cannot be simulated in the laboratory. For example, environmental conditions such as variable oxidation–reduction potential (ORP) can produce different odors, which are difficult to properly reproduce. Therefore, the odor compound generation and odor concentration can be variable based on these conditions. As a result, for the experiments conducted in the laboratory, the odor analyses do not portray any of these field conditions in particular. Concentration values do not necessarily correspond to emission rates from a storage, transport, or biosolids application site.

The approach used in this project provides a relative comparison between heat-dried products as a means to determine the factors that lead to odor production and the factors that may control the odor potential. Conditions produced in these experiments were designed to minimize variables to give investigators a high level of confidence regarding the relative differences between samples. Reported results do not represent potential field emissions. Results may, however, be used for determining methods to control odors from heat-dried products.

Experimental Setup. The experimental setup for the sample analysis is illustrated in Figure 1. Anaerobic conditions are often experienced during odor-producing events. Therefore, the study was conducted under pure anaerobic conditions using a constant flow (72 mL/min) of nitrogen gas in the headspace to continuously flush the sample during the period of storage and analysis. Site-specific conditions will need to be simulated to predict actual odors under a variable ORP.

The heat-dried sample (600 g) was transferred to a 1-L Teflon jar, and the headspace of the jar was flushed with pure nitrogen gas at a constant rate of 72 mL/min. The typical setup in Figure 1 was configured such that the airflow from nine of these 1-L Teflon chambers was connected to a single nitrogen cylinder using a flow-splitting system. The odors from nine samples were collected simultaneously.

The odorous compounds in the offgas from the headspace to the collecting chamber were collected in Tedlar bags or extracted by exposing solid-phase microextraction (SPME) fibers to the offgas for 1 hour in a laboratory of the wastewater treatment plant, where the room temperature is controlled at 20 ± 2 °C. Subsequent to extraction, the fibers were transferred to a cooler (under dry ice) and transported to the laboratory for gas chromatographic analysis.

Olfactometric Analyses. All olfactometric analysis was conducted in accordance with American Society for Testing and Materials (ASTM) standard practices (ASTM, 1991, 1999) and the European normalization standard (ECS, 1999). Samples were collected in tedlar bags and transported overnight to a qualified odor panel for analysis.

The analyses included the following olfactometric parameters (using a trained odor panel): odor intensity, odor persistence, hedonic tone, and odor descriptor. These parameters are described as follows:

(1) Odor intensity: the relative strength of the odor above the recognition threshold. The odor intensity is expressed as parts per million of butanol.
(2) Odor persistence: the rate at which an odor's intensity decreases as the odor is diluted. Persistence is a dose–response function and is the slope of the log intensity–log dilution graph. A more negative slope indicates a less persistent odor (the odor dilutes more quickly).
(3) Hedonic tone: a measure of odor pleasantness or unpleasantness on a scale from −10 to +10. The more negative a number is, the more unpleasant the odor is. The hedonic tone is a subjective assessment and is based on the personal experience and memories of the assessor. Hedonic tone is independent of odor character.
(4) Odor descriptors: Odor panelists' descriptions of specific odor characteristics of the samples such as sour, earthy, ammonia, fishy, and so on.

Analyses of Odor Compounds. The analytical parameters were determined using a gas chromatograph in two sets: reduced-sulfur compounds and trimethylamine (TMA) and volatile fatty acids (VFAs) (propionic acid and butyric acid).

Analysis of Reduced-Sulfur Compounds. Reduced-sulfur compounds were sampled using tedlar bags and analyzed by gas chromatography via the ASTM D5504-98 method (ASTM, 1998). Twenty reduced-sulfur compounds that included hydrogen sulfide

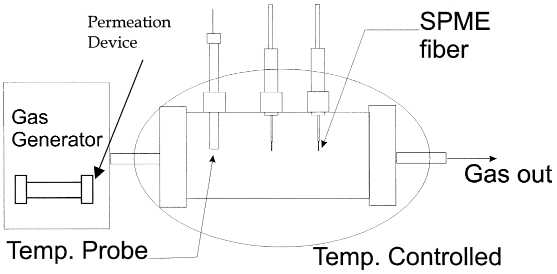

Figure 2—Schematic diagram of experimental setup for SPME calibration.

(H_2S), mercaptans, dimethyl disulfide (DMDS), carbonyl sulfide, and carbon disulfide (CS_2) were analyzed. The sum of the 20 compounds (volumetric addition of compounds in parts per million by volume) is reported as total-reduced sulfur (TRS_V).

Analysis of Trimethylamine and Volatile Fatty Acids. Trimethylamine and VFAs (propionic acid and butyric acid) were sampled using a specially coated fiber and analyzed using an SPME method and gas chromatography. In this study, gas standards were generated using certified Teflon membrane permeation devices (National Institute for Science and Technology traceable, VICI Metronics, Inc., Santa Clara, California) for each compound. The permeation devices were placed together in a thermostated glass chamber of a dynacalibrator (model 320, VICI Metronics, Inc.). The base flow of high-purity (99.99%) nitrogen gas through the permeation chamber was 72 mL/min, and the concentration was varied using additional dilution gas. Two SPME fibers were exposed to the gas standard in a temperature-controlled (20 °C), cylindrical, Teflon collection chamber (i.d. of 4.1 cm, Savillex, Co., Minnetonka, Minnesota) (Figure 2). The temperature inside the chamber was measured by inserting a temperature probe (Traceable-4085, Control Co., Houston, Texas) to the chamber. The chamber was equipped with two septa ports with Teflon-coated septa, through which the needle of the SPME device was inserted so that duplicate measurements could be made for all calibration points. Additional information about the experimental setup or the use of SPME can be found in literature by Abalos et al. (1999), Eisert et al. (1997), and Kim et al. (2001a, 2001b).

Trimethylamine Analysis. A 75-μm Carboxen–polydimethylsiloxane coating was used to capture TMA. The TMA was analyzed using capillary gas chromatography with mass spectrometry detection in selected-ion monitoring mode. A gas chromatograph (model HP 5890, Hewlett Packard, Palo Alto, California) coupled to a mass spectrometer (model HP 5988, Hewlett Packard) was used.

Volatile Fatty Acid Analysis. An 85-μm polyacrylate coating was used for propionic acid and butyric acid (Supelco, Bellefonte, Pennsylvania). Analysis of propionic and butyric acids was performed using capillary gas chromatography with flame-ionization detection using a gas chromatograph (model HP 5890, Hewlett Packard).

Both gas chromotography systems were equipped with a Merlin microseal septum (Supelco) designed for SPME to ensure reproducibility between injections. Table 1 shows the characteristics of analytes and method detection limits.

Table 1—Physical properties of analytes, method detection limits of analytes, and odor thresholds for human detection.

Compound	Molecular weight (g/mol)	Boiling point[a] (°C)	MDL[b] (ppb_v)	Odor threshold (ppb_v)
Propionic acid	74	141.4	1.80	28 (Hellman and Small, 1974)
Butyric acid	88	163.5	1.32	0.5 (Fazzalari, 1978)
Trimethylamine	59	2.87	2.38	0.44 (O'Neill and Phillips, 1992)

[a] Obtained from Budavari et al. (1996).

[b] Method detection limit; determined with eight samples; U.S. EPA standard calculation procedure was followed (Longbottom and Lichtenberg, 1982).

Results

Odor Characteristics of Dry Pellets. Olfactometric odor characteristics of the dry pellets are presented in Table 2. The data are sorted by hedonic tone from most unpleasant to least unpleasant. The odor intensity, persistence, and descriptors are provided for each sample. The four most common and descriptive odors are provided. A more negative hedonic tone value indicates a more unpleasant odor and a more negative persistence value indicates a less persistent odor. The odor characteristics of the Blue Plains AWWTP oven-dried undigested and digested products are provided for comparison.

The lime-stabilized WAS dried product produced the most unpleasant and intense odor. The next most unpleasant odors were for the Blue Plains undigested blend and the all-undigested products. Primary digested and WAS undigested product was next in terms of unpleasantness and intensity. The products with the least unpleasantness and intensity were the digested pellets. Interestingly, the odor from the Blue Plains digested heat-dried product was the least unpleasant and intense for dry pellets.

The products (lime-stabilized WAS and all-undigested pellets) that exhibited the greatest odor intensity and unpleasantness were found to be less persistent. This is seemingly contradictory and may be because the different types of compounds that are generated by these products generate different odor intensity and persistence values.

The analytical data for heat-dried biosolids pellets are presented in Table 3. Carbon disulfide, carbonyl sulfide, and DMDS were the predominant reduced-sulfur compounds released from heat-dried

Table 2—Odor panel results for heat-dried biosolids.

Sample type	Hedonic tone	Intensity	Persistence	Typical odor descriptor
Lime-stabilized WAS	−7.1	630	−0.59	Medicinal, ammonia, chlorinous, fishy
All undigested	−4.1	150	−0.45	Sour, decay, rancid, earthy
Primary digested–WAS undigested	−3.9	110	−0.35	Earthy, burnt, rancid, plastic
All digested	−2.7	45	−0.30	Earthy, decay, burnt, stale
Blue Plains undigested blend	−4.9	190	−0.40	Garbage, sour, earthy, stale
Blue Plains digested	−1.3	25	−0.18	Petroleum, earthy, musty, stale

Table 3—Odor compounds for heat-dried biosolids (all units in ppb$_v$).

Sample type	TRS$_v$	Carbon disulfide	Carbonyl sulfide	Dimethyl disulfide	Trimethylamine	Volatile fatty acids[a]
Lime-stabilized WAS	149	2	ND	147	2970	ND[b]
All undigested	70	57	7.5	5.6	ND	7340
Primary digested–WAS undigested	27	20	ND	6.9	ND	ND
All digested	82	69	13	ND	ND	ND

[a] Volumetric sum of butyric and propionic acids.
[b] ND = not detected.

products and accounted for most (greater than 99%) of the 20 reduced-sulfur compounds (including hydrogen sulfide and mercaptans) that were analyzed using the ASTM D5504-98 method (ASTM, 1998).

Lime-Stabilized Waste Activated Sludge Product. The primary organic odor compound released from the lime-stabilized WAS product that relates to ammonia or fishy odors was TMA. Dimethyl disulfide was the primary reduced-sulfur compound released, and contributed to most of the TRS$_V$. These compounds are typically released from lime-stabilized biosolids (Murthy et al., 2001). It seems that these compounds produced the unpleasant and intense odors that were also the least persistent.

All-Undigested Pellets. The undigested products were typically described as ‘‘sour’’. This odor descriptor may be related to the release of VFAs. Table 3 shows the presence and release of two odorous VFAs (propionic and butyric acids) from these products. It seems that the odors from these compounds are less persistent as well. In addition to VFAs, smaller amounts of reduced-sulfur compounds were released from the undigested products. Unlike typical unstabilized solids, where the released odor compounds are typically dimethyl sulfide or methyl mercaptan (Kim et al., 2001a), the reduced-sulfur compounds that were released from the undigested heat-dried products were primarily carbonyl sulfide and carbon disulfide.

Primary Digested–Waste Activated Sludge Undigested Pellets. The primary compounds released from Milorganite were reduced-sulfur compounds (carbon disulfide and DMDS). Volatile fatty acids were not detected (unlike for the all-undigested pellets).

Table 4—Odor panel results for heat-dried materials with 33% moisture added.

Sample	Hedonic tone	Persistence	Typical odor descriptor
Lime-stabilized WAS	−6.0	−0.64	Medicinal, ammonia, garbage, earthy
Primary digested–WAS undigested	−5.9	−0.52	Sour, garbage, decay, earthy
All undigested	−5.7	−0.44	Earthy, garbage, sour, decay
All digested	−5.6	−0.50	Garbage, sour, earthy, burnt
Blue Plains undigested blend	−5.0	−0.43	Vegetable, burnt, earthy, sour
Blue Plains digested	−2.9	−0.20	Burnt, sour, vegetable, earthy

All-Digested Pellets. The primary compounds released from the digested heat-dried products were carbonyl sulfide and carbon disulfide. These compounds are not commonly reported in digested biosolids (WEF, 1995).

Odor Characteristics of Pellets with Moisture. Moisture can affect the odors from a heat-dried product. The pellets can become moist during storage or transportation. For these experiments, water was added to heat-dried pellets to simulate these conditions. Moisture was added at 33% of the total weight of pellets. The wetted pellets were stored for 24 hours and evaluated for odor characteristics. The olfactometric odor characteristics for moistened pellets are presented in Table 4. Interestingly, the hedonic tones for all of the pellets were similar. The hedonic tone for the lime-stabilized waste activated sludge pellets improved from −7.1 to −6.0. In contrast, the hedonic tone for all-digested pellets deteriorated substantially (from −2.7 to −5.6). The hedonic tone for the all-undigested and primary digested–WAS undigested also deteriorated. The persistence of the all-digested pellets decreased from −0.30 to −0.50 and, for the primary digested–WAS undigested pellets, it decreased from −0.35 to −0.52.

The analytical data for moistened heat-dried biosolids pellets are presented in Table 5. Carbon disulfide, carbonyl sulfide, and DMDS were again the predominant reduced-sulfur compounds released from heat-dried products.

Lime-Stabilized Waste Activated Sludge Pellets. The lime-stabilized WAS product, although the most unpleasant when dry, became less odorous (lower hedonic tone) when wetted. The moist lime-stabilized WAS product released less TMA (Table 5) when wetted compared with the dry pellets (Table 3).

All-Undigested Pellets. For the all-undigested pellets, the addition of moisture resulted in a deterioration of the hedonic tone, but had little effect on persistence. The reasons for these changes are not clearly explained from the odor compound release data presented in Table 5.

Primary Digested–Waste Activated Sludge Undigested Pellets. The primary compounds released from moistened Milorganite were reduced-sulfur compounds. The concentration of carbonyl sulfide increased for moistened pellets.

All-Digested Pellets. The primary compounds released from the digested heat-dried products were also reduced-sulfur compounds. The concentration of carbonyl sulfide increased for moistened pellets. Volatile fatty acids were observed for these pellets, indicating solublization and volatilization of these acids or fermentation reactions in this product. The source of fermentation reactions that may occur in sterile pellets remains unexplored, although it may be a result of residual enzymatic activity.

Table 5—Odor compounds for heat-dried materials with 33% moisture added (all units in ppb$_v$).

Sample	TRS$_v$	Carbon disulfide	Carbonyl sulfide	Dimethyl disulfide	Trimethylamine	Volatile fatty acids[a]
Lime-stabilized WAS	11	2.1	ND[b]	8.7	90	ND
Primary digested–WAS undigested	48	20	16	12	ND	ND
All undigested	20	8.7	12	ND	ND	2280
All digested	198	77	99	22	ND	180

[a] Volumetric sum of butyric and propionic acids.

[b] ND = not detected.

Odor Characteristics of Pellets with Moisture and Soil Amendment. Pellets that are wetted and contacted with soil (such as during land application) may be subject to microbial degradation by soil microorganisms to produce odors. To simulate this condition, a set of pellets was mixed with potting soil (33% of weight of pellets) and water (33% of weight of pellets).

Tables 6 and 7 present the effect of moisture and soil amendment on pellet odor characteristics. The products that were stabilized (lime-stabilized WAS and all-digested pellets) prior to heat drying produced the least unpleasant odor compared with the hedonic tone from unstabilized heat-dried pellets. Previously stabilized pellets are not subject to microbial reactions to the same extent as unstabilized pellets. The hedonic tone for the lime-stabilized WAS and all-digested pellets improved with soil amendment compared with wetted pellets.

Lime-Stabilized Waste Activated Sludge Pellets. The lime-stabilized WAS product was comparatively less odorous (hedonic tone) than the undigested or partly digested pellets. The pH remained elevated for the sample set. Amending the product with more soil may result in a decrease in pH and a corresponding increase in microbial activity. It is hypothesized that microbial activity will remain diminished as long as the pH remains elevated.

All-Undigested Pellets. For the soil amendment of all-undigested pellets, the hedonic tone deteriorated (compared with moisture alone), but there was little effect on persistence. The reasons for the deterioration may be explained by microbiologically assisted release of odor compounds that were not measured in this study.

Primary Digested–Waste Activated Sludge Undigested Pellets. The primary compounds released from moistened and soil-amended Milorganite were reduced-sulfur compounds. The increase in TRS$_V$ may have resulted in deterioration in hedonic tone.

All-Digested Pellets. The primary compounds released from the digested heat-dried products were also reduced-sulfur compounds.

Discussion

Effect of Moisture Addition and Soil Amendment. Figures 3 and 4 provide a summary of odor comparisons for the dry, wetted, and soil-amended pellets.

Lime-Stabilized Waste Activated Sludge Pellets. For the lime-stabilized WAS product, both moisture addition and soil amendment resulted in an improvement in hedonic tone. The reasons for this improvement may be related to the decrease in emission of TMA and TRS$_V$ compounds. Trimethylamine is a highly water-soluble compound, and the addition of moisture may have contributed to its remaining in the product. The persistence of this sample increased with moisture and soil amendment and decrease in TMA. This relationship indicates that TMA may not possess a high odor persistence. Further research is required to determine persistence of individual and groups of compounds.

All-Undigested Pellets. Both moisture addition and soil amendment had a negative effect on the hedonic tone of all-undigested pellets. The reason for the deterioration in hedonic tone may be due to the presence of VFAs in the product and the lack of stabilization prior to heat drying. The effect of prolonged (more than 24 hours) microbial contact or variations in ORP was not investigated. It is anticipated that an increase in contact time may increase the release of TRS$_V$ compounds. The persistence for the all-undigested sample remained constant for dry, wetted, and soil-amended pellets.

Primary Digested–Waste Activated Sludge Undigested Pellets. The hedonic tone for these pellets deteriorated with moisture addition. The reason for this deterioration may be due to corresponding increase in TRS$_V$ and shifts in relative proportions of reduced-sulfur compounds (carbon disulfide and carbonyl sulfide) released from the heat-dried product. The odors were less persistent with added moisture, but more persistent with soil amendment.

All-Digested Pellets. The hedonic tone of all-digested pellets deteriorated substantially with the addition of moisture, but improved with soil amendment. This deterioration with moisture addition may be due to the release of carbonyl sulfide, and its improvement with soil amendment implies lack of microbial reactions in the stabilized pellets. As shown in Figure 4, the addition of moisture resulted in an increase in TRS$_V$ (primarily because of carbonyl sulfide) for all-digested pellets. The all-digested pellets were less persistent with added moisture, but more persistent with soil amendment. Recently, Murthy et al. (2002) showed that odor compound production from digested biosolids peak after several days (approximately 1 week) of storage. The

Table 6—Odor panel results for heat-dried materials with 33% moisture added and soil inoculation.

Sample	Hedonic tone	Persistence	Typical odor descriptor
All undigested	−6.3	−0.46	Earthy, rancid, garbage, sour
Primary digested–WAS undigested	−6.0	−0.40	Burnt, sour, earthy, rancid
Lime-stabilized WAS	−5.3	−0.35	Burnt, earthy, garbage, smoky
All digested	−5.0	−0.31	Vegetable, sour, burnt, earthy

Table 7—Odor compounds for heat-dried materials with 33% moisture added and soil inoculation (all units in ppb$_v$).

Sample	TRS$_v$	Carbon disulfide	Carbonyl sulfide	Dimethyl disulfide	Trimethylamine	Volatile fatty acids[a]
All undigested	48	22	26	ND[b]	ND	4520
Primary digested–WAS undigested	96	27	50	11	ND	ND
All digested	176	72	86	14	ND	ND
Lime-stabilized WAS	22	ND	ND	22.3	330	ND

[a] Volumetric sum of butyric and propionic acids.

[b] ND = not detected.

storage time used in these experiments was limited to 24 hours. Any future investigation of odor production in heat-dried pellets should take into account longer storage times to more thoroughly understand odor compound production trends.

Source of Odor Compounds. The source of the odor compounds in this study are either a result of upstream treatment, odors that are produced from the drying process, odors generated from reactions induced by moisture addition, or odors generated from reactions induced by soil amendment. Trimethylamine was only observed in the headspace of the lime-stabilized WAS sample, and the release is a result of increase in pH during upstream liming reactions (Murthy et al., 2001). In addition to TMA, reduced-sulfur compounds and VFAs were observed.

Source of Volatile Fatty Acids. Kim et al. (2001b) showed that butyric and propionic acids are mainly released from primary thickened sludge. They also showed that these acids are absent in thickened WAS. Table 8 presents the VFA data for wetted pellets. To further understand the upstream source of VFAs, the analysis of four sets of pellets from full-scale heat drying facilities are provided. To help link VFA release to an upstream source, the odors from an additional plant that heat dries primary undigested solids (not previously described in the results section) was evaluated and compared to all-undigested, primary digested–WAS undigested, and all-digested pellets. The primary undigested and the all-undigested pellets released substantial concentrations of propionic and butyric acids. Volatile fatty acid release was not observed for the primary digested–WAS undigested pellets. This comparison suggests that VFA release primarily occurs if the upstream primary solids remain undigested. The practice of digesting primary solids may be desirable for plants that release substantial VFA from primary clarifiers or gravity thickeners; this practice may produce more moderated odor characteristics.

The reason for VFA release from the all-digested pellet sample is not known. Typically, a properly operating digester (such as the source of this pellet) does not possess substantial propionic and

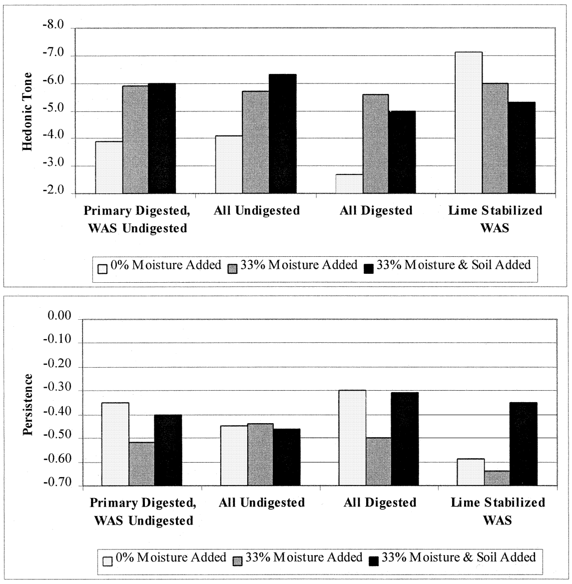

Figure 3—Effect of moisture and soil amendment on odor characteristics after 24-hour storage.

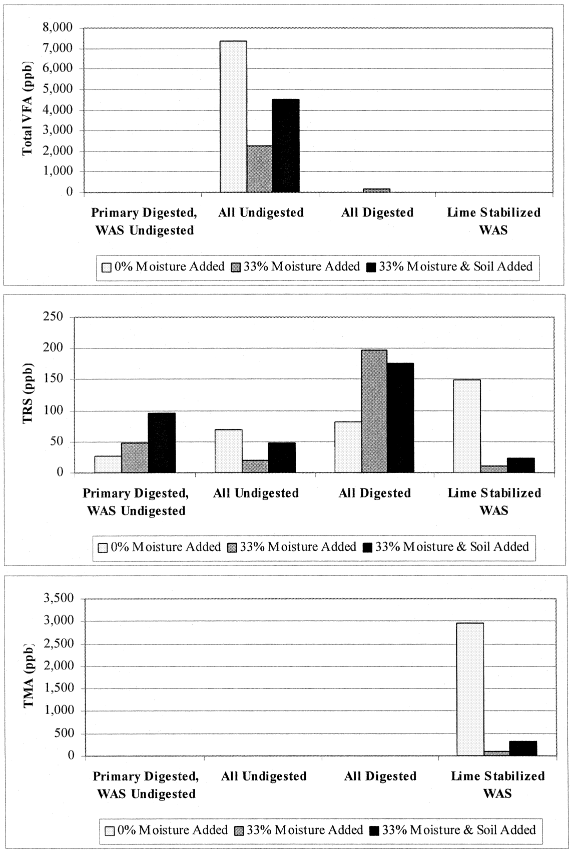

Figure 4—Effect of moisture and soil amendment on release of VFAs, reduced-sulfur compounds, and TMA after 24-hour storage.

butyric acids. This release may be a result of residual enzymatic activity present in the sterilized and rewetted heat-dried pellets.

Source of Reduced-Sulfur Compounds. Kim et al. (2001a) showed that dimethyl sulfide and DMDS are the predominant reduced-sulfur compounds present in primary thickened, WAS thickened, and dewatered solids. Carbon disulfide was only observed in the raw wastewater and in the primary process, not in dewatered biosolids.

Table 9 presents the two primary reduced-sulfur compounds (carbon disulfide and carbonyl sulfide) for undigested, partly digested, and completely digested pellets (DMDS was the primary reduced-sulfur compound released from lime-stabilized WAS pellets). The release of carbon disulfide and carbonyl sulfide is presented for both dry pellets and wetted pellets. The pellet sample labeled ‘‘all digested 2’’ is from an additional facility (not previously described in the ‘‘Results’’ section) that completely digests its solids (primary and WAS) prior to drying and pelletization. This additional plant was selected because it reports good stabilization of its solids (greater than 60% volatile solids destruction) in its digesters. Several observations are apparent from analysis of data in Table 9. Carbon disulfide and carbonyl sulfide constitute most of the reduced-sulfur odor compounds released from these heat-dried pellets. The relative percentage of contribution of carbonyl sulfide increases with moisture addition. For wetted pellets, the concentration of these reduced-sulfur compounds increases in the following order: undigested sample followed by partly digested sample followed by completely digested samples. In relation to all other samples, these compounds are released from the second all-digested sample in substantially higher concentrations. The second all-digested sample was derived from a facility that achieves good digestion (greater than 60% volatile solids destruction) and, therefore, the degree of stabilization does not seem to diminish the release of these compounds (rather, it seems to increase their release).

The release of carbon disulfide and carbonyl sulfide may be a result of the heat drying process itself. The release of these compounds may be due to a breakdown of sulfur-containing macromolecular fragments present in the solids during heat drying. The reason for the apparent relationship between digestion and release of these compounds is not clear and requires further elucidation. The reason for the increase in release of carbonyl sulfide from wetted pellets compared with dry pellets is also not clear and may relate to relative partitioning of this compound between solid, liquid, and gas phases.

Table 8—Volatile fatty acids from wetted pellets (all units in ppb$_v$).

Pellet type	Propionic acid	Butyric acid	Total VFAs[a]
All undigested	1750	530	2280
Primary undigested	3300	1650	4950
Primary digested–WAS undigested	ND[b]	ND	ND
All digested	130	50	180

[a] Volumetric sum of butyric and propionic acids.

[b] ND = not detected.

In summary, the mechanisms for the production of carbonyl sulfide and carbon disulfide are not clear, although they may be related to the heat drying process itself. These compounds seem to be the primary source of odors from digested pellets. The source of this reaction requires further verification. Eliminating the release of these odor compounds may allow for production of low-odor digested pellets.

Effect of Dilution on Odor Intensity. Table 2 established that the odor intensity decreased in the following order: lime-stabilized WAS, all-undigested, primary digested–WAS undigested, and all-digested pellet samples. However, the odor persistence was exactly the reverse and decreased in the following order: all-digested, primary digested–WAS undigested, all-undigested, and lime-stabilized WAS samples. The significance of these two relationships is explained in Figure 5, in which dose–response curves are provided for the odor samples. Although the lime-stabilized WAS pellets had a greater odor intensity at a dilution of 1, its lower persistence results in the odor intensity rapidly decreasing with dilution. Conversely, for digested pellets, the higher persistence results in a less rapid decrease in odor intensity with dilution. Therefore, although the odor intensity at a dilution of 1 is well separated for the four samples (as shown in Table 2 and Figure 5), the odor intensity for the four samples is similar for dilutions of 100 and 1000.

In summary, the dilution and persistence of a sample will define its odor intensity at a receptor location downstream of the odor source. Similar charts can be generated for pellet samples to describe the changes in odor intensity with dilution for the other experimental sets or at a field site using a flux chamber.

Effect of Storage of Wetted Pellets. Odors from moistened pellets (25 and 33% additional moisture) were characterized after

Table 9—The TRS$_v$ from dry and wetted pellets.

	Dry pellets				Wetted pellets			
	Carbon disulfide		Carbonyl sulfide		Carbon disulfide		Carbonyl sulfide	
Pellet type	ppb$_v$	TRS$_v$[a]	ppb$_v$	TRS$_v$[a]	ppb$_v$	TRS$_v$[a]	Ppb$_v$	TRS$_v$[a]
All undigested	57	81	7.5	11	8.7	43	12	57
Primary digested–WAS undigested	19.6	74	ND[b]	0	20	42	16	33
All digested	69	84	13	16	77	39	99	50
All digested 2	248	87	28	10	96	48	85	43

[a] Percentage of 20 reduced sulfur compounds.

[b] ND = not detected.

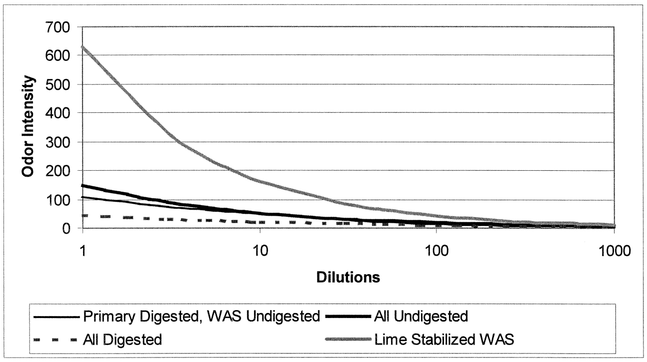

Figure 5—Dose–response curves for heat-dried pellets.

6- and 24-hour storage (Figure 6). An increase in storage time resulted in deterioration in hedonic tone (unpleasantness) for all of the products investigated (primary digested–WAS undigested, all-undigested, all-digested, and lime-stabilized WAS pellets). This evaluation indicates that the odors from wetted pellets will tend to become more unpleasant with an increase in storage time. The odor persistence decreased with an increase in storage time for primary digested–WAS undigested, all-undigested, and lime-stabilized WAS products. An opposite trend was observed for all-digested product. The cause of the changes in persistence is not known, although it may be related to changes in the type of odor compounds emitted with storage.

These experiments were conducted without prior addition of external microorganisms. Therefore, the cause of the deterioration in hedonic tones with the wetting of pellets remains unexplained. The changes in odor production may relate to the presence of heat-resistant microbial spores, residual enzymatic activity, or solubilization and subsequent volatilization of odor compounds from the pellet material.

Conclusions

Lime-Stabilized Waste Activated Sludge Dried Product. The lime-stabilized heat-dried product produced the most unpleasant and intense odor for dry pellets when compared with digested and undigested pellets. The odor descriptions were related to ammonia and TMA. The primary organic odor compounds identified for the product were TMA and DMDS. Odors were less persistent and, therefore, the odor intensity is diluted rapidly. Compared with the dry product, the wetted product had less unpleasant odors. The product was not biologically active when amended with soil. Therefore, the odor from the lime-stabilized soil-amended product was less unpleasant than odor from unstabilized soil-amended pellets.

All-Undigested Pellets. The odors from this product were more unpleasant and more intense than for completely digested dry pellets. The hedonic tone deteriorated with moisture addition and with soil amendment. The odors are partly related to VFAs (for pellets produced from undigested primary solids) and other reduced-sulfur compounds (carbonyl sulfide and carbon disulfide). The moistened undigested product may become more odorous with prolonged exposure to microorganisms.

Primary Digested–Waste Activated Sludge Undigested Pellets. The relative hedonic tone for these pellets lies between that for the all-undigested and all-digested pellet samples. The compounds released from these pellets are reduced-sulfur compounds. The release of VFAs was not observed under any condition for this pellet sample. The hedonic tone deteriorated and TRS_V increased with moisture addition and soil amendment. Interestingly, this product is successfully marketed to homeowners throughout the United States, which shows that levels of odor production may be acceptable.

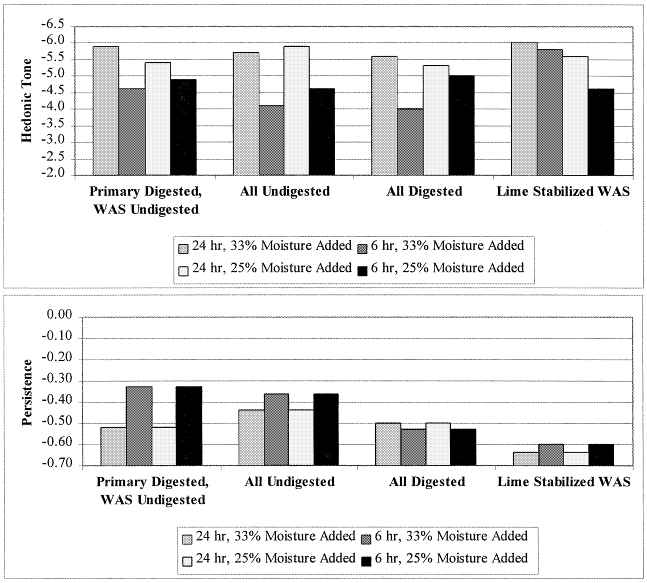

Figure 6—Effect of storage of wetted pellets (33% moisture added) on odor characteristics.

All-Digested Pellets. The digested pellets produced odors of low unpleasantness (hedonic tone) and low intensity for dry pellets. The hedonic tone deteriorated substantially with wetting resulting from release of carbon disulfide and carbonyl sulfide. The source of these reduced-sulfur compounds may be the heat drying process itself. It remains to be investigated if the odor characteristics are different for different types of dryers (direct vs indirect). Overall, these pellets produced odors with the least unpleasant hedonic tones for all experimental sets. However, the odors from these pellets were more persistent than from other pellets.

An increase in storage time of moistened pellets resulted in more unpleasant odors for all pellets investigated (unstabilized and stabilized). Typically, the odors were less persistent with storage.

Heat drying will generate a Class A product if product quality can be maintained. A low-odor product is desirable for successful marketing efforts. Each product type has advantages and disadvantages based on economic considerations and unique product characteristics. The decision-making process for a plant will depend on the unique upstream conditions already existing at the plant and the downstream distribution and marketing requirements. At the Blue Plains AWWTP, the oven-dried digested product possessed considerably lower odors than the oven-dried undigested product. This conclusion supports the plant managers' decision to proceed with anaerobic digestion of its wastewater solids.

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