ARTICLE

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Evaluation of Thermophilic Anaerobic Digestion Processes for Full-Scale Class A Biosolids Disinfection at Hyperion Treatment Plant

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ABSTRACT: This paper describes 5 phases of full-scale testing at the City of Los Angeles Hyperion Treatment Plant (HTP) for producing Class A biosolids (U.S. EPA Part 503 Biosolids Rule) by thermophilic anaerobic digestion. Phases I and II were tests with a two-stage continuous-batch process in a thermophilic battery of six digesters and a designated post-digestion train that was isolated from mesophilic operations. These tests demonstrated that digester outflow biosolids met the Class A limits for fecal coliforms and *Salmonella* sp. However, fecal coliform densities sharply increased during post-digestion. The recurrence was possibly related to a combination of a large drop of the biosolids temperature after the dewatering centrifuges and contamination of thermophilically digested biosolids from mesophilic operations. Phase III was conducted after insulation and electrical heat-tracing of the post-digestion train to maintain a biosolids temperature throughout post-digestion at about the same level as in the digester outflow. Biosolids monitoring at the last points of plant control (silos at Truck Loading Facility and farm for land application) indicated that fecal coliform recurrence was prevented. After completing the conversion of HTP to thermophilic operation, certification tests of Phases IV and V demonstrated Class A compliance of a two-stage continuous-batch process under Alternatives 1 and 3 of the Part 503 Biosolids Rule, respectively. HTP received the permit for Class A (indeed exceptional quality) biosolids land application in Kern County, California, in December 2002 under Alternative 3. Since 2003, HTP has consistently complied with the federal and local standards for Class A biosolids, indicating that Class A limits can be met under conditions less stringent than defined by the Alternative 1 time-temperature requirement for batch treatment.

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KEYWORDS: Class A biosolids; thermophilic anaerobic digestion; disinfection; continuous and batch operations; fecal coliforms; pathogens

Introduction

Many wastewater treatment plants in the U.S. use the biosolids from anaerobic sludge digestion as a fertilizer or soil enhancer in agriculture or other applications. Early investigations on thermophilic anaerobic digestion have focused on sludge stabilization and improving the gas production during digestion (Andrews and Pearson, 1965; McCarty, 1964; Pohland and Bloodgood, 1963). However, public concern in many areas in the U.S. about potentially negative impacts of pathogens and pollutants in biosolids on the environment and human health has renewed the interest in thermophilic anaerobic digestion. This is because thermophilic temperatures can achieve a higher degree of pathogen removal than mesophilic temperatures. In addition, thermophilic anaerobic digestion provides an opportunity for operating the digester at a greater capacity due to higher performances.

Production and land application of biosolids in the U.S. is regulated by the U.S. EPA in the Part 503 Biosolids Rule (U.S. EPA, 1993). This rule sets standards for different types of biosolids, including Class A biosolids which must meet the most stringent limits for pathogens. The federal standards for Class A biosolids contain a general requirement for pathogen densities in biosolids as well as six Alternatives with operational standards and additional requirements for pathogen monitoring (Regulations, next section). The operational standards for disinfection by high temperature were mainly developed from experiences obtained in the food industry and other sectors. The experience with biosolids disinfection by thermophilic anaerobic digestion at wastewater treatment plants was very limited when the Part 503 Biosolids Rule was promulgated in 1993. Since then, several digester process configurations have been investigated, mostly on bench and

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pilot-scale (Ghosh, 1998; Huyard et al., 1998; Watanabe et al., 1997), but also on a full-scale (Schafer et al., 2003; Wilson et al., 2002, 2004).

The City of Los Angeles is one of the pioneers in thermophilic digestion and has conducted extensive research at its wastewater treatment plants. Garber (1954) and Garber et al. (1975) raised the temperatures of the digesters at the Hyperion Treatment Plant (HTP) with the objective of improving digestion performance, but mesophilic operation was resumed in the late 1970s. In 1999, the City of Los Angeles initiated the Class A Biosolids Program with the objective of converting the City's plant to thermophilic operation for improving biosolids disinfection (Iranpour et al., 2004a,b,c,d; Oh et al., 2005; Palacios et al., 2005; Shao et al., 2002). This was motivated by a ban on the land application of Class B biosolids in Kern County, California, where HTP's biosolids have been land applied since 1994. At HTP, conversion of the digesters to thermophilic operation started in early 2001 and was completed by the end of September 2002. During this period, five phases of full-scale tests were conducted to optimize process conditions, certify the final process and demonstrate compliance after certification.

HTP is one of the first plants in the U.S. that land applies Class A biosolids produced by thermophilic anaerobic digestion. This contribution presents the results of the full-scale tests, the process modifications that were made in order to ensure compliance, and the final certification and compliance tests. The specific objectives were:

- Phase I: two-stage continuous/batch process for evaluation of compliance with Alternatives 1 of 40 CFR 503.32 (October and November 2001; Battery D1 with six digesters; 20% of the plant feed sludge in thermophilic operation, isolated from mesophilic operations).
- Phase II: same process and objective as in Phase I, but with a change of temperature and holding time during the batch stage (February and March 2002; Battery D1 with six digesters; 20% of the plant feed sludge in thermophilic operation, isolated from mesophilic operations).
- Phase III: two-stage continuous process after post-digestion design modifications for evaluation of compliance with Alternative 3 (August and September 2002; Batteries D1, D2, and E with 17 digesters; 90% of the plant feed sludge in thermophilic operation, blended with 10% mesophilic biosolids in the second stage).
- Phase IV: two-stage continuous/batch process for certification according to Alternative 1 (October 2002; Batteries D1, D2, and E with 20 digesters; 100% of the plant feed sludge in thermophilic operation).
- Phase V: two-stage continuous/batch process for certification according to Alternative 3 (November 2002; Batteries D1, D2, and E with 20 digesters; 100% of the plant feed sludge in thermophilic operation).
- Post-Phase V: demonstration of compliance with Alternative 3 by monthly monitoring of the biosolids for pathogens and continuous monitoring of process conditions (January 2003 to December 2004; Batteries D1, D2, and E with 20 digesters; 100% of the plant feed sludge in thermophilic operation).

The effects of rapidly and slowly increasing the temperatures during the conversion from mesophilic to thermophilic operations and during thermophilic operation on digestion performance have been discussed by Iranpour et al. (2005).

Regulations

Production and land application of biosolids in the U.S. is regulated by the U.S. EPA in 40 CFR 503 or the Part 503 Biosolids Rule (U.S. EPA, 1993, 1994). This rule states that the pathogen densities in Class A biosolids must be reduced to a non-detect level (40 CFR 503, Section 32). The general requirement is that either the fecal coliform (indicator) density needs to be less than 1000 Most Probable Number/gram dry weight (MPN/g dry wt) or the *Salmonella* sp. (pathogen) density needs to be less than 3 MPN/4 g dry wt. These limits must be met in biosolids at the last point of plant control, usually the Truck Loading Facility where the biosolids are prepared for transport or the farm for land application. Local ordinances may impose additional requirements over federal regulations (Iranpour et al., 2004b). This is the case in Kern County, California, where the City of Los Angeles land applies most of its biosolids. The Kern County ordinance requires that both limits for fecal coliforms and *Salmonella* sp. be met for Class A biosolids instead of only one limit.

Federal regulations also require one of six Alternatives in 40 CFR 503, Section 32, to be used. These Alternatives specify process operation conditions or requirements for additional monitoring of the biosolids. Wastewater treatment plants that employ thermophilic anaerobic digestion may comply with Alternatives 1, 3, or 6:

- Alternative 1 specifies the required time and temperature for disinfection of biosolids. Although not specifically defined in the regulations, it is usually understood that the time-temperature requirement needs to be met in a batch process. For sewage sludge with less than 7% solids, the time-temperature requirement is defined by Eq. (1):

$$D = \frac{50,070,000}{10^{0.14T}} \tag{1}$$

where D is the holding time (days) and T is temperature (°C). The temperature shall be at least 50°C and the holding period at least 30 min.

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– Alternative 3 can be used for continuous processes or other processes that do not meet the time-temperature requirement of Alternative 1. Alternative 3 requires monitoring of the process conditions and the monitoring of the biosolids for non-bacterial pathogens. The densities for viable helminth ova and enteric viruses in Class A biosolids shall be less than 1 viable ova/4 g dry wt and 1 Plaque Forming Units (PFU)/4 g dry wt, respectively.
– If a process has been demonstrated to achieve the Class A pathogen reduction requirements, Alternative 6 provides the opportunity of seeking equivalency as a Process to Further Reduce Pathogens (i.e., ''recognized'' Class A processes, which are included in Alternative 5) as decided by the U.S. EPA Pathogen Equivalency Committee. This requires extensive testing to demonstrate the equivalency.

Alternative 2 specifies the conditions for chemical stabilization and disinfection of biosolids. Alternative 4 can be used for undefined processes and requires that each batch of biosolids be tested for viable helminth ova and enteric viruses. This alternative is not feasible for plants that produce biosolids on a continuous basis. Alternative 5 contains Processes to Further Reduce Pathogens, which does not include thermophilic anaerobic digestion.

Plants that produce Class A biosolids must demonstrate compliance by periodic monitoring of the biosolids at a frequency that depends on the size of the plant (40 CFR 503, Section 16). For larger plants such as HTP, monthly analysis of the biosolids is required. The pathogens to be tested depend on the Alternative under which the plant produces the biosolids, which also determines the requirements for monitoring the process conditions.

Exceptional quality (EQ) biosolids are the highest quality of biosolids. Apart from the Class A pathogen reduction requirements, EQ biosolids must also comply with the vector attraction reduction requirements (40 CFR 503, Section 33) and the strictest limits for metal concentrations (40 CFR 503, Section 13, Tables I and III).

Materials and Methods

Hyperion Treatment Plant

HTP is the main wastewater treatment facility for the City of Los Angeles, servicing an area of about 1,500 km^2 and a population of about 4 million. The average daily flow rate is 1.3×10^6 m^3/day. The treatment process consists of preliminary screening, enhanced primary treatment and a pure oxygen secondary activated sludge process (Fig. 1). HTP has three batteries with in total 20 egg-shaped digesters and several other batteries with cylindrical digesters. HTP converted the egg-shaped digesters from mesophilic to thermophilic operation in 2001 and 2002. Cylindrical digesters were kept at mesophilic temperatures until taken out of service upon completing the conversion of HTP to thermophilic operation. Each egg-shaped digester has a volume of 9.5×10^3 m^3 and is equipped with an internal draft system for mixing. The total average feed to digesters is 1.1×10^4 m^3/day of primary sludge (average of 3.0% total solids with 78% volatile solids) and 3.0×10^3 m^3/day of thickened waste activated sludge (TWAS) (average of 5.1% total solids with 81% volatile solids). The digesters were converted from mesophilic to thermophilic operation in 2001 and 2002. Digester heating is by steam injection either into the top of the digesters (continuous digesters) or into the sludge recirculation line (batch digesters, during feeding only). Temperatures are measured by two sensors in each digester, continuously monitored in HTP's Control Room and reported as daily averages. Post-digestion includes

Table I. Summary of process operation parameters.

	Phase I[a]	Phase II[a]	Phase III[b]		Phase IV	Phase V	Post Phase V (2003/2004)
Parameter	Thermophilic (20% of plant)	Thermophilic (20% of plant)	Thermophilic (90% of plant)	Mesophilic (10% of plant)	Thermophilic (100% of plant)	Thermophilic (100% of plant)	Thermophilic (100% of plant)
First stage							
Operation	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous	Continuous
Number of digesters	4	4	15	6	16	16	16
Temperature (°C)	57.9	57.7	54.4	35.2	57.5	52.7	53.5
HRT (d)	13	13	10.9	39	10.5	9.9	11.6
Second stage							
Operation	Batch	Batch	Continuous		Batch	Batch	Batch
Number of digesters	2	2	2		4	4	4
Temperature (°C)	54.4	53.5	51.4		56.6	52.6	53.8
Holding time (h)	13	24	NA		16	16	16
HRT (d)	NA	NA	1.3		NA	NA	NA
Minimum temperature required by Alternative 1	56.9	55.0	NA		56.3	56.3	56.3

[a]Phases I and II: thermophilic digesters and dedicated post-digestion train isolated from mesophilic operations.
[b]Phase III: blending of thermophilic and mesophilic biosolids in second stage.

Table II. Phases I, II, IV, and V—Batch digester cycles.

Phase I (Fig. 2a)								
Batch digester 5D1	Feed 62 h			Hold 13 h			Draw 75 h	
Batch digester 6D1		Draw 75 h			Feed 62 h			Hold 13 h
Phase II (Fig. 2a)								
Batch digester 1E	Feed 55 h			Hold 24 h			Draw 79 h	
Batch digester 5E		Draw 79 h			Feed 55 h			Hold 24 h
Phase III (Fig. 2b)								
No batch digesters								
Phases IV and V and post-Phase V (Fig. 2c)								
Batch digester 1E	Feed 8 h		Hold 16 h			Draw 8 h		
Batch digester 5E	Draw 8 h		Feed 8 h		Hold 16 h			
Batch digester 6E	Hold 8 h		Draw 8 h		Feed 8 h		Hold 8 h	
Batch digester 7E		Hold 16 h			Draw 8 h		Feed 8 h	

screening, centrifuge dewatering, transport of biosolids through pipes with Able pumps, and biosolids storage in silos for a maximum of 1 day. HTP produces 700–800 wet tons of biosolids per day (about 30% total solids), which are transported to the City's farm in Kern County on a daily basis. The biosolids are used for the cultivation of non-edible crops and incorporated into the soil immediately after arrival at the farm.

Experimental Setup

Digestion Performance

Digestion performance during Phases I–V and Post-Phase V was determined by analysis of primary sludge, TWAS and biosolids for total solids, volatile solids, pH, volatile fatty acids, and alkalinity on a daily to biweekly basis.

Phase I

Phase I (October and November 2001) was conducted with the six digesters of Battery D1 after conversion of these digesters to thermophilic operation (20% of the plant's feed sludge). As the other digesters were still at a mesophilic temperature (80% of the plant's feed sludge rate), Battery D1 and its dedicated post-digestion train were isolated from other digester batteries and post-digestion trains. Figure 2a shows the schematic of the two-stage continuous-batch process and Table I summarizes the main operation parameters. The second-stage digesters were operated with a holding time of 13 h according to the feed, hold and withdraw cycles shown in Table II. A wetwell provided temporary storage for the outflow from the first stage during the periods when there was no filling of the batch digesters. It was the intention to operate the Phase I process according to the time-temperature relationship of Alternative 1 by maintaining a temperature greater than 56.9°C in the second stage. However, due to operational problems with the supply of steam, only the first-stage digesters could be heated to an average temperature of 57.9°C. Cooling of the digested sludge during transport to the second stage and holding in the batch digesters resulted in an average batch holding temperature of 54.4°C. Biosolids were collected from digester inflow and outflow and various locations in the post-digestion train, shown in Figure 2a, over a period of 2 months and analyzed for fecal coliforms and *Salmonella* sp.

Table III. Analytical procedures.

Parameter	Method	Instrumentation	Sampling frequency
Digestion performance			
Total solids	Gravimetric, SM 2540 B[a]	Balance, oven	Daily
Volatile solids	Gravimetric, SM 2540 E[a]	Balance, furnace	Daily
pH	Electrometric, SM 4500-H^{+}[a]	pH meter	Twice weekly
Volatile fatty acids (total)	Distillation and titration, SM 5560 C[a]	Centrifuge, distillation assembly	Twice weekly
Alkalinity	Titration, SM 2320 B[a]	pH meter	Twice weekly
Disinfection			
Total solids	Gravimetric, SM 2540 G[a]	Balance, oven	Daily
Fecal coliforms	Multiple tube fermentation technique, SM 9221 E.2[a]		Daily
Salmonella sp.	Multiple tube enrichment technique, SM 9260[a]		Daily
Enteric viruses	U.S. EPA 600 (samples composited in laboratory)[b]		Daily
Viable helminth ova	ASTM D 4994-89 (samples composited in laboratory)[c]		Daily

[a]Standards methods (APHA et al., 1992).
[b]U.S. EPA (1987).
[c]ASTM (1992).

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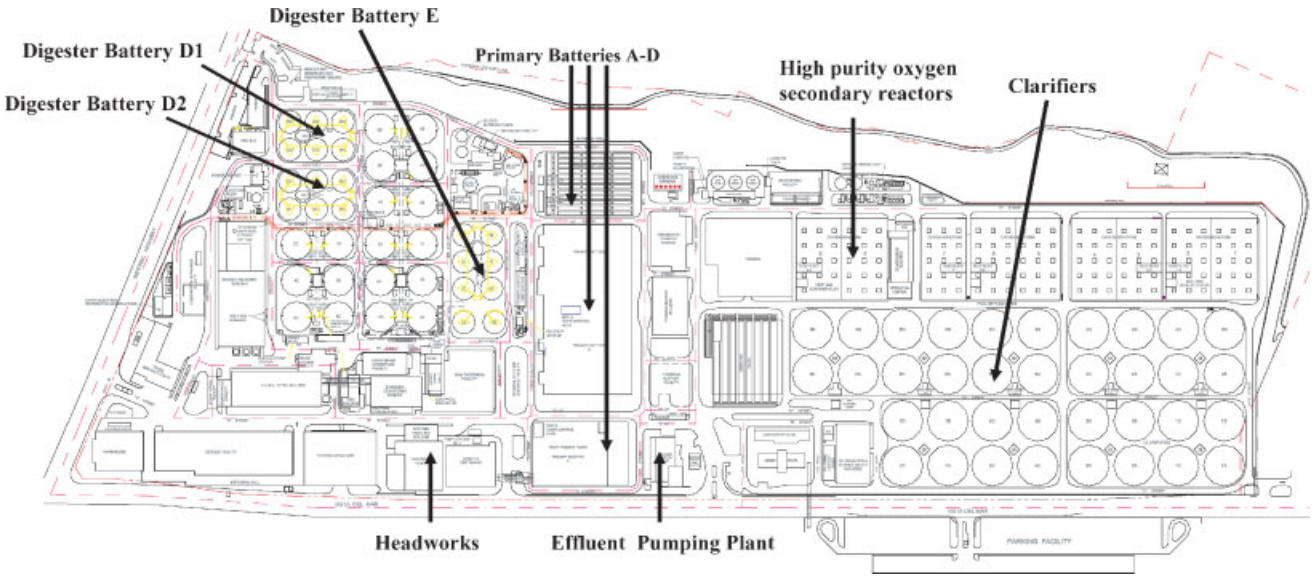

Figure 1. HTP site plan. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

Phase II Process

Phase II tests were conducted in February and March 2002. The process was the same as the Phase I process in Figure 2a, but the batch holding time in the second stage was increased from 13 to 24 h (Table II). The operational problems with steam supply to the batch digesters were still not resolved, hence, the temperature in the second stage was still less than required by Alternative 1 (Table I). Biosolids were daily sampled from various locations in digestion and post-digestion (Fig. 2a) and analyzed for fecal coliforms and *Salmonella* sp. over a period of 4 weeks.

Phase III Process

Following the Phase I and II tests, the post-digestion trains at HTP were insulated and electrically heat-traced between the digesters and the silos at the Truck Loading Facility. The Phase III process was tested in August and September 2002 (Fig. 2b), when the conversion of HTP to thermophilic operation still was in progress. The first stage contained 15 egg-shaped thermophilic digesters for 90% of the plant's feed sludge (Table I). Approximately 10% of the feed sludge was digested in 6 mesophilic cylindrical digesters. Digested biosolids from mesophilic and thermophilic digesters were mixed in two blending digesters (second stage) operated in a continuous mode (Table I). Biosolids were sampled over several weeks in September 2002, and was mostly focused on the Truck Loading Facility (silo biosolids) and the farm for land application (farm biosolids) as the last points of plant control. Microbial analyses included fecal coliforms, *Salmonella* sp., viable helminth ova and enteric viruses.

Phase IV Process

The tests were conducted for 2 weeks in October 2002, after conversion of all egg-shaped digesters to thermophilic operation and all mesophilic cylindrical digesters were taken out of service (Fig. 2c). The first stage contained 16 digesters that were operated in a continuous mode (Table I). The second stage contained four digesters that were operated in a batch mode to comply with the time-temperature requirement of Alternative 1. The holding time was 16 h, which required a temperature of at least 56.3°C. Continuous measurements indicated that the minimum temperature in any of the batch digesters during the test period was 56.6°C. Feeding and withdrawing was for 8 h each. At any time, one digester was feeding, one digester was withdrawing and two digesters were holding (Table II). This enabled a continuous feed to and withdrawal from the second stage, while ensuring that all biosolids would receive treatment for a minimum of 16 h. The Phase IV process was tested with analysis of silo and farm biosolids for fecal coliforms, *Salmonella* sp., viable helminth ova and enteric viruses.

Phase V Process

This process was the same as the one in Phase IV (Fig. 2c), but the digester temperatures were lowered. As the time-temperature requirement of Alternative 1 would not be met (Table I), tests were conducted for 2 weeks in November 2002, to demonstrate compliance with Alternative 3 by analysis of silo and farm biosolids for fecal coliforms, *Salmonella* sp., viable helminth ova and enteric viruses.

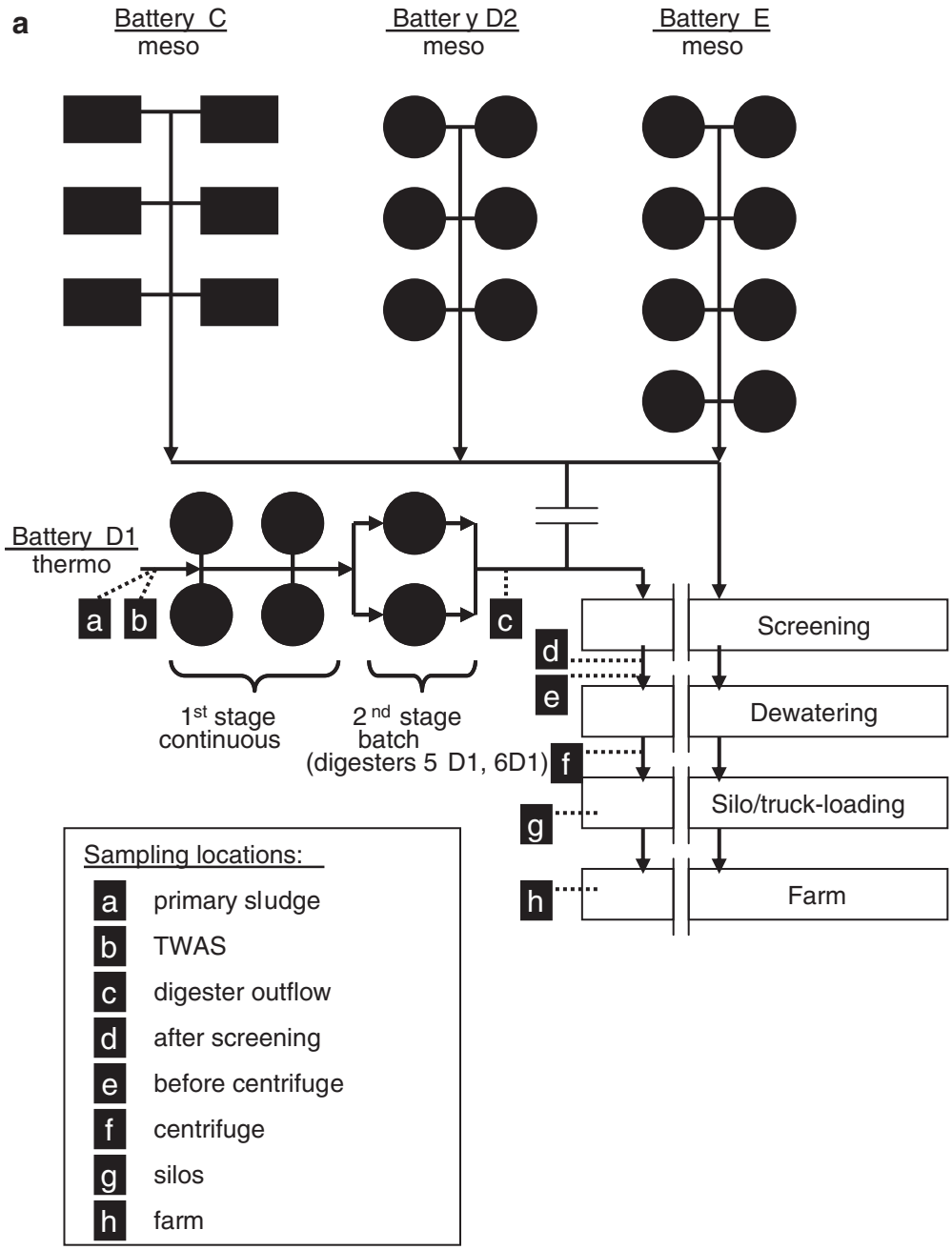

Figure 2. **a**: Phases I and II—process schematic. **b**: Phase III—process schematic. **c**: Phases IV and V, and Post-Phase V—process schematic.

Post-Phase V Process (Compliance Monitoring)

After completion of the Phase V tests, HTP continued the operation of the digesters in a two-stage continuous/batch process as shown in Figure 2c and under conditions that were very similar to the conditions during the Phase V test (Table I). Compliance with Class A disinfection standards in 2003 and 2004 was determined by monthly analysis of the biosolids, sampled at the silos of the Truck Loading Facility or at the farm for land application.

Analytical Procedures

Temperature Measurements

On-line average temperatures were continuously recorded from two sensors on both sides of the digester. Profiles of the biosolids temperature along the post-digestion train were determined with a digital thermometer in the biosolids immediately after sample collection from various locations.

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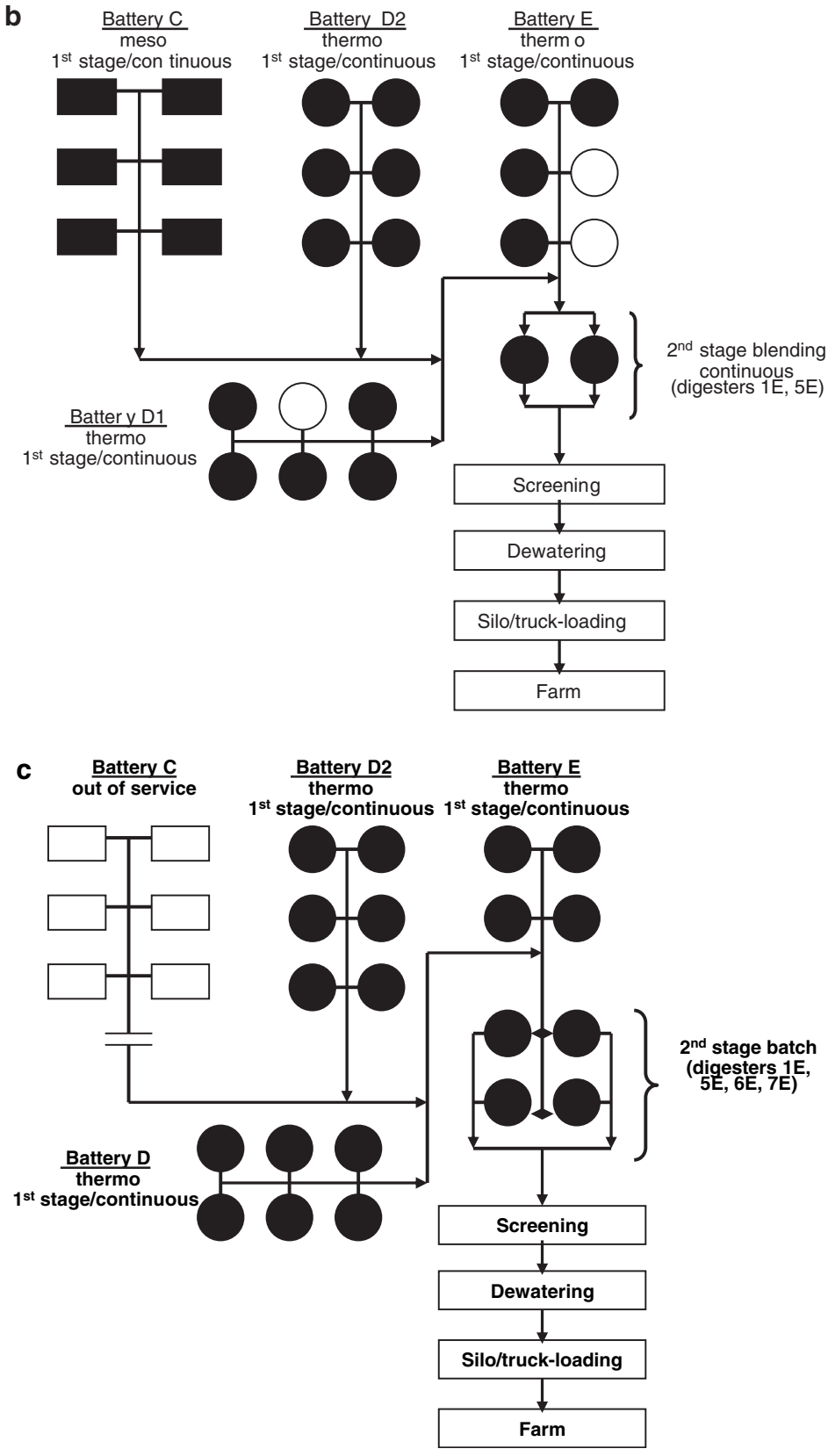

Figure 2. *(Continued)*

Chemical Analyses

Biosolids were taken from the combined digester outflow of the first stage and analyzed for pH, volatile fatty acids, alkalinity, and total and volatile solids according to the procedures in Table III. Primary sludge and TWAS were taken from the inflow to the first-stage digesters and analyzed for total and volatile solids. The samples were collected in plastic containers and transported to the laboratory for analysis on the same day.

Microbial analyses. Sample collection and preservation were according to procedures as described in Part 9020 of *Standard Methods* (APHA et al., 1992) and by U.S. EPA (1999). Samples for fecal coliforms and *Salmonella* sp. were transported to the laboratory for immediate analysis by the Environmental Monitoring Division at HTP according to the procedures in Table III. Samples for viable helminth ova and enteric viruses were stored at 4 and −18°C, respectively, prior to the preparation of composited samples for final analysis by BioVir Laboratories (Benicia, CA).

Post-digestion laboratory tests. Biosolids were aseptically collected from the post-digestion train, transferred to sterile, capped bottles and incubated in the laboratory at 21°C. At regular time intervals over a period of up to 100 h, samples were aseptically withdrawn and analyzed for total solids and fecal coliforms or *Salmonella* sp. Parallel tests were performed with the same samples but spiked in the laboratory with primary sludge as a source of fecal coliforms or with a pure culture of *Salmonella typhimurium* ATCC 14028. Spiked samples were then processed the same way as unspiked samples.

Results

Digestion Performance

After conversion from mesophilic to thermophilic operations by rapidly increasing the temperatures, the digesters rapidly displayed stable operation and performance. Digestion performance during Phases I–V and Post-Phase V was biochemically stable and stayed about the same, as summarized in Table IV. The low and relatively constant ratio of volatile fatty acids to total alkalinity in each phase indicates that a healthy thermophilic microbial population had developed. Volatile solids destruction remained relatively constant at 60%.

The dewaterability of thermophilically digested biosolids seemed to have improved as compared to before when the digesters were at mesophilic temperatures. Although our investigations are still ongoing, the preliminary data indicate that chemical usage has slightly decreased whereas the solids content of the wetcake has increased. This has reduced the costs for dewatering chemicals as well as the tonnage for transport to the farm. We expect to present a full comparison in a separate paper.

Post-digestion Temperatures

As shown in Table V, temperatures in post-digestion remained relatively constant between digester outflow and the dewatering centrifuges in Phases I and II, but a large drop of the biosolids temperature was observed during transport from the centrifuges to the silos at the Truck Loading Facility. Biosolids temperatures in the silos depended on the location of sampling. The average temperature in the upper part of the silo (containing newly arrived biosolids) was somewhat higher than in the bottom part (containing biosolids after a maximum storage time of 1 day), indicating that heat losses also occurred in the silos. Biosolids temperatures at the farm and the silo were almost the same, indicating that the heat losses during transport were not significant. After insulation and electrical heat-tracing of the post-digestion train, the large drop of the biosolids temperature after the centrifuges did not occur. Biosolids temperatures at the silos and the farm during Phases III, IV, and V (Table V) were only a few degrees less than in the second-stage digesters (Table I).

Phase I

Disinfection by Digesters

Figure 3a shows that the fecal coliform densities in primary sludge and thickened waste activated were in the range of 10^7–10^8 MPN/g dry wt. Fecal coliforms were not detected in biosolids from the digester outflow in about half the samples. If detected, the density of fecal coliforms was always

Table IV. All phases—summary of digestion performance (average ± SD).

Parameter	Phase I	Phase II	Phase III	Phase IV	Phase V	Post-Phase V
Period	October to November 2001	February to March 2002	September 2002	October 2002	November 2002	January 2003 to December 2004
TS in inflow (%)	3.5 ± 0.3	3.6 ± 0.2	3.7 ± 0.4	4.2 ± 0.3	4.2 ± 0.3	4.1 ± 0.5
VS in inflow (% of TS)	79.4 ± 1.4	80.5 ± 0.8	79.3 ± 0.8	80.1 ± 1.2	80.1 ± 0.9	80.5 ± 1.2
VS destruction (%)	57.9 ± 3.9	61.6 ± 5.5	59.7 ± 5.6	58.3 ± 9.2	58.4 ± 6.1	60.0 ± 7.3
pH	7.2 ± 0.1	7.2 ± 0.1	7.2 ± 0.1	7.4 ± 0.3	7.1 ± 0.8	7.4 ± 0.2
VFA (mg/L as acetic acid)	656 ± 303	334 ± 107	389 ± 75	878 ± 223	749 ± 85	348 ± 152
Alkalinity (mg/L as $CaCO_3$)	3,496 ± 155	3,401 ± 129	3,317 ± 235	3,235 ± 154	3,635 ± 92	4,091 ± 295
VFA/alkalinity ratio	0.081 ± 0.049	0.099 ± 0.035	0.117 ± 0.02	0.274 ± 0.078	0.206 ± 0.027	0.087 ± 0.047

TS, total solids; VS, volatile solids; VFA, volatile fatty acids.

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Table V. All phases—temperature (°C) profiles of post-digestion.

Post-digestion location	Phase I	Phase II	Phase III	Phase IV	Phase V
Digester outflow	51.4	52.6	51.4	57.6	52.5
Before digester screening facility	50.8	—	—	—	—
After digester screening facility	50.0	—	—	—	—
Before polymer addition	50.8	—	—	—	—
After polymer addition	48.6	—	—	56.9	—
After centrifuge dewatering	50.4	48.2	—	55.0	—
Truck Loading Facility					
-top of silo	43.6	41.0	—	—	—
-bottom of silo	41.9	40.5	51.1	—	—
Farm	—	40.2	51.5	54.0	51.5

well below the Class A limit of 1,000 MPN/g dry wt. The densities of *Salmonella* sp. in raw sludge were much smaller that those of fecal coliforms and *Salmonella* sp. were never detected in digester outflow biosolids (Fig. 3b).

Post-Digestion Counts

The densities of fecal coliforms in biosolids during post-digestion remained well below the Class A limit up to the dewatering centrifuges (Fig. 4a). However, a large increase of fecal coliforms was observed in biosolids from the silos at the Truck Loading Facility, causing exceedance of the Class A limit at the last point of plant control. In contrast, *Salmonella* sp. remained non-detect in biosolids throughout the post-digestion train (Fig. 4b).

Phase II

Disinfection by Digesters

Fecal coliforms were detected in the outflow of the two-stage thermophilic process, but the densities were always well below the Class A limit (Fig. 5a). Disinfection of *Salmonella* sp. was complete as they were never detected in digester outflow biosolids (Fig. 5b).

Post-Digestion Counts

The results of Phase II confirmed those of Phase I. Fecal coliforms were not detected at the centrifuges, but the density sharply increased in silos bioslids at the Truck Loading Facility (Fig. 6a). The fecal coliform density was higher in farm biosolids, indicating that growth of these bacteria could have occurred during transport to the farm. *Salmonella* sp. were never detected in post-digestion biosolids up to the farm for land application (Fig. 6b)

Post-Digestion Laboratory Tests

Growth of fecal coliforms in digester outflow biosolids was not observed for up to 100 h, even if these biosolids were spiked with fecal coliforms (Fig. 7a). Likewise, incubation of centrifuged biosolids at 21°C did not result in growth of fecal coliforms (Fig. 7b). However, when fecal coliforms were added to centrifuge biosolids, their density rapidly increased with time (Fig. 7b). The same results were observed at other incubation temperatures in the range of 21–45°C, but fecal coliform growth was always absent at a temperature of 55°C. Similar tests after spiking with *S. typhimurium* indicated that digester outflow and centrifuge biosolids were not capable of supporting the growth of *Salmonella* sp. in the temperature range of 21–45°C (results not shown).

Phase III

Disinfection by Digesters

The results were similar as in Phases I and II. *Salmonella* sp. were not detected, and fecal coliform densities were always below the Class A limit.

Post-Digestion Counts

Microbial testing in September 2002 demonstrated that the Class A limit for fecal coliforms in biosolids at the silos and the farm was met in 95% (two exceedances) and 88% (one exceedance) of the samples, respectively (Fig. 8). These exceedances occurred at times that electrical shut-downs caused a discontinuation of solids processing with periods of relatively low biosolids temperatures at the silos (Fig. 8). *Salmonella* sp. were never detected in farm biosolids. Helminth ova and enteric viruses were detected in primary sludge, but the densities of these non-bacterial pathogens in farm biosolids were reduced to below their Class A limits (non-detect).

Post-Digestion Laboratory Tests

Fecal coliform growth did not occur in centrifuge and silo biosolids during incubation at 21°C for 144 h (Fig. 9).

Phase IV

Disinfection by Digesters

The Phase IV process was the configuration originally planned for HTP to demonstrate compliance with local and federal requirements for EQ biosolids. Hence, sampling in

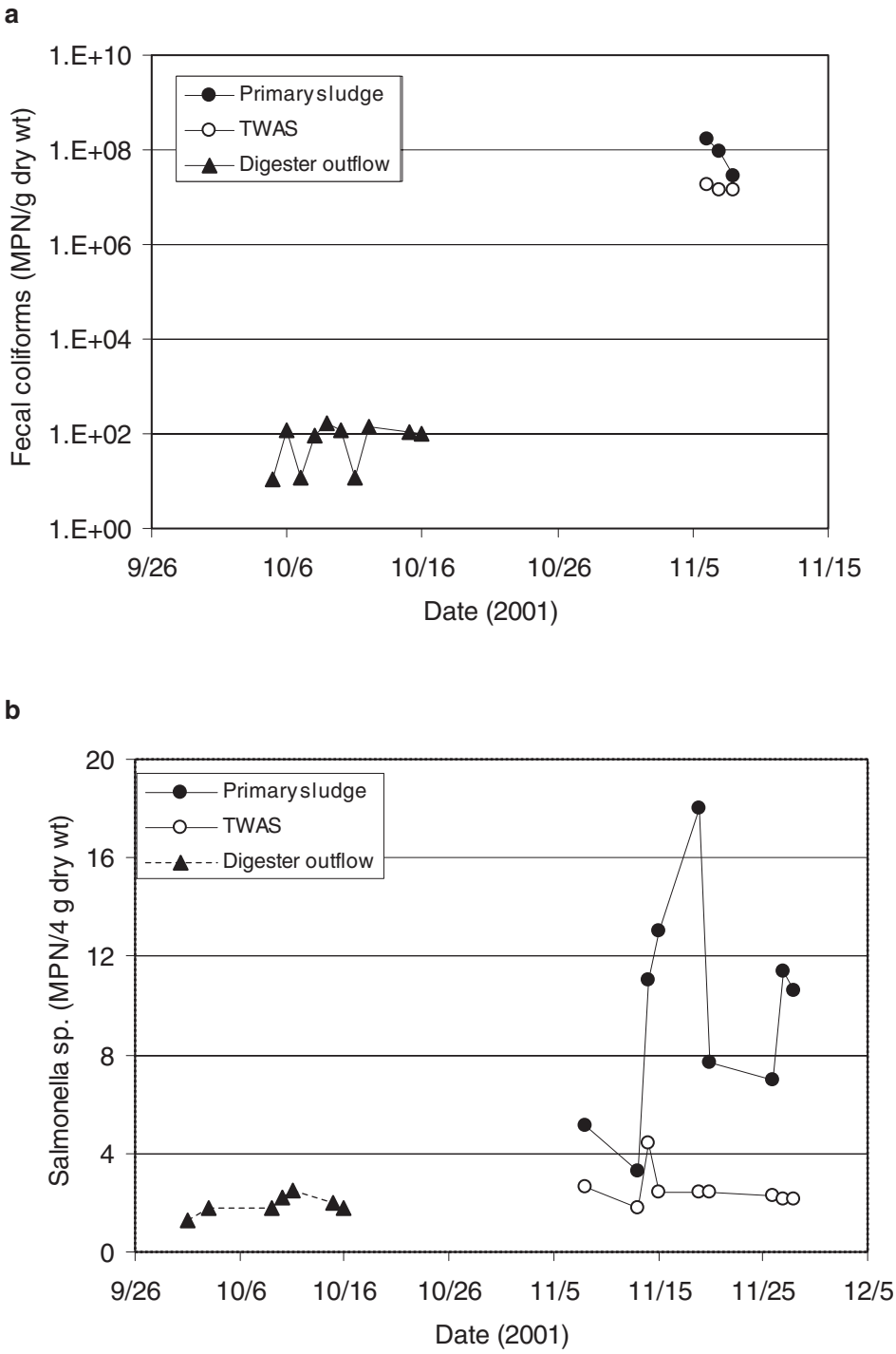

Figure 3. **a**: Phase I—fecal coliforms in digester inflow of stage 1 and digester outflow of stage 2. **b**: Phase I—Salmonella sp. in digester inflow from stage 1 and digester outflow from stage 2 (dashed line indicates upper-bound values).

this phase was more focused on the last point of plant control. Analyses of digester outflow biosolids indicated that disinfection by the digesters was about the same as in previous phases (results not shown).

Post-Digestion Counts

Fecal coliforms and *Salmonella* sp. were never detected during daily sampling of farm biosolids over a period of 2½

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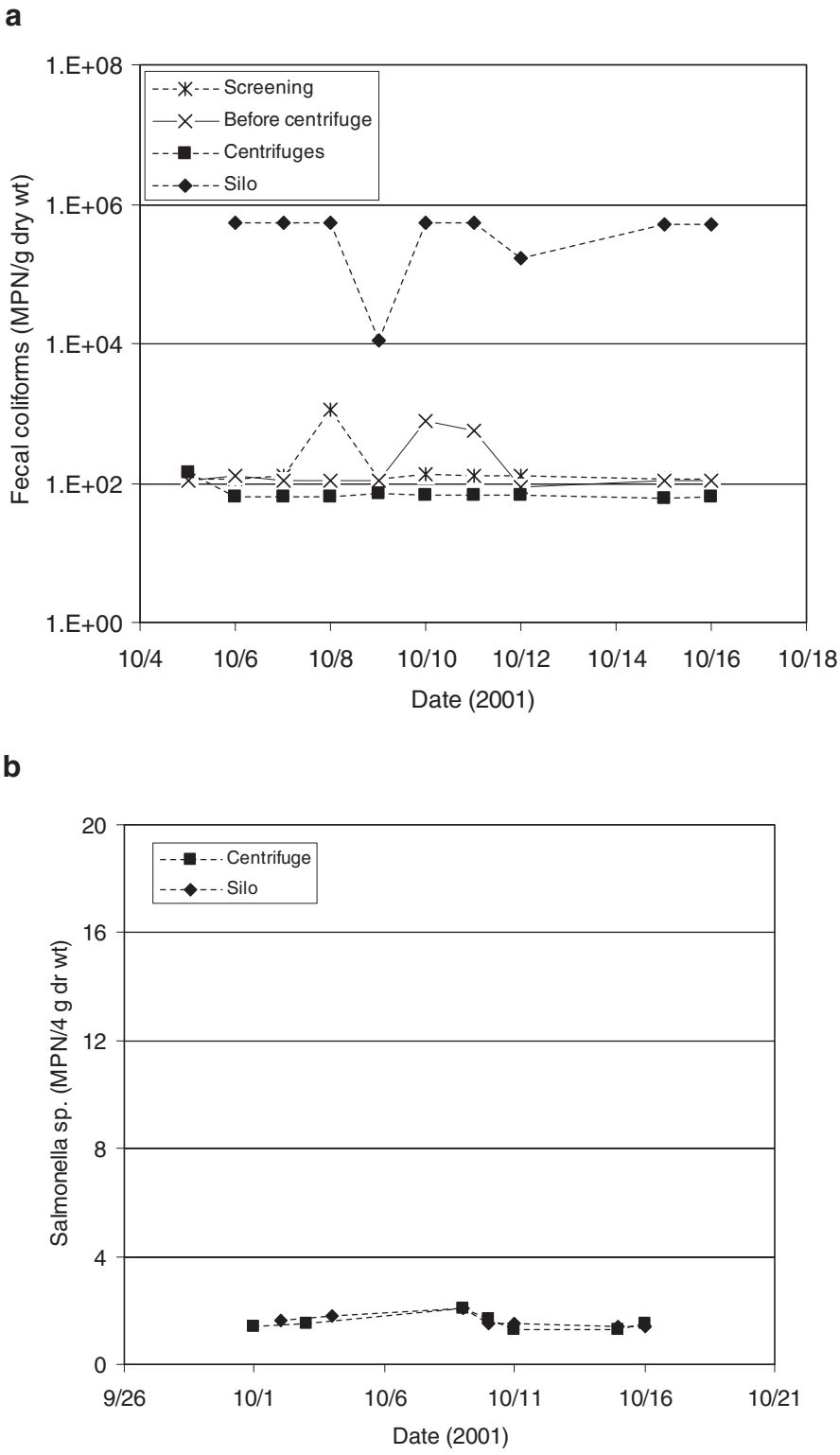

Figure 4. **a**: Phase I—fecal coliforms in post-digestion (dashed line indicates upper-bound values at screening and centrifuges, and lower-bound values at silos). **b**: Phase I—Salmonella sp. in post-digestion (dashed lines indicate upper-bound values).

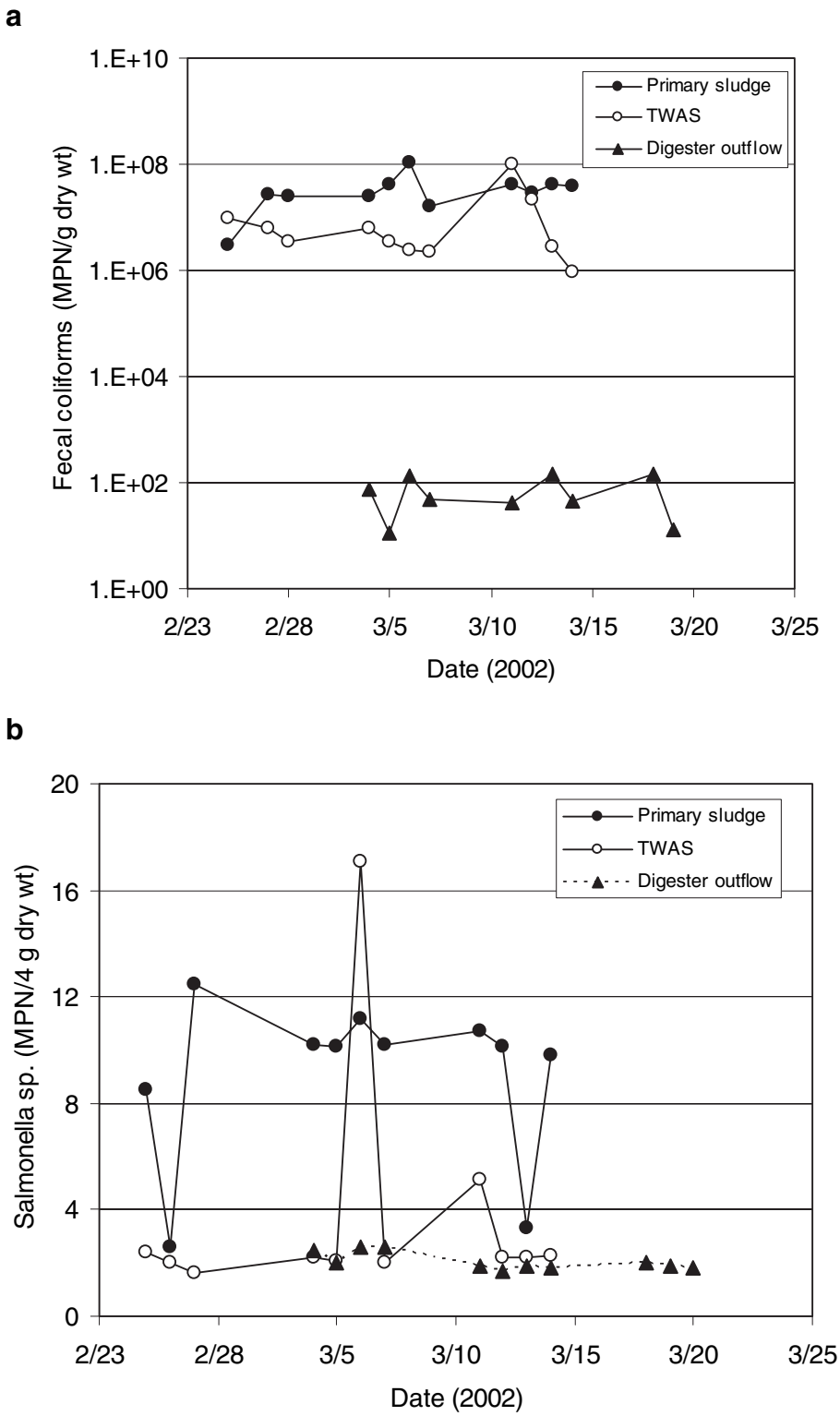

Figure 5. **a**: Phase II—fecal coliforms in digester inflow of stage 1 and digester outflow from stage 2. **b**: Phase II—Salmonella sp. in digester inflow of stage 1 and digester outflow from stage 2 (dashed line indicates upper-bound values).

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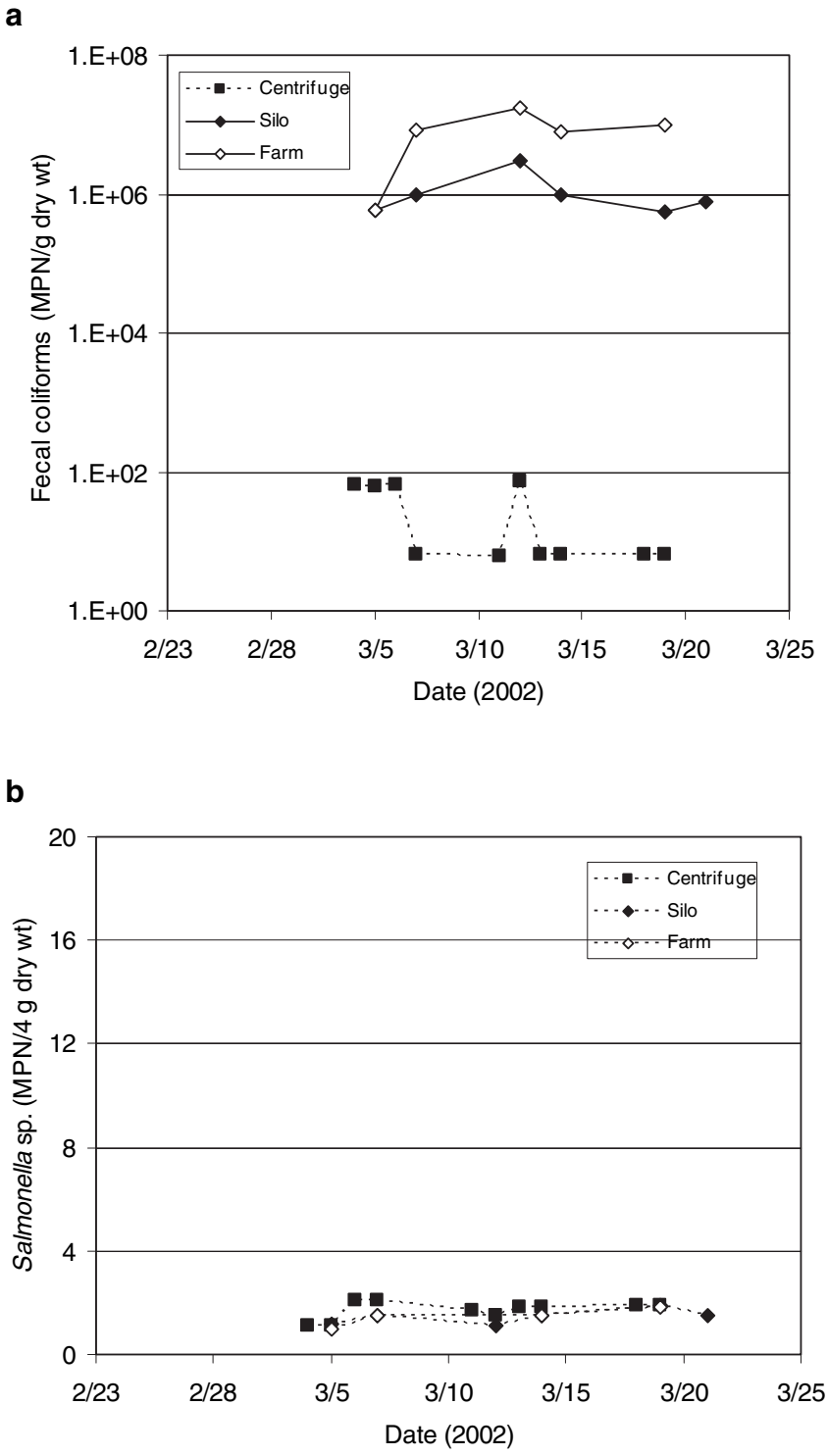

Figure 6. **a**: Phase II—fecal coliforms in post-digestion (dashed line indicates upper-bound values). **b**: Phase II—Salmonella sp. in post-digestion (dashed lines indicate upper-bound values).

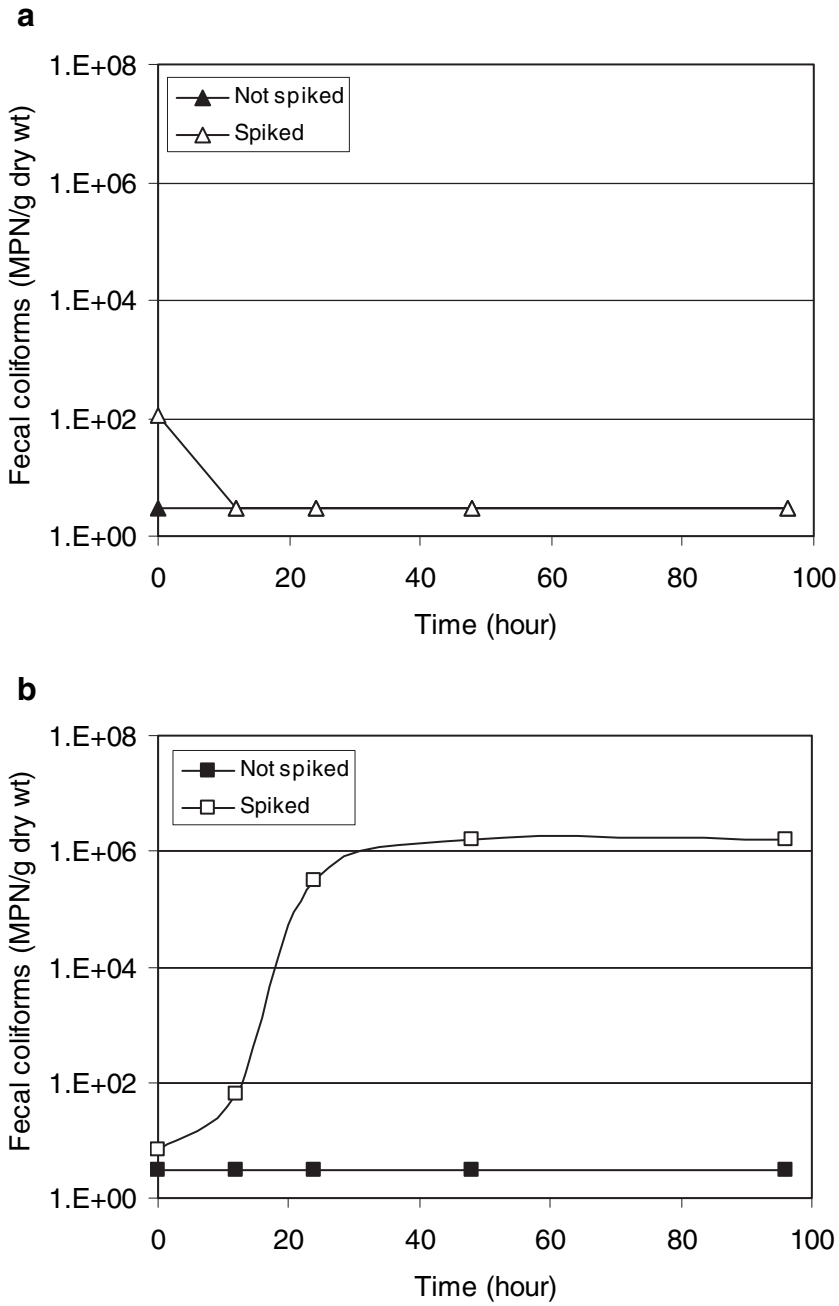

Figure 7. **a**: Phase II—growth of fecal coliforms in spiked and unspiked digester outflow biosolids (laboratory test at 21°C). **b**: Phase II—growth of fecal coliforms in spiked and unspiked centrifuge biosolids (laboratory test at 21°C).

weeks, and, hence, the Class A limits were always met (Figs. 10a and b, respectively). Biosolids temperatures during sampling at the farm ranged from 53.2 to 55.3°C, which was a few degrees less that the second-stage holding temperature. Although analysis of helminth ova and enteric viruses is not required for Alternative 1, composited samples of farm biosolids were tested for these pathogens but they were not detected. Thus, compliance with the Kern County and federal regulations was demonstrated for the first time with HTP fully in thermophilic operation. However, a large increase of odorous emissions from thermophilic operations was observed when the digester temperature was rapidly raised to meet the time-temperature requirement of Alternative 1 at a holding time of 16 h (Iranpour et al., 2005). Analysis of the digester gas showed a sharp increase of the production of methyl mercaptan. Digester temperatures were subsequently reduced in order to reduce odorous air emissions.

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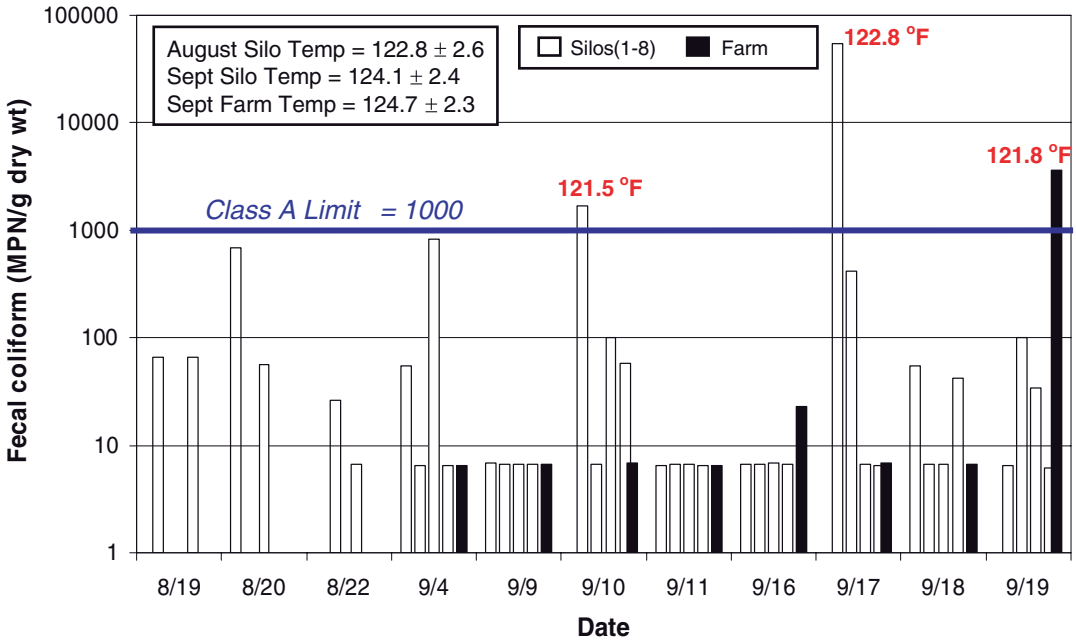

Figure 8. Phase III–fecal coliform densities in silo and farm biosolids. [Color figure can be seen in the online version of this article, available at www.interscience.wiley.com.]

Phase V

Disinfection by Digesters

The results were the same as in Phase IV.

Post-Digestion Counts

These tests became necessary because the time-temperature requirement of Alternative 1 would not be met after lowering the digester temperature, hence, demonstration of

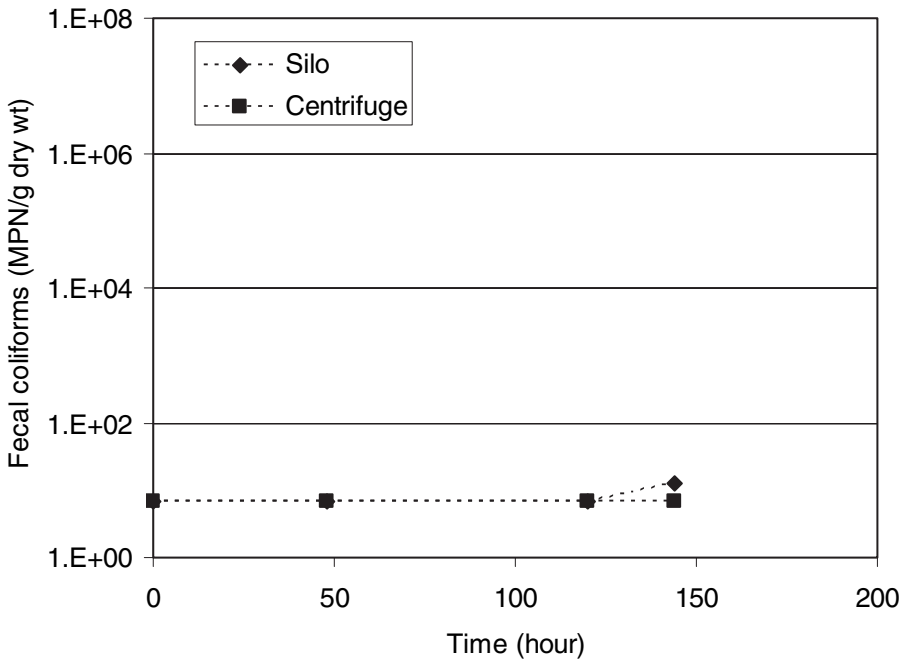

Figure 9. Phase III—growth of fecal coliforms in centrifuge and silo biosolids (laboratory test at 21°C).

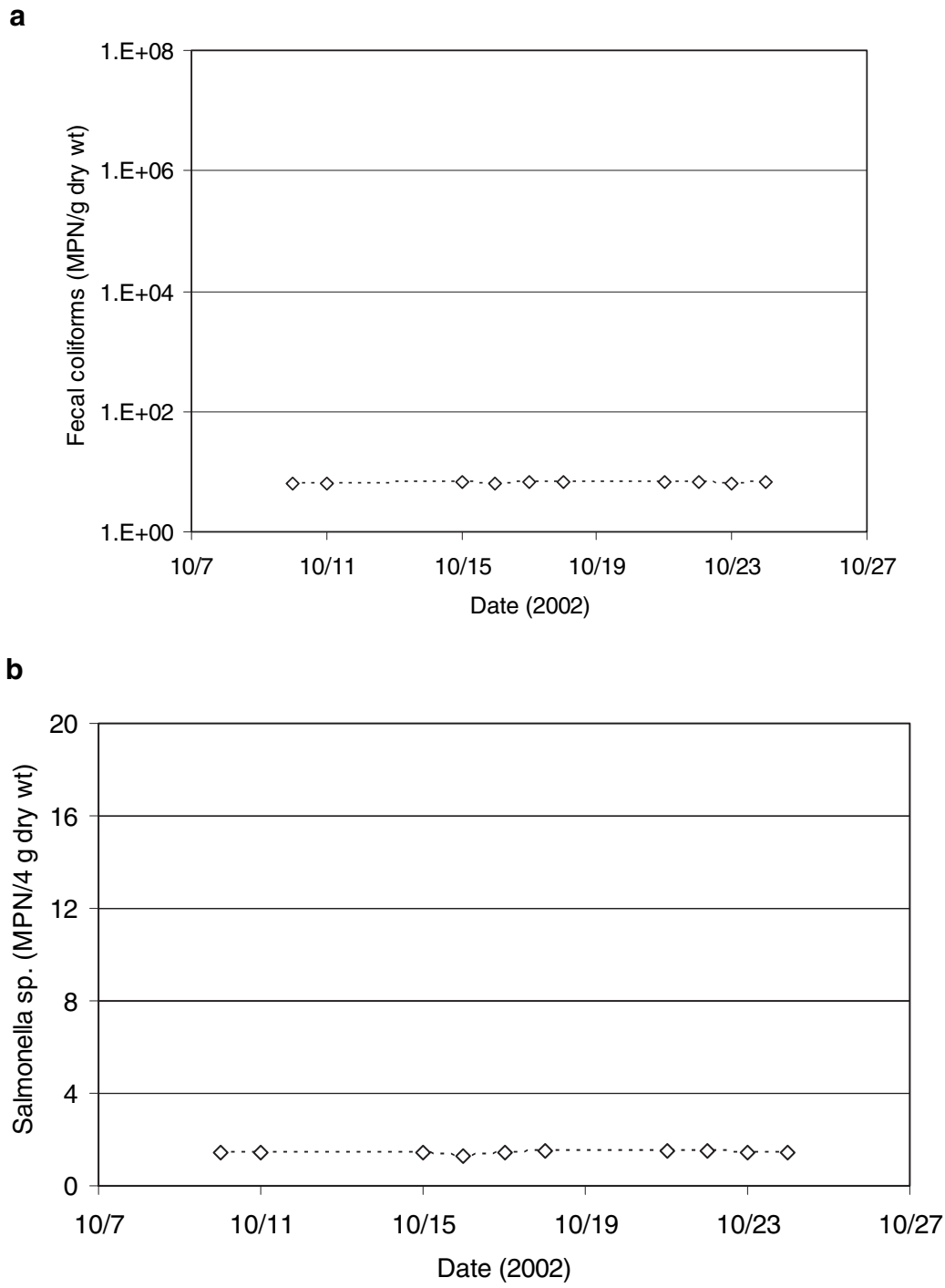

Figure 10. **a**: Phase IV—fecal coliforms in farm biosolids (dashed line indicates upper-bound values). **b**: Phase IV—Salmonella sp. in farm biosolids (dashed line indicates upper-bound values).

compliance with Alternative 3 was required. One week of daily testing in November, 2002, demonstrated that fecal coliforms (Fig. 11a) and *Salmonella* sp. (Fig. 11b) were below the Class A limits (non-detect) in biosolid samples taken at the farm. Likewise, viable helminth ova and enteric viruses were below the Class A limit (non-detect) in composited samples of farm biosolids, as required by Alternative 3.

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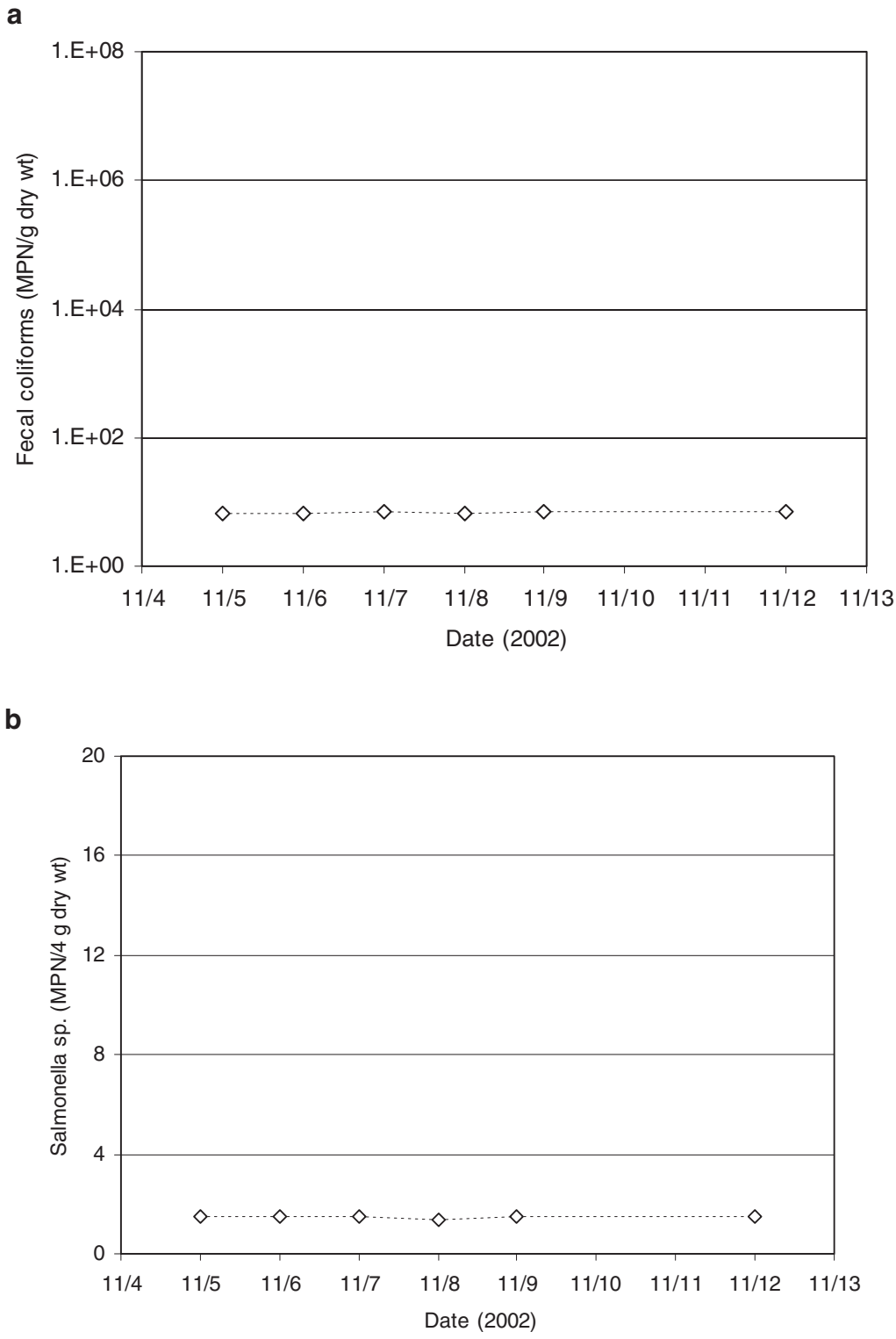

Figure 11. **a**: Phase V—fecal coliforms in farm biosolids (dashed line indicates upper-bound values). **b**: Phase V—Salmonella sp. in farm biosolids (dashed line indicates upper-bound values).

Table VI. Post-Phase V—monthly compliance monitoring of biosolids.

	Primary sludge					Silo biosolis				Farm biosolids		
Month (2003)	Fecal coliforms	*Salmonella* sp.	Helminth ova	Enteric viruses	Fecal coliforms	*Salmonella* sp.	Helminth ova	Enteric viruses	Fecal coliforms	*Salmonella* sp.	Helminth ova	Enteric viruses
January 2003	NS	7.8	<1	10	<6.5	<1.4	<1	<1	NS	NS	NS	NS
February2003	NS	3.6	<1	10	<6.5	<1.4	<1	<1	NS	NS	NS	NS
March 2003	NS	6.4	<1	15	<6.8	<1.4	<1	<1	NS	NS	NS	NS
April 2003	NS	4.1	<1	9	NS	NS	NS	NS	22	<1.4	<1	<1
May 2003	NS	>11.2	<1	13	<6.6	<1.4	<1	<1	NS	NS	NS	NS
June2003	NS	>11.8	<1	34	<6.7	<1.4	<1	<1	NS	NS	NS	NS
July 2003	NS	>12.3	<1	51	NS	NS	NS	NS	<6.5	<1.4	<1	<1
August 2003	NS	>12.8	<1	48	<7.8	<1.7	<1	<1	NS	NS	NS	NS
September 2003	NS	<2.2	2	36	<6.7	<1.0	<1	<1	NS	NS	NS	NS
October 2003	NS	>18.2	2	19	NS	NS	NS	NS	<6.8	<1.2	<1	<1
November 2003	NS	>16.8	<1	40	<6.6	<1.2	<1	<1	NS	NS	NS	NS
December 2003	NS	>14.9	2	18	44.8	<1.5	<1	<1	NS	NS	NS	NS
January 2004	NS	>14.4	<1	19	NS	NS	NS	NS	6.9	<1.4	<1	<1
February 2004	NS	>13	<1	2	<6.6	<1.4	<1	<1	NS	NS	NS	NS
March 2004	NS	>12	<1	2	<6.7	<1.5	<1	<1	NS	NS	NS	NS
April2004	NS	>13	<1	7	NS	NS	NS	NS	<6.7	<1.5	<1	<1
May 2004	NS	>14.2	1	21	<6.6	<1.4	<1	<1	NS	NS	NS	NS
June 2004	NS	>11	2	59	<6.5	<1.4	<1	<1	NS	NS	NS	NS
July 2004	$>4 \times 10^4$	>13.3	<1	102	NS	NS	NS	NS	<7.4	<1.6	<1	<1
August 2004	NS	>16.0	5	62	<6.5	<1.3	<1	<1	NS	NS	NS	NS
September 2004	2.8×10^8	>16.3	1	36	<6.6	<1.5	<1	<1	NS	NS	NS	NS
October 2004	NS	>15.9	4	16	NS	NS	NS	NS	<6.6	<1.4	<1	<1
November 2004	NS	>15.6	<1	30	<6.5	<1.4	<1	<1	NS	NS	NS	NS
December2004	NS	>11.7	1	8	<6.9	<1.5	<1	<1	NS	NS	NS	NS

NS, no sampling; units, fecal coliforms (MPN/g dry wt); *Salmonella* sp. (MPN/4 g dry wt); viable helminth ova (ova/4 g dry wt); enteric viruses (PFU/4 g dry wt).

Post-Phase V

Disinfection by Digesters

Digester outflow biosolids were not analyzed because compliance needs to be demonstrated only at the last points of plant control.

Post-Digestion Counts

Results of monthly monitoring of silo and farm biosolids indicated consistent compliance with all Class A limits for fecal coliforms and pathogens (Table VI). Fecal coliforms were detected only twice, but the densities were well below 1,000 MPN/g dry wt. *Salmonella* sp., helminth ova and enteric viruses were never detected. Since they were found to be present in the raw sludge, it can be assumed that the process established at HTP achieved complete destruction of these pathogens.

EQ Biosolids

Volatile solids destruction was consistently around 60%, thereby complying with the limit of 38% solids destruction for vector attraction (Option 1 in 40 CFR 503, Section 33). Metal concentrations in the biosolids were always below the limits specified in Tables I and III of 40 CFR 503, Section 13 (Iranpour et al., 2004a). Hence, HTP's biosolids always met all requirements of EQ biosolids.

Discussion

In all phases, *Salmonella* sp., helminth ova and enteric viruses were never detected in biosolids immediately after the digesters or in the post-digestion train, including the silos at the Truck Loading Facility and the farm for land application as the last points of plant control. Each one of the processes at HTP, therefore, met the federal requirements for Class A biosolids, either under Alternative 1 or Alternative 3. This is because the general requirement is that only one of the Class A limits for fecal coliforms and *Salmonella* sp. must be met (U.S. EPA, 1993). The main challenge for HTP, however, was to also meet the Class A limit for fecal coliforms, as local regulations required both limits to be met.

Several studies have demonstrated meeting the Class A limits in digester outflow biosolids on pilot or full-scale. It should be noted, however, that for the purpose of compliance these limits should be met at the last points of plant control. The recurrence of fecal coliforms in biosolids from the Truck loading facility and the farm for land application, therefore, caused non-compliance during Phases I and II at HTP. Recurrence of pathogens requires their initial presence in biosolids as well as conditions that allow their growth. Several factors have been identified as stimulating pathogen recurrence in Class A biosolids produced by composting (Burge et al., 1987; Hussong et al., 1985; Soares et al., 1995). Fecal coliform recurrence in

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biosolids from thermophilic digesters is relatively new and observed only at a few other wastewater treatment plants (Oh et al., 2005). There are several possible explanations for the results of the Phase I and II tests (Iranpour et al., 2006a). First, failure to meet the Alternative 1 time-temperature requirement may have caused incomplete disinfection with about half of the digester outflow samples containing fecal coliforms, albeit below the Class A limit. Second, post-digestion biosolids may have been contaminated by mesophilically digested biosolids, because complete isolation of the dedicated post-digestion train is difficult to ensure. Irrespective of the origin of fecal coliforms, their recurrence in Phases I and II coincided with a large drop of the biosolids temperature after the centrifuges. It may be postulated, therefore, that the lower temperature allowed rapid proliferation of fecal coliforms. Subsequently, the density at the Truck Loading Facility and farm for land application increased to the same order as originally present in raw sludge. A similar situation may arise in plants that intend the use of Temperature Phased Anaerobic Digestion (TPAD) in which the last stage is mesophilic, as the biosolids temperature will be relatively low at the beginning of the post-digestion train. To our knowledge, however, TPAD has only been tested in the laboratory, that is, immediately after the digesters. Full-scale investigations are required to evaluate the effect of post-digestion, in particular at truck loading and farm, on the final quality of biosolids produced by TAPD.

The processes tested in Phases III, IV, and V met the Class A limit for fecal coliforms at the Truck Loading Facility and the farm for land application, which may be attributed to two possible factors. First, completing the conversion of the plant to thermophilic operation would have eliminated the possibility of contamination by mesophilically digested biosolids. Second, insulation and electrical heat-tracing of the post-digestion train maintained a high biosolids temperature, thereby preventing reactivation and growth of fecal coliforms. It is likely that further disinfection occurred in post-digestion after equipping the trains with insulation and electrical heat-tracing, because biosolids from the Truck Loading Facility did not show fecal coliform growth, even when the samples were cooled down to 21°C.

The continuous-batch process in Phase IV was the only process that met the time-temperature relationship of Alternative 1 (Iranpour et al., 2006b). As expected, fecal coliforms and pathogens were completely eliminated in the digesters and fecal coliform recurrence in post-digestion did not occur. Alternative 1 required a minimum temperature of 56.3°C, hence, the digester temperature was rapidly increased from 54 to 58°C over 2 weeks in September and October 2002 to meet the deadline of the Class B biosolids ban in Kern County as of January 1, 2003. This rapid temperature increase probably caused a biochemical instability in the digesters, resulting in elevated production of hydrogen sulfide and methyl mercaptan (Iranpour et al., 2005). As prevention of odor nuisance is a high priority for the City of Los Angeles, digester temperatures were immediately reduced to about the same levels as in previous phases. It should be noted that subsequent investigations have shown that the digester temperature can be raised to a maximum of at least 56–57°C and without excessive odor emissions if the temperature rise is gradually and slowly (Iranpour et al., 2005).

The 2003 and 2004 compliance data showed that the two-stage continuous batch process also achieved consistent compliance when the batch holding time and temperature in the second stage were well below those required by the time-temperature relationship of Alternative 1. This may indicate this relationship is conservative, and that the Class A limits can possibly be met at a lower temperature or shorter holding time. This is confirmed by the remarkable disinfection results of Phase III: (a) the digester temperature was relatively low; (b) both stages were operated in a continuous mode; (c) the second blending stage received 10% mesophilically digested biosolids with a high density of fecal coliforms.

Conclusions

The conclusions of the five phases of full-scale tests at HTP are:

1. Phase I: The two-stage continuous-batch process reduced densities of fecal coliforms and *Salmonella* sp. to below the limits for Class A biosolids, but recurrence of fecal coliforms in post-digestion caused non-compliance at the last points of plant control. Potential causes of fecal coliform recurrence were: (a) non-compliance with the time-temperature requirement of Alternative 1 for batch holding, possibly causing incomplete destruction of fecal coliforms in the digesters; (b) contamination of thermophilically digested biosolids by mesophilically digested biosolids; (c) a large drop of the biosolids temperature after the centrifuges, possibly allowing the reactivation and growth of fecal coliforms.
2. Phase II: This phase confirmed the findings of Phase I. In addition, increasing the holding time in the second stage from 13 to 24 h did not have a significant effect on preventing fecal coliform recurrence in post-digestion.
3. Phase III: Insulation and electrical heat-tracing of the post-digestion train prevented the large temperature drop after the centrifuges. This probably contributed to preventing fecal coliform recurrence in post-digestion, possibly in combination with eliminating contamination by mesophilically digested biosolids in post-digestion as the Phase III process was entirely thermophilic after the first-stage digesters.
4. Phase IV: Operation of this process met the requirements for the digester temperature and batch holding time as specified by Alternative 1 of 40 CFR 503. Fecal coliforms and pathogens were non-detect at the last points of plant control, hence, this process fully complied with the Class

A pathogen reduction requirements. However, the rapidly increasing digester temperature caused an unexpected increase of odor emissions from thermophilic operations.

5. Phase V: This process achieved the same disinfection as in Phase IV, but at a lower digester temperature to prevent excessive odor emissions. Since the time-temperature relationship of Alternative 1 was not met, compliance was achieved under Alternative 3 by demonstrating that helminth ova and enteric viruses were absent in biosolids at the last point of plant control.

Overall, the tests of Phases III and V demonstrated that Class A compliance by thermophilic anaerobic digestion can be achieved by different processes and with operation conditions less stringent than required by Alternative 1 of the Part 503 Biosolids Rule. This would imply that there is more flexibility for plants in designing thermophilic processes and a potential for cost savings than would be available if following the operation requirements of Alternative 1. Alternative 3 allows plants to do so by requiring additional monitoring of helminth ova and enteric viruses in biosolids. Our tests show, however, that meeting this additional requirement is not a major concern as compared to meeting the general requirement of compliance with the Class A limits for *Salmonella* sp. and in particular fecal coliforms. Other plants that experience fecal coliform recurrence in post-digestion may consider similar post-digestion design modifications as at HTP. Maintaining a post-digestion biosolids temperature above the maximum for growth of fecal coliforms will prevent their recurrence irrespective of plant-specific conditions that may have caused it.

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