CO-MANAGEMENT OF MUNICIPAL SOLID WASTE AND WASTEWATER TREATMENT PLANT SLUDGES USING AN ANAEROBIC COMPOSTING PROCESS

A report prepared for the

California Integrated Waste Management Board

and

West County Wastewater District,
West County Agency,
Richmond Sanitary Service, and
Delta Diablo Sanitation District

March, 1994

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NOTE: Legislation (SB 63, Strickland, Chapter 21, Statutes of 2009) signed into law by Gov. Arnold Schwarzenegger eliminated the California Integrated Waste Management Board (CIWMB) and its six-member governing board effective Dec. 31, 2009.

CIWMB programs and oversight responsibilities were retained and reorganized effective Jan. 1, 2010, and merged with the beverage container recycling program previously managed by the California Department of Conservation.

The new entity is known as the Department of Resources Recycling and Recovery (CalRecycle) and is part of the California Natural Resources Agency.

This document was originally printed in hard-copy format and was declared out of print when all known copies had been distributed. A complete version of the report was located in 2011 and was scanned to a digital format, making it available for downloading.

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Publication # DRRR-2012-015

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
BOF/MSW	Biodegradable organic fraction of municipal solid waste
BF	Biodegradable fraction
BF of alkalinity	Bicarbonate fraction of alkalinity
BVS	Biodegradable volatile solids
BVS OLR	Biodegradable volatile solids organic loading rate
BVS RE	Biodegradable volatile solids removal efficiency
BVS MR	Biodegradable volatile solids mass removal
C/N	Carbon to nitrogen ratio
CODH	The enzyme carbon monoxide dehydrogenase
f	Overall mass balance correction factor accounting for stoichiometric and water vapor loss (dimensionless)
FDH	The enzyme formate dehydrogenase
GPR	Gas production rate
LC	Lignin content
MC	Moisture Content
MPN	Most probable number
MRT	Mass retention time
MSW	Municipal solid waste
OLR	Organic loading rate
OF/MSW	Organic fraction of municpal solid waste
PIA	Prision Industry Authority
PFRP	Process to further reduce pathogens
PSRP	Process to significantly reduce pathogens
RDF	Refuse derived fuel
RE	Removal efficiency
RT	Retention time
SODM	The enzyme super dismutase
TKN	Total Kajeldahl nitrogen
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids
WWTP	Wastewater treatment plant

EXECUTIVE SUMMARY

The anaerobic co-composting process is a promising technology for the co-management of various organic fractions of municipal solid waste (MSW) and wastewater treatment plant (WWTP) sludges. In the anaerobic co-composting process, the biodegradable organic fraction of MSW (BOF/MSW) and WWTP sludge are converted biologically to biogas and a stabilized humus material. This technology has the potential to eliminate conventional sludge processing, to divert wastes from landfills or combustion facilities, and to produce a high-energy biogas and environmentally safe humus material.

This report contains the results of a year-long study of the anaerobic co-composting process conducted at the University of California at Davis. Three different types of wastewater treatment plant sludge: primary, secondary, and digested were co-composted with the organic fraction of MSW. The specific objectives of the study were:

- To demonstrate the technical feasibility (proof-of-concept) of the high-solids anaerobic composting process for the co-digestion of the organic fraction of MSW with various types of wastewater treatment plant sludges.
- To evaluate the process performance under various operating conditions
- To characterize the nutritional requirements for the co-digestion process
- To evaluate the characteristics of the final humus material.
- To assess the process for waste volume reduction.

PROCESS DESCRIPTION

The anaerobic composting process is a two-stage process. The first stage involves the high-solids (typically 23- 30 percent) anaerobic digestion of the commingled biodegradable organic fraction of MSW (BOF/MSW) and the sludge feedstock. During digestion, the biodegradable material in the feedstock is converted to a biogas composed principally of methane (CH_4) and carbon dioxide (CO_2) and a stabilized sludge. In the second stage of the process, the anaerobically digested solids are aerobically biodried to increase the solids content to 65 percent or more and to further stabilize the wastes. The residual humus is a fine, odorless material.

The BOF/MSW is typically comprised of newsprint, office paper, food wastes, and yard wastes. These fractions typically make-up approximately 60 to 70 percent of the total municipal waste stream, most of which potentially could be diverted for beneficial use. Wastes from the residential community of Davis, CA were used to simulate the BOF/MSW. Shredded newsprint and office paper were obtained in bundles, as would be produced from a materials recovery facility. Dried grass clippings were used to simulate yard wastes. Food waste was obtained from local restaurants.

The sludges used in the study represent the three typical types of sludge produced during wastewater treatment. The three sludges (primary, waste activated, and digested) were provided by West County Sanitary District. The West County Sanitary District treatment plant treats a mixture of both domestic and industrial wastewater. The sludges ranged from 2 to 7 percent total solids (digested sludge lowest, primary sludge highest) and were mixed with the simulated BOF/MSW to increase the moisture content of commingled waste to appropriate levels for digestion.

EXPERIMENTAL PROTOCOL

A pilot-scale digester reactor was operated as a semi-continuously fed (once per day) complete-mix reactor. The digester was operated under thermophilic conditions (55°C) with a nominal 30 day mass retention time and constant organic loading rate of about 6 - 7 g biodegradable volatile solids (BVS) per kg active reactor mass per day. Each sludge feedstock was evaluated over three months of continuous digester operation. Daily reactor performance was measured in terms of gas production and mass conversion rates, as well as digestion stability parameters such as pH, total solids, the concentration of volatile acids and ammonia, and gas composition. For each sludge feedstock, steady-state performance parameters were established. As part of the co-digestion study, nutritional requirements for sustained high-solids digestion were determined by supplementing the digester feedstock with nutrient rich organic wastes (dairy manure) and synthetic chemical solutions. The final humus material was analyzed with respect to its potential for beneficial use. The humus was analyzed for pollutant concentrations, the presence of pathogens, and other physical and chemical properties.

PROCESS PERFORMANCE

All three sludge types were successfully co-digested with the BOF/MSW. Representative gas production rates were 0.66, 0.68, and 0.73 m^3/kg BVS added for digested sludge, activated sludge, and primary sludge, respectively. At these gas production rates, the corresponding removal efficiencies for biodegradable solids were 79, 82, and 85 percent, respectively. Typical reactor pH values for the three different sludge feedstocks were 6.96 for digested sludge, 7.0 for activated sludge, and 7.2 for primary sludge. Similarly, reactor alkalinity, representing the buffering capacity of the process, was found to be the highest with primary sludge as a commingled feedstock.

The slight difference in performance observed for the different types of sludge is due to the different physical, chemical, and biological characteristics of the sludges. For example, of the three sludges, digested sludge contains less readily biodegradable material. By comparison, primary sludge is comprised primarily of non-degraded organic solids. Overall, digester performance appears to increase with both the total solids and biodegradability of the sludges.

NUTRIENT REQUIREMENTS

The differing nutrient availability of the sludges may be the fundamental reason of the observed changes in reactor performance. Compared to the BOF/MSW, the sludge solids have high concentrations of a variety of mineral nutrients. Although these nutrients are required in only trace quantities in the digestion process, they are essential for healthy and sustained digestion. The feedstock with primary sludge had a greater proportion of nutrients due to the higher total solids concentrations. Additionally, the higher biodegradability of the primary sludge potentially allow the nutrients to be more readily available to the bacteria. The importance of a variety of nutrients was confirmed by the addition of nutrient supplements in the form of dairy manure and synthetic chemical solutions. Nutrients provided in the proper feedstock ratios enhanced the overall digestion process. In addition to nitrogen and phosphorus, potassium and nickel are the nutrients that appear to have the most pronounced effect on the overall performance of the digester.

HUMUS CHARACTERISTICS

The recently adopted U.S. Environmental Protection Agency sewage sludge use and disposal regulations: Chapter 40 Code of Federal Regulations Part 503 (1993) set national standards for sludge products that are land-applied, distributed or marketed. Part 503 contains limits for 10 metal pollutant concentrations, pathogen reduction requirements, and vector attraction reduction requirements. Based on elemental analyses of the sludges and of the humus produced with the sludges, it was found that both are below the EPA metal pollutant concentration limits. In fact, the humus material was significantly below the limits. The relatively low pollutant concentrations in the humus are due to the commingling of the sludge with the BOF/MSW. Typically, the pollutant concentrations in the humus are reduced to between 10 and 20 percent of the input WWTP sludge concentrations.

To detect the presence of any pathogens, the humus was tested for total coliform, fecal coliform, and streptococcus and enterococcus bacteria with a detection limit of 0 to 6 organisms/10 mL at a 95 percent confidence level. No pathogens were found in the humus. This finding was expected because both the anaerobic digestion and aerobic composting processes are operated in the thermophilic range (54 - 58 °C). As a result, this process would be considered a process to further reduce pathogens (PFRP), affording the humus material a Class A pathogen reduction designation. The residual humus produced with the high-solids anaerobic digestion process also meets the Part 503 vector attraction reduction requirement.

WASTE VOLUME REDUCTION

The anaerobic composting process was shown to achieve significant feedstock mass and volume reduction. As mentioned previously, the anaerobic digestion process, on average, converted 79 to 85 percent of the biodegradable organic material in the commingled feedstock to biogas. The aerobic biodrying process further degraded the digested solids, resulting in the final humus material containing less than 10 percent readily biodegradable solids. Additionally, the digested sludge was dewatered from about 25 to in excess of 65 percent total solids. It has been determined that the waste volume reduction relative to (1) dewatered sludge (at 51 percent total solids) layered on the top of well-compacted MSW, and (2) dewatered sludge (at 51 percent total solids) mixed with a well-compacted MSW in a landfill is on the order of 66 to 70 percent, respectively.

STUDY CONCLUSIONS

The co-digestion of WWTP sludge with BOF/MSW was successful for all of the sludges tested. The biodegradable material in the two substrates are converted to a biogas comprised of methane and carbon dioxide that may be used for the production of energy. Through the conversion of the biodegradable material and dewatering the residual humus, significant waste mass and volume reduction is accomplished. The residual humus material may be used as an environmentally safe, nutrient/mineral rich soil amendment, which meets the most stringent EPA application criteria. Based on the findings of this study the anaerobic co-composting process appears to be an attractive alternative to the disposal of MSW and wastewater sludge in landfills.

1
INTRODUCTION

In the United States today, the cost-effective handling and disposal of municipal solid waste (MSW) and wastewater treatment plant (WWTP) sludge present two distinct waste management philosophies. Until recently, conventional MSW management has focused on disposal, with little or no emphasis on preprocessing or resource recovery alternatives. Wastewater sludge management, in contrast, has involved extensive sludge treatment (stabilization, volume reductions) and beneficial-use practices (sludge composting, land application). Recent environmental concerns and increased waste disposal costs, however, have highlighted the shortcomings of the conventional management approaches for both MSW and wastewater sludge.

Waste management environmental concerns have been made explicit with the adoption of recent federal compliance regulations, effecting most conventional waste disposal practices (See Figure 1-1). Subtitle D of the Resource Recovery Act, effective October 9, 1993, imposes more stringent mandates on waste management sites. Its implementation is expected to force the closing of 22 percent of existing landfills in the United States, and require extensive upgrades to many more (Goldstein, et al. 1993). The updated Clean Air Act of 1990, as well as the more stringent state air pollution control standards, have forced retrofitting or closing of combustion facilities. Even land application, accounting for one-third of all sludge disposed, has been subject to new restrictions. In early 1993, the United States Environmental Protection Agency released 40 CFR Part 503: Standards for the Use and Disposal of Sewage Sludge. The ruling sets restrictions on the land application of sludges based on sludge pollutant concentrations, cumulative pollutant loading rates in the soil, pathogen exposure, and vector attraction potential. While this ruling was designed to foster the "beneficial use of biosolids" (EPA Part 503), sludge-based products not conforming to the rule may be required to utilize alternative management practices.

Increased waste management costs may be a direct consequence of these more stringent environmental regulations. Compliance problems will continue to increase tipping fees as municipalities are required to conduct expensive facility upgrades or forced to haul MSW and sludge cake longer distances to regional landfills or appropriate combustion facilities. At the same time, decreasing landfill capacity has resulted in sharp increases in landfill tipping fees. In some areas of New York, for example, landfill fees

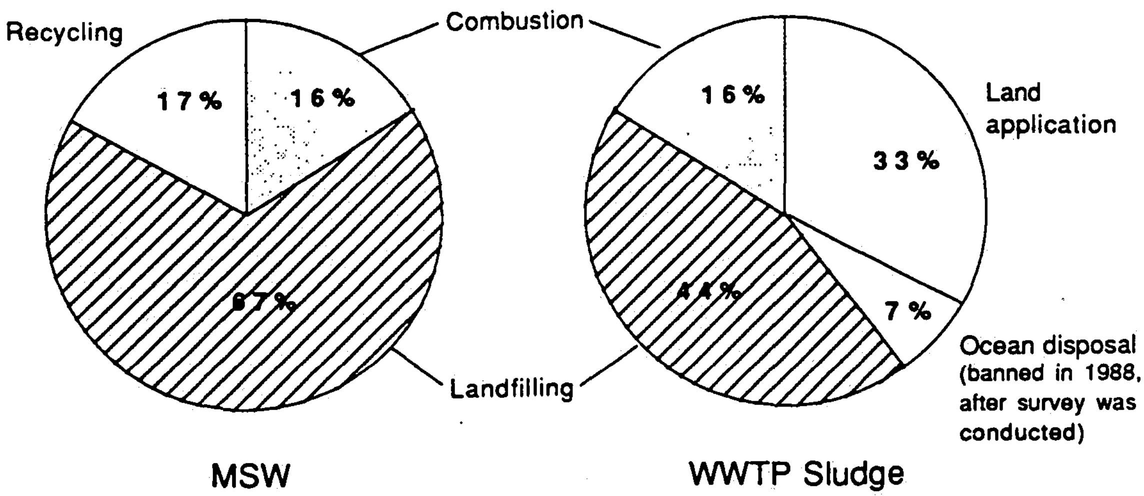

Figure 1-1
Summary of current U.S. disposal methods for MSW and wastewater sludges. Values based on the percentage of waste disposed (from EPA Part 530, 1992 and EPA Part 503,1993).

approach $100 per ton, three times the national average (Tchobanoglous, 1993). Ironically, the recent MSW recycling efforts may, in fact, force higher combustion costs, as the high BTU content plastic materials and paper products are diverted from the waste stream. Cost-effective wastewater sludge management will balance the costs of more effective and extensive sludge treatment against the increased costs and restrictions of disposal.

PURPOSE OF THE STUDY

Ever increasing waste management costs, coupled with renewed interests for resource recovery and environmentally safe management practices, have promoted interest in alternative waste management technologies . A combined high-solids anaerobic digestion and aerobic biodrying process, termed "anaerobic composting", appears to be a promising avenue for the co-management of MSW and wastewater treatment plant (WWTP) sludge. Anaerobic composting is a biological stabilization/volume reduction process, which uses the biodegradable organic fraction of MSW (BOF/MSW) as the primary substrate. Wastewater treatment plant sludge is commingled with the BOF/MSW to lower the solids content to appropriate levels for high-solids anaerobic digestion. The principal advantages associated with anaerobic composting include: (1) recovery of a biogas that can be used as a fuel for energy production, (2) the production of a humus material that can be used as a soil amendment or as boiler fuel, and (3) the elimination of a liquid waste stream that needs further treatment.

A pilot-scale project was undertaken at the University of California, Davis to evaluate the feasibility of the anaerobic composting process for the co-processing of the biodegradable fraction of MSW and WWTP sludges. The specific objectives of this study were:

1. To demonstrate the technical feasibility (proof-of-concept) of the high-solids anaerobic composting process for the co-digestion of BOF/MSW with various types of WWTP sludges. The sludges investigated included: (1) raw primary, (2) thickened waste activated, and (3) digested.

2. To evaluate performance of the process under various operating conditions. Emphasis was placed on steady-state operation and optimum gas production rates.

3. To assess the impact of wastewater sludges as nutrient supplements, and then characterize the nutritional requirements for high-solids anaerobic digestion of BOF/MSW.

4. To evaluate the characteristics of the final humus material.

5. To assess the anaerobic composting process for waste volume reduction.

ACKNOWLEDGMENTS

This study was conducted under a contract with the California Integrated Waste Management Board. Funds were also given by the California Prison Industry Authority (PIA), West County Wastewater District, West County Agency, Richmond Sanitary Service, and Delta Diablo Sanitation District. The continued support of these organizations for this study and other related works are greatly acknowledged.

Thanks to the staff of West County Wastewater District for hauling the sludge from the City of Richmond, California to the University of California at Davis. Thanks also to the staff from UC Davis Animal Science Department for the preparation of autoclaved dairy manure. We thank Dr. Calvert from Animal Science for conducting the fiber analyses. We also acknowledge the effort of the DANR staff for the elemental analyses of the feedstocks and humus materials. The pilot anaerobic and aerobic units were designed and constructed by the Microgen Corporation under the direction of Professor Bill Jewell of Cornell University.

2
LITERATURE REVIEW

The following topics are reviewed in this chapter: (1) the anaerobic digestion process, (2) nutrient requirements of anaerobic digestion, (3) anaerobic digestion of wastewater sludges, (4) anaerobic digestion of MSW, and (5) anaerobic co-digestion of MSW and wastewater treatment plant sludges.

THE ANAEROBIC DIGESTION PROCESS

Anaerobic digestion is a biological process in which organic waste is converted to biogas and other stable end-products. A generalized scheme for the anaerobic digestion process is shown in Figure 2-1. Anaerobic digestion is generally considered to take place in three distinct stages. The three stages have been described as (1) hydrolysis, (2) acidogenesis, and (3) methanogenesis. Each of the three stages has distinct bacterial groups and chemical reactions, and proceeds in an assembly-line fashion (Holland et al., 1987).

As depicted in Figure 2-1, the overall process begins with the hydrolysis of complex organic compounds into soluble components. Next, the acid-forming bacteria ferment the soluble components to a group of extracellular intermediates including various volatile fatty acids (VFAs), H_2, and CO_2. The concentrations of these intermediate acids are usually small in proportion to their production and degradation rates, and quickly give rise to methanogenic substrates including acetate, methanol, and formate. These products are then converted to methane by the methanogenic bacteria.

Of particular importance is the fact that the methanogenic bacteria are especially sensitive to accumulation of fermentation products, such as excess VFA, H_2, or ammonia concentrations. The acetogenic bacteria, however, are fairly resilient and tolerant of such increases and continue to produce soluble products; potentially further inhibiting methanogenesis. As a result, the conversion of volatile acids by the methanogens is considered to be the rate-limiting step in most digestion processes.

The biogas produced from the healthy anaerobic digestion of an organic substrate consists primarily of methane (CH_4) and carbon dioxide (CO_2). Other gases such as hydrogen sulfide (H_2S), hydrogen (H_2), and nitrogen (N_2) may also be produced in trace amounts. The gases produced from the anaerobic digestion process are collectively called "biogas". Biogas typically has a thermal energy value between

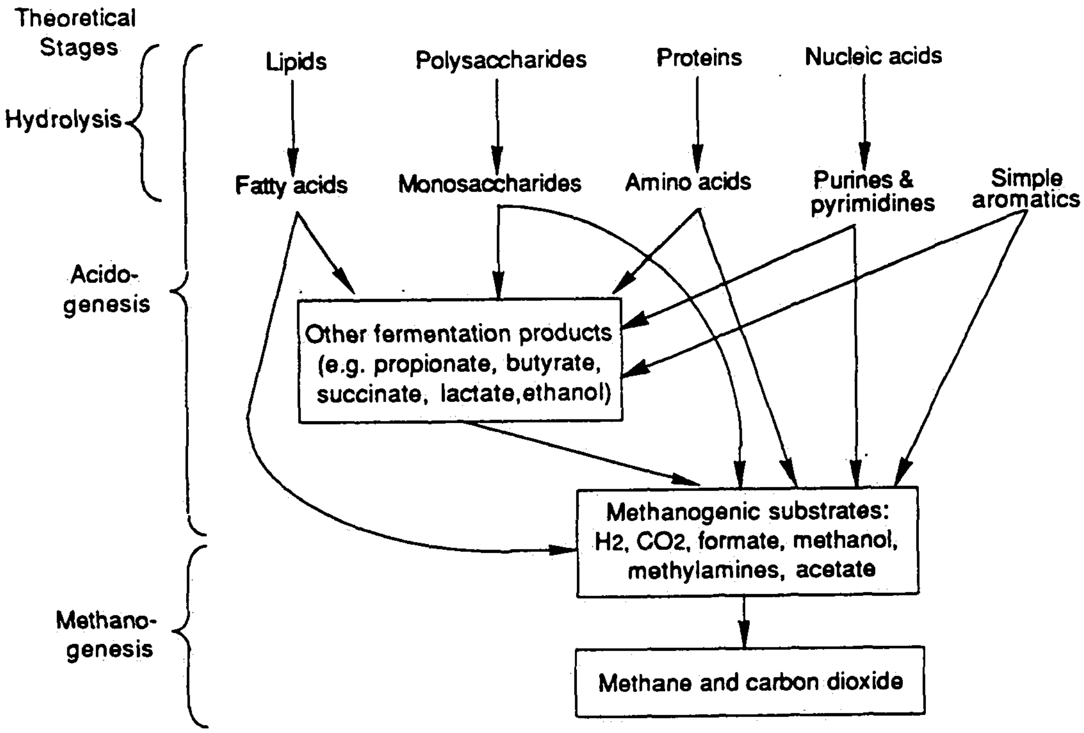

Figure 2-1
Stages of Anaerobic Digestion (from Holland, et al., 1987)

500-600 Btu/ft^3 (18.6-22.4 MJ/m^3), depending on the methane content. Natural gas, by comparison, has an energy value of around 1000 Btu/ft^3 (37.3 MJ/m^3).

NUTRIENT REQUIREMENTS FOR ANAEROBIC DIGESTION

Because anaerobic digestion has been primarily used in the treatment of wastewater sludges, which are typically rich in a variety of essential metal nutrients, nutrient requirements for anaerobic digestion have often been overlooked. However, as the digestion process is applied to alternative feedstocks (i.e. agricultural, industrial, and municipal solid wastes), feedstock nutrient availability becomes an important aspect of the total digestion process (Rivard et al., 1989).

The methanogenic bacterial nutrient requirements can generally be categorized into macro or micro-nutrient requirements. The macro-nutrients include carbon, nitrogen, phosphorus, potassium, and sulfur. The micro-nutrients include cobalt, copper, iron, molybdenum, nickel, selenium, tungsten, and zinc. The importance of macro and micro-nutrients for stable anaerobic digestion is well documented in the literature and is summarized in Tables 2-1 and 2-2, respectively.

Table 2-1
Functions of macro-nutrients in anaerobic digestion[a]

Nutrient	Functions	Ref.	Remarks
Carbon, C	Energy, cell material	1, 2	Carbon is the basic building block of bacterial cell material and is the primary source of energy. Because organic substrates are carbon-rich, carbon requirements will generally not be a limiting nutrient. Instead, the ratios of carbon to nitrogen (C/N), phosphorus (C/P), and potassium (C/K), may define the nutritional requirements.
Nitrogen, N	Protein synthesis	1, 2	Nitrogen is the primary nutrient required for microbial synthesis. Nitrogen occurs in the cell material in the reduced-form as amino nitrogen ($R\text{-}NH_2$). Amino-nitrogen is essential for the synthesis of proteins [2].
Phosphorus, P	Nucleic acid synthesis	1, 2	Phosphorus requirements for bacterial synthesis are generally much less than that of nitrogen or carbon. Phosphorus aids in the synthesis of nucleic acids [2].
Potassium, K	Cell wall permeability	1, 2	Potassium increases cell wall permeability by aiding the cellular transport of nutrients and providing cation balancing [2].
Sulfur, S	Numerous enzymes.	3, 4, 5, 6, 7	Sulfur requirement for methangens is quite complex because methanogens may use only certain forms of sulfur and there are numerous sinks for sulfur in the anaerobic digestion process. Generally, sulfur will take the non-reduced-form of sulfates or the reduced-form of sulfides. Sulfates may inhibit methanogenesis because methanogens can use only a fully reduced form of sulfur and sulfate reduction is considered rate-limiting. The sulfide form of sulfur, however, has been shown to have stimulatory growth effects for various methanogens. [4, 5, 6, 7]. Sulfide is required in numerous enzymes including carbon monoxide dehydrogenase (CODH) and formate dehydrogenase (FDH). The sulfur sinks include hydrogen sulfide (H_2S) gas production and precipitation of sulfides by heavy metals. Consequently, as bacterial activity and gas production rates increase, essential sulfides may be stripped from solution. Similarly, essential heavy metals (described below) may also be removed from bacterial contact by sulfide precipitation [3].

[a] Adapted, in part, from Ref. 1.
References: 1. Takashima et al., 1990; 2. Wang et al., 1984; 3. Speece et al., 1987; 4. Speece et al., 1964; 5. Bryant et al., 1971; 6. Wolfe et al., 1977; 7. Zehnder et al., 1977.

Table 2-2
Functions of micro-nutrients in anaerobic digestion[a]

Nutrient	Functions	Ref.	Remarks
Cobalt, Co	Corrinoids, CODH[b]	8, 9	Cobalt is present in specific enzymes and corrinoids. The common enzyme carbon onoxide dehydrogenase (CODH) uses cobalt [9]. CODH plays an essential role in acetogenic (acetate-forming) activity.
Copper, Cu	SODM[c], hydrogenase	8, 10	Copper has been found in the analysis of many methanogenic bacteria strands. Copper may be a component in super dismutase (SODH) and hydrogenase [10]. However, copper addition has not been found to have any noticeable stimulatory effects [1].
Iron, Fe	CODH, precips. sulfides	8, 11	Iron has been found to be present in methanogenic tissue in concentrations higher than that of any other heavy metal. Iron plays numerous roles in anaerobic processes, primarily due to its extremely large reduction capacity. Iron is found in, and helps activate, numerous enzymes. In addition, iron may form sulfide precipitates and may promote excretion of extracellular polymers [8].
Molybdenum, Mo	FDH[d], inhibits sulfur reducers	8, 12	Molybdenum is present in the common enzyme formate dehydrogenase (FDH). However, molybdenum may also inhibit sulfate reducing bacteria, limiting the formation of necessary sulfides [12].
Nickel, Ni	CODH, synthesis of F_{430}.essential for sulfate reducing bacteria, aids CO_2/H_2 conv.	8, 9, 13, 14, 15	Many anaerobic bacteria are dependent on nickel when carbon dioxide (CO_2) and hydrogen (H_2) are the sole sources of energy. Most nickel is taken up by cells in a compound named F Factor 430 (F_{430}). F_{430} has been found in every methanogenic bacterium ever examined. In addition, CODH is a nickel protein and may aid sulfur-reducing bacteria [9, 13].
Selenium, Se	Fatty acid metabolism, FDH	8, 16	Selenium is a component of several anaerobic bacterial enzymes and certain bacterial nucleic acids. A common selenium enzyme in anaerobic bacteria is formate dehydrogenase (FDH). Selenium-dependent enzymes tend to be very reactive at neutral pH, have a low redox potential, and may help metabolize fatty acids. The catalysts which contain selenium are synthesized when selenium is present at extremely low concentrations [16].

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Table 2-2, Continued from previous page

Nutrient	Functions	Ref.	Remarks
Tungsten, W	FDH, may aid conv. of CO_2/H_2 substrates	1, 17	Tungsten is also a component of the FDH enzyme. It is possible that tungsten may aid the metabolism of CO_2 and H_2, in a manner similar to nickel [17]. Limited studies have been conducted on the effect of tungsten supplementation.
Zinc, Zn	FDH, CODH, hydrogenase	8, 10	Zinc, like copper, is present in relatively large concentrations in many methanogens. It may be part of FDH, SODM, and hydrogenase. Zinc has not yet proven to be an essential metal [1].

[a] Adapted, in part, from Refs. 1 and 8.
[b] CODH = the enzyme carbon monoxide dehydrogenase.
[c] SODM = the enzyme super dismutase.
[d] FDH = the enzyme formate dehydrogenase.
References: 1. Takashima et al., 1990; 2. Wang et al., 1984; 8. Oleszkiewicz et al., 1990; 9. Schonheit et al., 1979; 10. Kirby et al., 1981; 11. Brock et al., 1984; 12. Schauer et al., 1982; 13. Thauer et al., 1980; 14. Hausinger, 1987; 15. Diekert et al., 1981; 16. Stadtmann, 1980; 17. Zellner et al., 1987.

For proper bacterial metabolism and stable anaerobic digestion, these nutrients must be present in the substrate in the correct ratios and concentrations. As shown in Table 2-3, nutrients have been supplemented to a variety of substrates to stimulate the digestion process. The variances in nutrient concentrations required are a reflection of the different primary substrate's nutrient content.

ANAEROBIC DIGESTION OF WASTEWATER SLUDGES

Anaerobic digestion is currently utilized at most major municipal wastewater treatment plants. A conventional activated sludge treatment flow diagram is shown in Figure 2-2. As shown, both the primary and secondary sludges may be anaerobically digested before further dewatering and disposal. Generally anaerobic digestion is utilized to: (1) reduce solids for ultimate disposal, (2) improve dewaterability, (3) reduce putrescibility, (4) generate methane for in-plant use, and (5) reduce pathogenic organisms in the sludge. However, due to the high level of water present, conventional anaerobic digestion requires substantial energy inputs per reactor volume.

ANAEROBIC DIGESTION OF MSW

Anaerobic digestion may also be applied to the biodegradable organic fraction of municipal solid waste (BOF/MSW). As shown in Figure 2-3, the BOF/MSW is comprised principally of paper products, yard waste, and food waste. These components comprise a significant portion of a typical MSW waste stream (68%), which may be available for biological degradation.

Of recent interest is the application of MSW digestion in a controlled high-solids process. High-solids anaerobic digestion has been loosely defined as digestion at solids concentrations between 22 - 30 percent (Kayhanian et al., 1991a,b). Digestion at high-solids concentrations requires smaller reactor volumes, thus lowering the capital costs for heating and mixing the contents of the reactor, as well as decreasing residue dewatering and disposal costs. High-solids digestion of MSW also permits stable digestion at four to six times the organic loading rates that can be maintained with comparable low-solids (2 to 8 percent) anaerobic practices (Rivard, 1993). Rivard et al. (1993) noted that digestion of MSW appears to be more efficient at high-solids compared to low-solids concentrations due to the increased contact of the substrate with hydrolytic enzymes.

Table 2-3
List of reported stimulatory ranges of nutrients for the anaerobic treatment of various substrates.

	Range of nutrient concentration added, mg/kg					
Substrate	Co	Fe	Mo	Ni	Se	Ref.
Dairy manure	1.7-8.3	6.9-34.4		4.2-6.2		1,2,3
Poultry waste				0.6-6.0		1,4
Cellulose		22-34				1,5
Whey	15	0.15-30		1.3-30		1,6,7
Biomass	0.19		0.3	0.25	0.062	1,8
Various food processing wastewaters	0.4-2.5	6-120	4.8	1.4-6		1,9,10,11

1. Takashima et al., 1990; 2. Wodzinski,1982; 3. Dar et al.,1987; 4. Williams et al., 1986; 5. Khan et al., 1979; 6. Kelly et al., 1984; 7. Canovas-Diaz et al., 1986; 8. Wilkie et al., 1986; 9. Murray, et al., 1981; 10. Hoban et al., 1979; 11. Kida et al., 1991

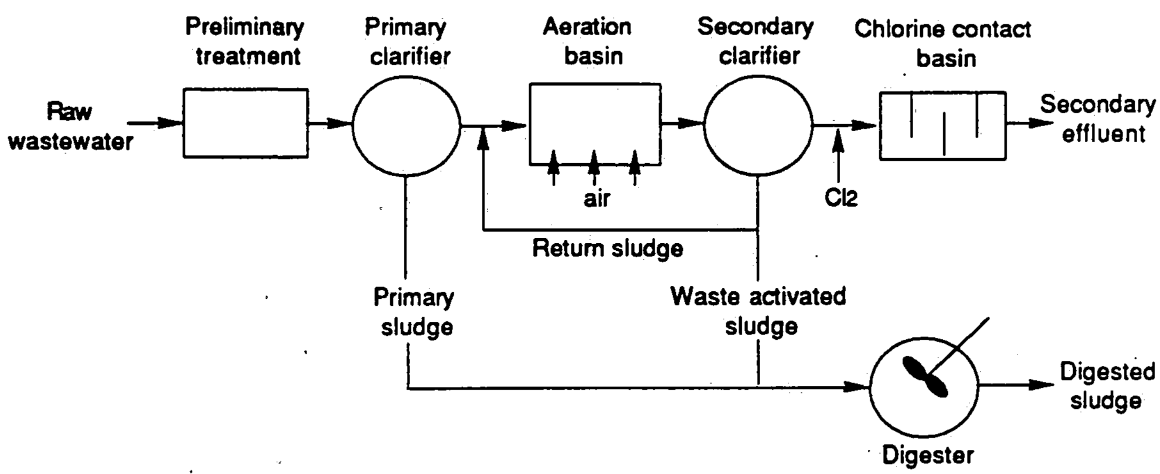

Figure 2-2
A typical treatment flow diagram for a conventional activated sludge process

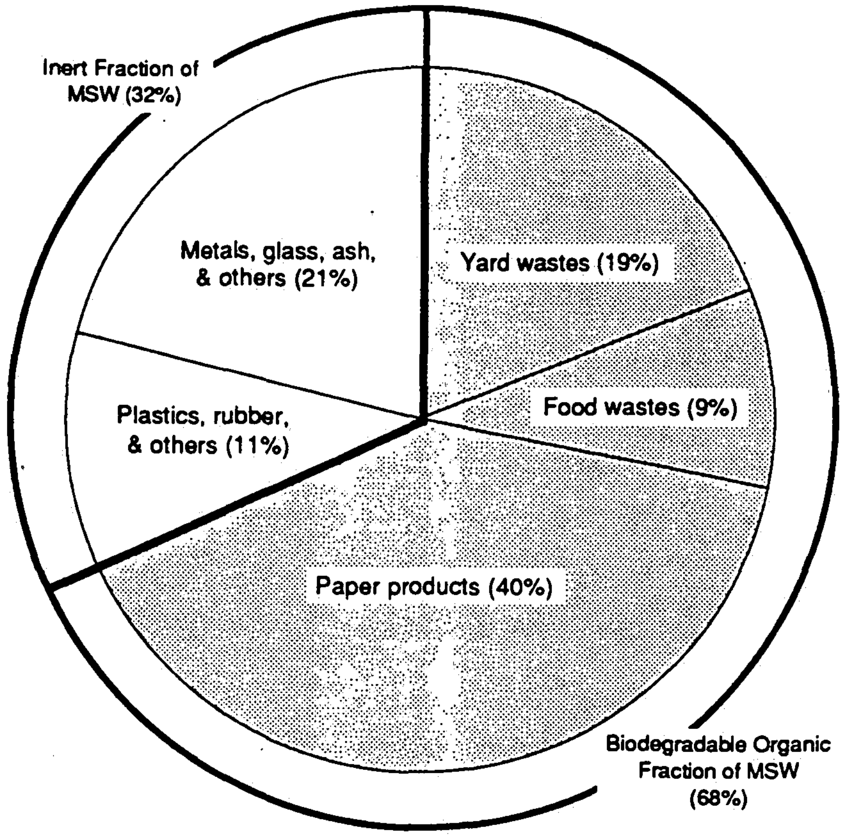

Figure 2-3
Typical distribution (percent by wet weight) of MSW.
Values obtained from Tchobanoglous et al. (1993)

Typical MSW, however, is deficient in many essential nutrients with respect to bacterial growth (Pfeffer et al. 1976, Rivard et al., 1990, Kayhanian et al., 1991b). Mah et al. (1980) confirmed the need for nutrient supplementation in the low-solids anaerobic digestion of a highly processed MSW. Their results indicated that the addition nutrients in the form of raw wastewater sludge could enhance gas production rates as well as provide a more stable process. Recent studies by Rivard, et al., (1990) indicate that the addition of chemical nutrient solutions or digested sludge stabilizes the digestion of highly processed MSW in a high-solids anaerobic digestion process. Overall, it appears that nutrient supplementation is essential for the stable digestion of MSW. It would, therefore, be advantageous to co-digest MSW and wastewater sludge, as described below.

ANAEROBIC CO-DIGESTION OF MSW AND WASTEWATER SLUDGES

Poggi-Varalado et al. (1992) noted that wastewater sludge may benefit the digestion of MSW in three ways: (1) the sludge enriches the solid waste with nitrogen and phosphorus, (2) the sludge improves the buffering capacity of the digestion by providing extra alkalinity, and (3) the sludge may provide bacterial seed to the process. A summary of past co-digestion of MSW and wastewater sludge studies is reported in Table 2-4. As shown, a variety of MSW preprocessing and digestion schemes have been employed in the co-digestion of MSW and wastewater sludges. Three aspects of the past studies , however, are of particular importance.

First, sludge appears to be essential in the sustained digestion of MSW. The series of experiments conducted for Cal Recovery Inc. (Diaz, et al. 1978, Mah et al. 1978, Stenstrom et al. 1981) found that an 80 percent MSW, 20 percent sludge (VS basis) feedstock mixture allowed optimum organic loading rates and a sufficiently stable process. Mah et al (1980) also added varying amounts of feedlot waste and found that optimum digestion was attained at a feedstock ratio of 0.7/0.14/0.7 (MSW/ sludge/ feedlot waste). Other studies (Cecchi et al. 1988b, Rivard et al. 1990, Poggi-Varaldo et al. 1992) confirmed the stabilizing effect of sludge, with sludge doses between 8 and 20 percent of the feedstock VS. These results are in direct contrast to those reported by Cecchi et al (1988a). In this pilot-scale study it was found that an almost linear decrease of the organic matter removal efficiency occured with an increase in sludge percentage (TS basis). It is possible that the sludge used in the study contained heavy metals or other constituents toxic to anaerobic bacteria.

Second, only the studies by Rivard et al. (1990) and Poggi-Varaldo et al. (1992) utilized high-solids (in excess of 20 percent TS) digestion. All other studies described in Table 2-4 were conducted at lower solids contents (typically between 4 to 10 percent TS). Low-solids processes are much less susceptible to process upsets, such as VFA buildup or ammonia toxicity, due to the buffering provided by the water, but lack the numerous advantages of high-solids processes described previously. For instance, in the studies by Rivard and by Poggi-Valardo, sustained digestion was achieved at relatively high organic loading rates (typically around 5 g $VS/m^3 \cdot d$). These high-solids studies, however, have been limited to laboratory-scale experimentation.

Finally, the various fractions and forms of MSW digested highlight the fact that MSW is, by nature, a highly heterogeneous material, which varies with respect to season and location. Each study shown in Table 2-4, in essence, utilized a different feedstock; and comparisons between the experiments are difficult to make. As a result, monitoring the digestion process based on volatile solids fed or destroyed is only partially descriptive in assessing MSW digestion performance. Feedstock biodegradability and nutrient availability, parameters typically ignored in the conventional digestion of wastewater sludge, become important factors in estimating solids conversion or in assessing feedstock suitability.

Table 2-4
Summary of past co-digestion of MSW and WWTP sludge studies.

MSW preprocessing	MSW/sludge ratio[a]	Exp. scale	Temp, °C	OLR, gVS/m³•d	RT, d	Mixing type	Gas Conv., m³/kgVS add	% CH_4	% RE[b]	Period of operation	Ref.
Shredded[c]	50/50	1500 L	35	1.23	30	Recirc-ulation	0.44	55-60	64.5	18 wk	McFarland et al.,1972
Screened, air-classified, dry milled[c]	20/80	9 L	35	1.0-1.1	30	Mech. stirrer	0.47,0.49		51.4,44.3	14,22 d	Diaz et al., 1974
Handsorted, shredded[c]		380 L	60	5.2	10	Mech. paddle	0.39,0.31	53	57	3, 7, 25 mo	Brown, et al., 1976
Fiberized RDF[c,d]	80/20	400 L	35	1.6-3.2		Mech., variable spds.	0.36	59	50.5	123 d	Ghosh et al., 1977
Shredded, cycloned	75/25	380 m³	35	1.28		Recirc-ulation	0.59	72	7.5	75 d	Swartzbaugh et al., 1977
Shredded, air-class., trommeled,screened[c]	(40-100)/(60-0)	3.8 L	35	6.4	30	Mech. stirrer, 4x/day	0.51-0.34	55-60	35-77	14 d	Diaz et al., 1978
Shredded, air-class. trommeled,screened[c]	(20-60)/(80-40)	1600 L	35	1.12	30	Recirc-ulation	0.39-0.75	60-63	64	24 d	Diaz et al., 1978
Shredded, air-class., trommeled (2x)	(90-60)/(10-40)[e]	3.8 L	37	1.28, 5.6	15, 10	Mech. stirrer, 1x/15 min	0.51-0.61, 0.64	61-63		140 d	Mah et al., 1980
Shredded, air-class., trommeled (2x)	80/20	190 L	37	1.6-4.0	15-30	Mech. stirrer	0.41-0.47	55-60			Stenstrom et al., 1981
RDF	94/6[f]	4540 L	35	3.2	16	Recirc-lation	0.27	60	37	5 wk	Biljetina 1987

Continued on following page

Table 2-4, Continued from previous page

MSW preprocessing	MSW/sludge ratio[a]	Exp. scale	Temp, °C	OLR, gVS/m^3·d	RT, d	Mixing type	Gas conv., m^3/kg VS add	% CH_4	% RE[b]	Period of operation	Ref.
Shredded OFMSW	(0-89)/ (100-11)[g]	2800 L	35	1.76-3.85	14-15	Mech. stirrer	0.09-0.20		20-72		Cecchi et al., 1988a
Shredded OFMSW	(0-100)/ (100-0)[g]	3500 L	35	1.28-2.08	14-15	Mech. stirrer	0.05-0.13		40-68		Cecchi et al., 1988a
Shredded OFMSW[h]	80/20[i]	2195 L	35	3.84	14	Mech. paddle	0.47	61	70-75		Cecchi et al.,1988b
Sorted OFMSW	85/15[i]	20 m^3	40	2.56	19	Mech., grid rotated	0.43	53	41		Cecchi et al.,1988b
Highly processed RDF[j]	83/17[k]	3.5 L	37	3.2-9.6	14,20, 30	Mech. low speed	0.45-0.52	64-69	60, 67, 81	12 wk	Rivard et al.,1990
Shredded OFMSW[l]	92/8	3.0 L	39,53	4.32, 4.49-4.96	21	Manual shaking	0.48, 0.69-0.93[m]		44, 53	16 wk	Poggi-Varaldo et al., 1992

Notes:

[a] Volatile solids basis. Raw primary sludge used unless otherwise noted.
[b] RE = Removal efficiency. Volatile solids basis.
[c] As cited from Strenstom (1981).
[d] RDF = Refuse derived fuel. MSW has been shredded, air classified, cycloned, stoned, and screened prior to fiberizing.
[e] Feedlot waste also added in various ratios. Optimum digestion at 0.7/0.14/0.7 (MSW/sludge/feedlot waste).
[f] Nutrient solution also added.
[g] Enhanced digester performance with lower sludge feeds.
[h] OFMSW = Organic fraction of MSW, 50% green waste, 50% food waste.
[i] TS basis.
[j] MSW has been sorted, shredded, dried, densified, and pelletized.
[k] Digested sludge used.
[l] Simulated OFMSW, 89% newsprint, 11 % food waste (TS basis).
[m] Calculated from methane production data. 60% methane assumed.

As a consequence of these past studies, this investigation will attempt to develop a more comprehensive understanding of the co-digestion of MSW and wastewater sludges as a waste management practice. Specifically, this study will: (1) show proof of concept on a pilot-scale, (2) optimize organic loading rates and reactor total solids concentrations, (3) identify the effects of various types of wastewater sludges on high-solids digestion of BOF/MSW, and (4) characterize the feedstock by more meaningful parameters which would apply to any fraction of MSW utilized.

3
METHODS AND MATERIALS

The methods and materials used in the investigation of anaerobic co-digestion of BOF/MSW and WWTP sludges are discussed in this chapter.

METHODS

The experimental methods used in the investigation include: (1) analytical techniques to monitor the anaerobic digestion process, (2) analytical techniques to monitor input feedstocks and final humus product, (3) computational techniques to monitor the operation and performance of the process, (4) laboratory batch digestion study experimental procedure, and (5) pilot study experimental procedure.

Analytical Techniques To Monitor The Anaerobic Digestion Process

All analytical procedures were performed in accordance with *Standard Methods for Water and Wastewater, 17th Edition (1989)*. The analytical measurements included physical measurements: total solids (TS), volatile solids (VS), biogas volume, temperature, and reactor mass; and chemical measurements: pH, ammonia-nitrogen, alkalinity, and volatile fatty acids (VFA). The analytical procedures are described below.

Total Solids and Volatile Solids

The method for solid and semisolid samples (§2540 G) was used to determine TS and VS concentrations. Clean evaporative dishes were ignited at 550 ± 50 °C for at least one hour in a muffle furnace and cooled and stored in a desiccator until weighed. Samples of 100 to 150 g were then placed in an oven at 103 to 105 °C overnight, cooled to balance temperature in a desiccator, and weighed for total solids. The dry samples were then transferred to a cool muffle furnace and ignited at 550±50 °C for at least one hour. Samples were then cooled in a desiccator and weighed for volatile solids.

Biogas Volume

Daily biogas volume was determined using a specially modified GCA/Precision Scientific wet test gas meter. The average daily biogas temperature was measured at the gas meter so that the volume of the biogas could be adjusted to dry biogas volume (excluding water vapor) at standard temperature and pressure (1 atm at 0 °C) using the perfect gas law.

Reactor Mass

Reactor mass was determined using a mechanical beam balance. The balance is a full capacity mechanical scale equipped with a two bar beam with an accuracy of 1/10 of 1 percent.

Reactor pH

Reactor pH was determined using a Fisher Scientific Accumet Model 955 portable pH/mV Temperature Meter. The sensitivity of the meter was 0.01 pH units. The meter was calibrated to the temperature of the sample (55 °C).

Ammonia Nitrogen

Ammonia-nitrogen concentrations were measured using the titrametric method (§4500-NH_3 E). Small amounts of sample (2-4 g wet) were weighed and diluted to 250 mL with distilled water. Then 25 mL of borate buffer solution was added to each sample and the pH was adjusted to greater than 9.5 using 6*N* sodium hydroxide (NaOH). Samples were then distilled (Buchi 323 distillation unit) until approximately 200 mL of distillate was collected in a 500 mL erlenmeyer flask containing 50 mL of indicating boric acid solution. The ammonia in the distillate was then titrated with 0.14N sulfuric acid (H_2SO_4).

Alkalinity

Alkalinity was measured using a double titration method described by Anderson et al (1992). Samples were centrifuged for 5 minutes and 20 mL of supernatant was collected in a 100 mL beaker. Supernatant was then titrated with 0.18 N sulfuric acid (H_2SO_4) to pH 5.1 and then to pH 4.5. The double titration allows an estimation of the bicarbonate fraction of the alkalinity (to pH 5.1), without interferences from volatile fatty acids.

Volatile Fatty Acids

Volatile fatty acids (VFAs) were measured using the distillation method (§5560 C). Samples were centrifuged for 5 minutes and 25 mL of supernatant was placed in a 500 mL distillation flask. Supernatant samples were then added 175 mL distilled water and 5 mL of 1*N* sulfuric acid (H_2SO_4). Flasks were connected to a condenser apparatus and distilled at a rate of 5 mL/min. The first 15 ml of distillate was discarded. Exactly 100 mL of distillate was collected and titrated with 0.19 *N* sodium hydroxide (NaOH). The recovery factor was determined using an 8,000 mg/L acetic acid stock solution.

The distillation method for VFA determination was utilized because the test is relatively fast and easy. However, the test gave values typically twice those measured by the more precise Isothermal GLC Method. Accordingly, only relative comparisons of the VFA values given in this report can be made.

Analytical Techniques To Monitor Input Feedstock and Humus Material

Analytical techniques used to monitor input feedstock and the final humus material included: elemental analysis, and fiber analysis. Elemental analysis was determined by atomic adsorption and the induced plasma method (§3120 B). Fiber analysis was determined by a method developed by Georing and Van Soest (1970). The fiber material was classified into cellulose, hemicellulose, and lignin. Additionally, feedstock TS, VS, alkalinity, and ammonia concentrations were determined, as described above.

Computational Techniques to Monitor the Operation and Performance of the Process

A number of computational techniques have been employed to monitor the operation and performance of a high-solids digestion process. The computed parameters include: biodegradable volatile solid (BVS), feedstock C/N ratio, organic loading rate, dry gas production rate, and solids removal rate and efficiency.

Biodegradable Volatile Solid

In conventional anaerobic digestion processes, process performance is gauged on a volatile solids basis. However, the use of VS in describing the organic fraction of MSW is misleading, as some of the components (e.g. newsprint, plastics) are highly volatile but low in biodegradability (Kayhanian et al., 1991a). Therefore, a more meaningful parameter for determining organic loading rates and process efficiencies would be based on the biodegradable fraction of the substrate.

Feedstock biodegradability can be determined in a number of ways including the conducting of batch digestion studies and using the lignin content of the material. In the batch digestion studies, the percentage of feedstock volatile solids destroyed is calculated from the change in reactor weight at the end of the digestion period. Biodegradability may also be estimated from the lignin content of the material. Lignin is generally considered non-degradable and appears to provide both a chemical and physical barrier to bacterial enzymes that can attack isolated cellulose. Chandler et al. (1981) developed an empirical estimate of a substrate's biodegradability based on lignin content:

$$BF = 0.83 - 0.028 \times LC \qquad [3\text{-}1]$$

where BF = Biodegradable fraction expressed on a volatile solids (VS) basis;
LC = Lignin content of the volatile solids expressed as a percent of the dry weight of the volatile solids.

C/N Ratio

Customarily, the C/N ratio is determined based on the total dry mass of the organic matter and the corresponding percentage concentrations of carbon and nitrogen. This commonly used method of determining the C/N ratio may not be appropriate for the organic fraction of MSW because not all of the organic carbon is biodegradable and/or available for biological decomposition. However, it appears that almost all of the nitrogen in the organic material is available for conversion to ammonia via microbial metabolism. Because the available nitrogen in the organic feedstock can be converted to ammonia, the C/N ratio should be computed using the following expression (Kayhanian et al., 1992):

$$C/N \text{ ratio} = \frac{BCM}{TNM} \qquad [3\text{-}2]$$

where BCM = biodegradable carbon mass
TNM = Total available nitrogen mass

Organic Loading Rate

As described previously, a more meaningful expression for describing the material which actually is available for biodegradation would be based on the BVS fraction of the substrate. Therefore, the organic loading rate (OLR) is computed using the following expression:

$$OLR = \frac{\text{g BVS fed}}{\text{kg active reactor mass} \cdot \text{day}} \qquad [3\text{-}3]$$

Gas Production Rate

The gas production rate (GPR) may be expressed based on the volume of gas produced per active reactor volume or based on the volume of gas produced per mass of BVS added. The gas volume expressed in Eqs. [3-4] and [3-5] are based on gas at dry and standard conditions.

$$GPR = \frac{\text{volume of gas produced}}{\text{active reactor volume} \cdot \text{day}} \qquad [3\text{-}4]$$

$$GPR = \frac{\text{volume of gas produced,m}^3}{\text{kg BVS added} \cdot \text{day}} \quad [3\text{-}5]$$

Solids Removal Rate and Efficiency

The solids removal rate and efficiency is computed based on the mass of biogas produced from the conversion of the biodegradable organic waste. In anaerobic treatment, the mass of gas formed is larger than the mass of the organic substrate involved in the process due to the consumption of water during digestion (Richards et al., 1991; Kayhanian et al., 1991b). Because of the water requirement, the actual BVS mass removed is some fraction, f, of the measured biogas mass as given by Eq. [3-6].

$$\text{BVS mass} = f\,(M_{biogas}) \quad [3\text{-}6]$$

where f = correction factor for water uptake (less than or equal to one)

M_{biogas} = mass of dry biogas produced at standard conditions, kg

The value of f normally ranges from 0.7 to 1, and depends largely on the nature of organic substrate (e.g., f = 1 for glucose). The f factor for the feedstock used in this study was found to be, on average, 0.84, using the method described by Richards et al. (1991). Using this correction factor and knowing the dry biogas volume and the biogas density at STP, the BVS removal rate can be determined. The BVS mass removal (MR) rate and removal rate efficiency (RE) can be calculated using the following formulas:

$$\text{BVS MR rate} = \frac{\text{g BVS removed}}{\text{kg active reactor mass} \cdot \text{day}} \quad [3\text{-}7]$$

$$\text{BVS RE} = \frac{\text{kg BVS removed}}{\text{kg BVS fed}} \cdot 100 \quad [3\text{-}8]$$

Laboratory Batch Digestion Study Experimental Procedure

A laboratory-scale batch study was conducted to determine the effect of varying concentrations of digested sludge on the high-solids digestion of BOF/MSW. In the experiment, the proportion of BOF/MSW to inoculum were combined at an approximate ratio of 1 to 1.5 (BOF/MSW to inoculum) in each of 6 reactors. Digested sludge was added to each reactor in varying doses: 0, 10, 20, 30, 40, and 50 percent by wet weight (0, 2.5, 4.9, 7.1, 9.3, and 11.3 percent by dry weight). Sodium bicarbonate was added to each reactor to adjust the pH to approximately 7.2. After each reactor was filled with material, nitrogen gas was used to purge the reactors of oxygen. The reactors were promptly sealed and weighed on an electric scale accurate to the nearest 1/10 gram. Control samples of only digested sludge and only inoculum (effluent) were also prepared in a similar fashion. A summary of the contents of each reactor are presented in Table 3-1. The eight reactors were immersed in the water bath and periodically removed, weighed, and shaken through the 20 day digestion period.

Pilot Study Experimental Procedure

The pilot-scale investigation may be divided into an evaluation of the high-solids digestion process and an evaluation of the humus material produced after aerobic biodrying. The digestion experiments may be further categorized into an evaluation of the co-digestion of BOF/MSW and various WWTP sludges and an assessment of the nutritional requirements for high-solids digestion of BOF/MSW. The time organization for the investigation is summarized in Table 3-2. The experimental procedures are described below:

Co-digestion of BOF/MSW and WWTP Sludges

The pilot investigation of the co-digestion of BOF/MSW and WWTP sludges may be divided into three -three month study periods: (1) anaerobic digestion of BOF/MSW and digested sludge, (2) anaerobic digestion of BOF/MSW and thickened activated sludge, and (3) anaerobic digestion of BOF/MSW and primary sludge. It is important to note that the digester was operated at a 30 day mass retention time, allowing digestion of each feedstock type to proceed for three 30 day retention times. The three month periods were spent determining the limits of digestion performance as well as establishing steady-

Table 3-1
Contents of batch digesters

	Percent (dry basis)		
Reactor	BOF/MSW	Inoculum	Digested Sludge
1	40.0	60.0	0
2	38.3	59.2	2.5
3	37.3	57.8	4.9
4	36.5	56.4	7.1
5	35.6	56.4	9.3
6	34.8	53.9	11.3
7	0	0	100
8	0	100	0

Table 3-2
Summary of the time organization for the UC Davis pilot investigations

Process investigation	Investigation period, days	
	From day	To day
Co-digestion study		
BOF/MSW and digested sludge	1	89
BOF/MSW and activated sludge	90	179
BOF/MSW and primary sludge	180	269
Nutrient study	270	360
Evaluation of the humus material	1	270

state operation. The organic loading rate was maintained between 6.0 and 7.2 grams of BVS per kg of active reactor mass. The dilute sludges were added to the BOF/MSW to increase the commingled feedstock solids content to about 25-30 percent. The feedstock C/N ratio, as previously defined, was held between 22-30.

Nutrient Study

A separate investigation was undertaken to assess the nutrient requirements for high-solids digestion of BOF/MSW using various nutritional supplements. The nutrient study was divided into four experiments. Each of the experiments were maintained at similar organic loading rates, nominal mass retention times, feedstock C/N ratios, and solids content, as described above.

In the first experiment (Experiment 1), BOF/MSW and water comprised the digester feedstocks. The digestion performance data for Experiment 1 were obtained from the studies conducted by Kayhanian et al. (1991b) and served as a basis for evaluating digester performance with different nutrient supplements.

In the second experiment (Experiment 2), WWTP sludges were substituted for the water in Experiment 1. The digestion performance data were obtained from the co-digestion of BOF/MSW and WWTP sludge investigation (See above).

In the third experiment (Experiment 3), dairy manure was added with the sludges to further stimulate the reactor and eliminate any possible nutrient deficiencies. Because large quantities of manure were collected and stored over a period of weeks, anaerobic bacteria were assumed to flourish in the manure. To eliminate the possibility of enhanced digestion due to "re-seeding" the system with new bacterial populations, the manure was eventually autoclaved prior to feeding. Typically, manure comprised less than 10% of the commingled feedstock on a dry basis.

The fourth and final experiment (Experiment 4) was conducted to evaluate the nutrient/seed effect of dairy manure on the digestion process by using soluble chemical nutrient solutions. The chemical solutions included: potassium phosphate, cobalt chloride, nickel sulfate, and sodium molybdenate. These chemical solutions were added to the reactor as a substitute for similar nutrients normally found in dairy manure, as reported in ASAE (1992). Additionally, sodium bicarbonate was added to duplicate the alkalinity of the manure.

Evaluation of the Humus Material

Throughout the digestion studies, samples of the humus material were periodically archived and analyzed. Samples were dried and ground to a size of about 60 mesh before elemental analysis. Other analyses used to characterize the humus material included: TS, VS, lignin content, and MPN.

MATERIALS

The materials utilized in the investigation are categorized into: (1) feedstock, (2) laboratory batch digestion apparatus, and (3) the pilot-scale facility.

Feedstock

The feedstocks used in this study include the biodegradable organic fraction of municipal solid waste (BOF/MSW), wastewater treatment plant (WWTP) sludges, and small quantities of dairy manure as a nutritional supplement.

As mentioned in Chapter 2, BOF/MSW may be considered to be comprised of three general components: paper products (office paper, newsprint), yard waste, and food waste. For this study the BOF/MSW was obtained from the residential community of Davis, CA. The office paper and newsprint were obtained in shredded bundles as would be produced from a materials recovery facility (MRF). Dried grass clippings were used to simulate yard waste. Food waste was obtained from local restaurants.

The WWTP sludges were provided by West County Sanitary District, City of Richmond, CA. The sludges resulted from a mix of domestic and industrial wastewater. The sludges used included primary, thickened activated, and digested sludge.

Dairy cow manure was obtained from the UC Davis Dairy Barn. Fresh manure was collected weekly and stored in an uncovered bin on-site.

Laboratory Batch Digestion Apparatus

Batch reactors were constructed of 2 Liter wide-mouth plastic bottles. The lid to each reactor had a 1 cm hole. A glass tube was inserted into the hole and a balloon was attached to the outside end. The balloon setup acted as a gas vent, allowing gas produced to diffuse out while preventing air from diffusing into the reactor. The lids were sealed with teflon tape and the glass tubes were secured to the lids with a chemical/water resistant epoxy. The reactors were batch fed prior to the beginning of the digestion period and partially immersed in a circulating water bath maintained at 55 ± 1 °C. A schematic diagram of the experimental setup is presented in Figure 3-1.

Feedstock and Inoculum Composition

The feedstocks used for the high-solids anaerobic digestion batch study consisted of BOF/MSW and digested sludge. To achieve a workable consistency and insure a homogenous sample, the sorted BOF/MSW was processed prior to mixing. The newsprint, office paper, and yard waste were comminuted using a bench-scale knife mill with a two millimeter rejection screen. Fresh food waste was comminuted with water in an industrial blender. The components of the BOF/MSW were combined together based on appropriate commingled C/N ratio for digestion as reported in Kayhanian et al. (1992). The composition of the simulated BOF/MSW used in the batch study is shown in Table 3-3. The inoculum utilized in the batch study was high-solids effluent obtained from UC Davis pilot-scale digester. The effluent was collected from the digester within 2 hours prior to experiment start-up.

Pilot Scale Facility

The pilot-scale anaerobic composting process is described in this section. The topics covered in the following discussion include: (1) process description, (2) high-solids anaerobic reactor, (3) aerobic biodrying reactor, and (4) process operation. Because this study was undertaken to investigate the feasibility of anaerobic composting of MSW with WWTP sludge, pilot-scale investigations comprised the majority of the study.

Table 3-3
Composition of simulated BOF/MSW used in the batch study

Component	Moisture content, % wet mass	Fraction of BOF/MSW % wet basis	C/N[a]
Food Waste	80	45	12.4
Mixed Paper[b]	5	50	143
Yard waste	6	5	14
BOF/MSW	38	100	23

[a] C/N ratios based on biodegradable carbon and total nitrogen.
[b] 25% newspaper, 75% office paper.

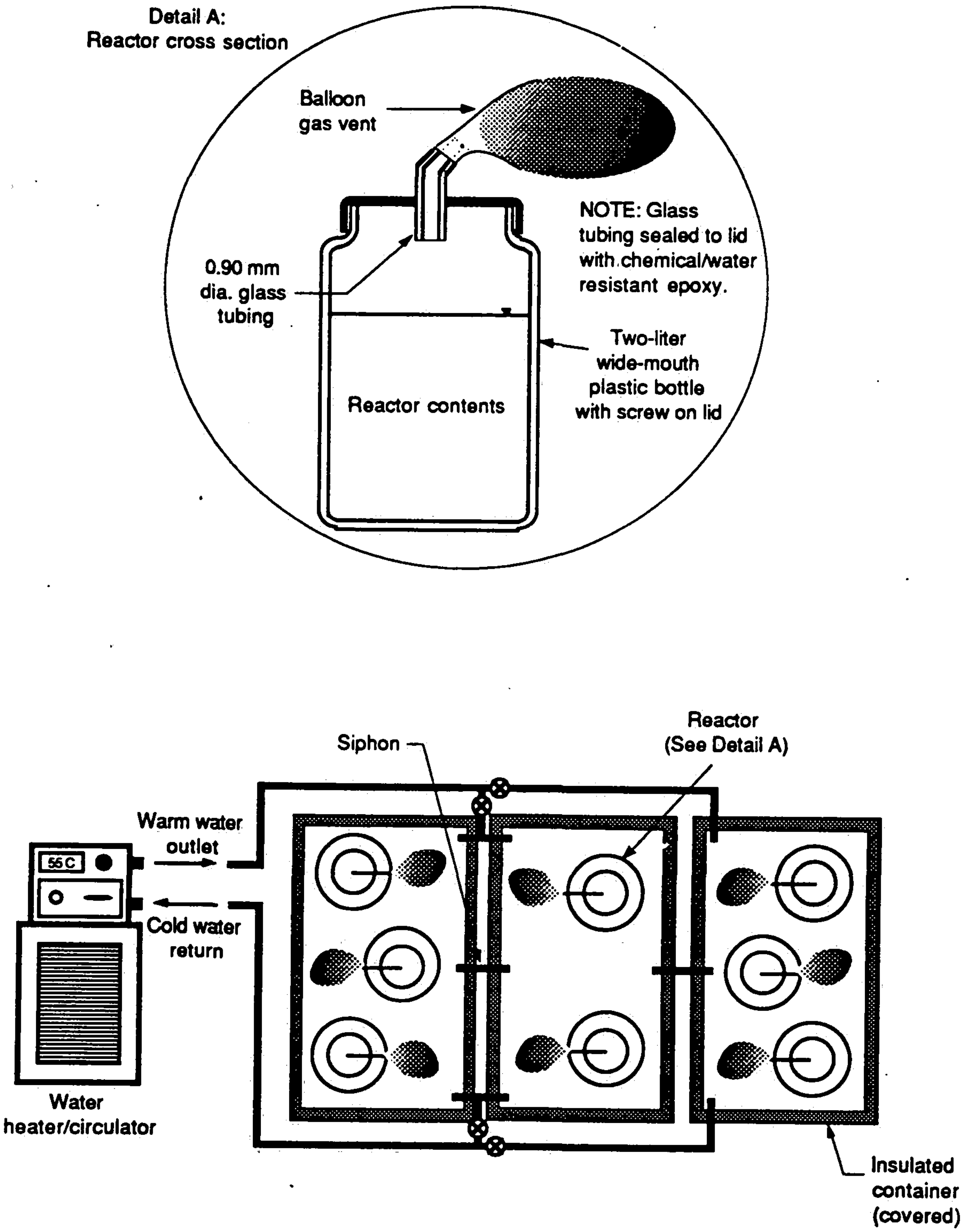

Figure 3-1
Schematic diagram of the batch reactors and experimental setup

Process Description

The pilot-scale anaerobic composting process is a two-stage process. As shown in Figure 3-2, the process combines high-solids anaerobic digestion and aerobic biodrying. The first stage involves the high-solids (typically 22-30 percent) digestion of commingled BOF/MSW and WWTP sludges to produce a gas composed principally of methane and carbon dioxide. The second stage involves the aerobic biodrying of the digested solids to increase the solids content to 65 percent or more. The characteristics of the digester and aerobic biodryers are described below. A more detailed description of the pilot facility can be found in Kayhanian et al. (1991b).

High-Solids Anaerobic Reactor

As shown in Figure 3-3, the anaerobic digester is a specially modified horizontal Davis stationary batch mixer. The mixer is a sealed reactor with an influent port, two effluent ports, and a biogas outlet port. All ports, with the exception of the biogas outlet port (which is not removed), are equipped with rubber gaskets to form an air-tight seal. The top of the reactor has a moveable hopper where the feedstock materials may be placed into the reactor. The entire reactor is mounted on a platform scale which allows total system weight (reactor + biomass) to be measured to the nearest pound. A specially modified wet gas meter and gas chromatograph are attached to the biogas outlet line. The reactor is designed to maintain constant temperature by two thermostatically controlled heat blankets. The reactor is mixed with a precision paddle agitator. Duration of mixing is controlled through an external control panel. A summary of important physical characteristics of the pilot-scale anaerobic digester is shown in Table 3-4.

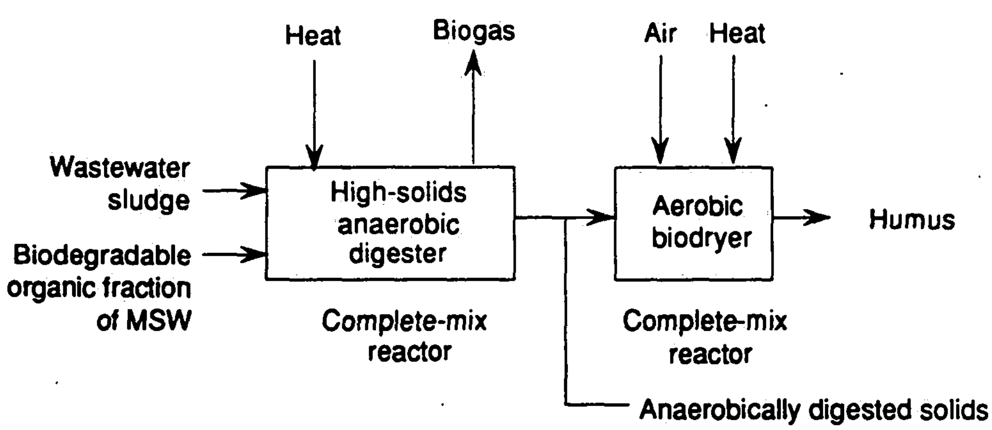

Figure 3-2
Basic flow diagram for the high-solids anaerobic composting process

= 11.7/13.1 = 0.89

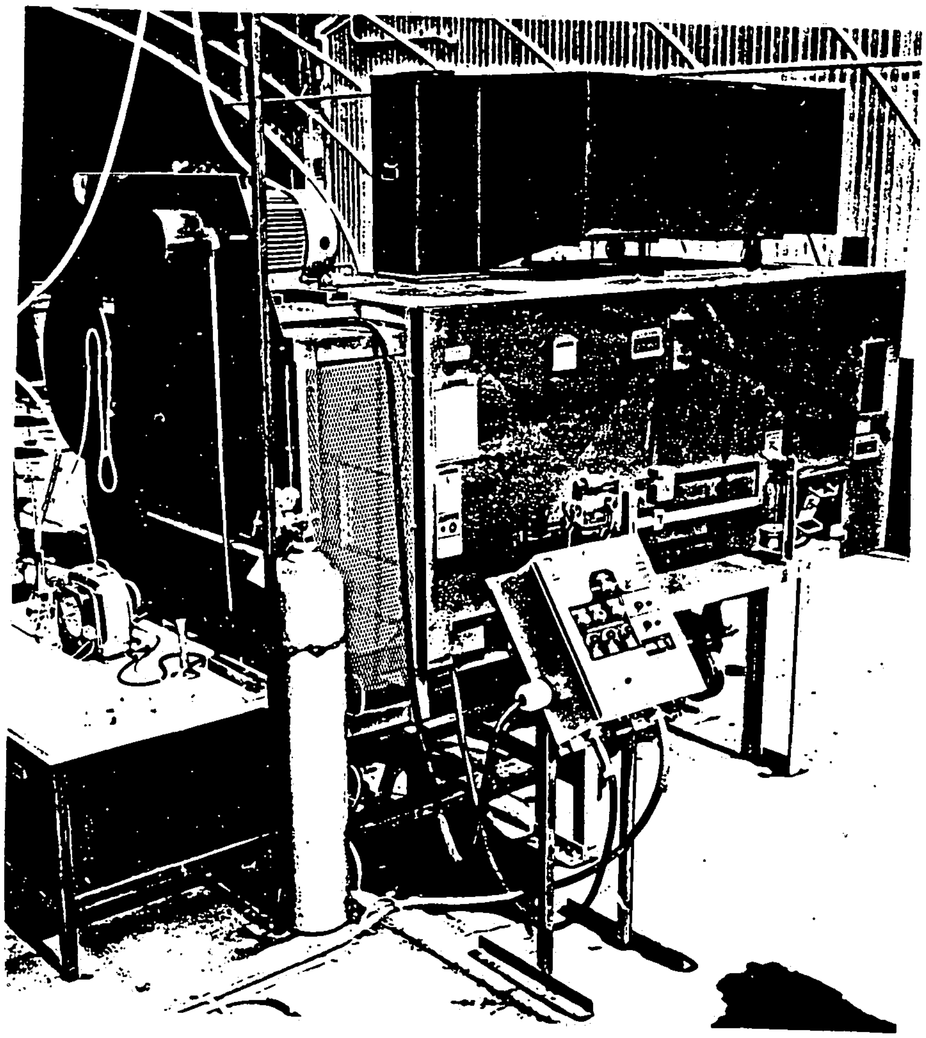

Figure 3-3
View of the high-solids anaerobic digester. Note mixer drive motor and feed trough located on top of the reactor, platform scale on which the reactor is set, discharge port for digested solids located at lower right hand side of the reactor, digester control panel located in foreground, and wet-test meter used to measure gas production located on desk in front of the reactor.

Table 3-4
Summary of the physical characteristics of the pilot scale high-solids anaerobic digester

Parameters	Unit	Range of values	Typical[a]
Reactor type		Complete-mix	
Mixing mechanism		Mechanical Paddle	
Total reactor volume	L	2,250	2,250
Total active reactor volume	L	1,800 -2,000	1,900

[a] The values reported are based on a mass retention time of 30 d.

Aerobic Biodrying Reactor

One of two identical aerobic biodryer reactors is shown in Figure 3-4. The reactors are specially modified horizontal Davis stationary batch mixers. The reactors are of similar construction and design as the high-solids digester with the exception of their size and heated aeration systems. The biodryers each have 1/3 the capacity of the high-solids digester and have an air blower to promote aerobic biological activity. A summary of important physical characteristics is presented in Table 3-5.

Mode of Operation

The anaerobic digester and aerobic biodryers are operated as a thermophilic, semi-continuously fed (once per day) mixed reactors. The daily feeding sequence is outlined below:

1. Biogas composition, biogas volume, and biogas temperature (at gas meter) are recorded.
2. The reactor is weighed.
3. Based on the reactor weight and the weight of that day's feeding, the amount of effluent to be removed is calculated so that the reactor is maintained at a constant weight.
4. The contents of the reactor are mixed.
5. The outlet port is opened and the desired amount of effluent is removed.
6. A small sample of effluent is collected and the pH is measured.
7. Pre-weighed portions of simulated BOF/MSW (newsprint, office paper, food waste, yard waste) and WWTP sludge are fed unmixed into the reactor.
8. A final reactor weight is taken to confirm influent and effluent mass measurements.

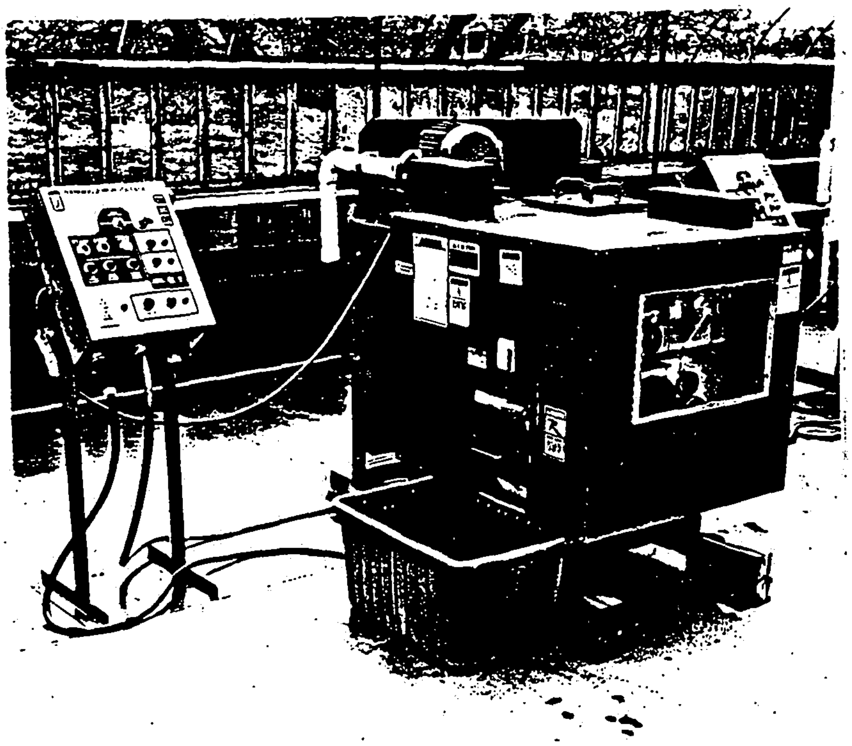

Figure 3-4
View of an aerobic biodrying reactor. Note the mixer drive motor and loading port for anaerobically digested solids (located on top of the biodrying unit), discharge port for composted solids (located at the side of biodryer) and the control panel (located in the foreground).

Table 3-5
Summary of the physical characteristics of the aerobic biodrying reactor

Parameters	Unit	Value
Reactor type		Complete-mix
Mixing mechanism		Mechanical Paddle
Total reactor volume	L	850
Total active reactor volume	L	680

9. The digester effluent is taken to the aerobic biodrying reactors where the material is dried to approximately 65 percent solids over the course of one or two days.

10. The effluent sample is taken to the laboratory for a variety of analytical measurements.

Operating Characteristics of the Process

A summary of the operating characteristics of the pilot-scale anaerobic composting process is presented in Table 3-6 and Table 3-7. As reported in Table 3-6, the anaerobic digester is operated under thermophilic conditions (53-60 °C) with a nominal mass retention time of 30 days. Of particular importance is the fact the organic loading rates are expressed on a biodegradable volatile solids (BVS) basis .

Table 3-6
Summary of the operational characteristics of the pilot-scale high-solids anaerobic digester

Parameters	Unit	Value	
		Range	Typical[a]
Operating temperature	°C	53 - 60	55
Mixing rate (intermittent)	min/min	2/30	2/30
Reactor TS concentration	% of wet weight	23 - 30	26
Total wet mass loading rate	kg/d	58 -126	63
TS loading rate	kg/d	18 - 42	21
VS loading rate	kg/d	15 - 34	17
BVS loading rate	kg/d	10 -13	11
Organic loading rate	g BVS/kg active biomass•d	6 - 7.2	6.5
First order rate constant, k	1/d	0.14 - 0.2	0.18
Influent substrate conc., Si	kg BVS /kg feed	0.095 - 0.21	0.19

[a] The values reported are based on a mass retention time of 30 d.

Table 3-7
Summary of the operational characteristics of the aerobic biodryer reactor.

Parameters	Unit	Typical value
Operating temperature	°C	55
Mixing (intermittent)	min/min	0.5/15
Air flow rate	m^3/min	0.20

4
RESULTS

The results of the experimental work are organized and presented in the following sections: (1) feedstock characteristics, (2) the results of the lab-scale batch study, (3) performance of the pilot-scale high solids anaerobic digestion process, (4) performance of the pilot-scale aerobic biodrying process, and (5) feedstock mass and volume reduction using the anaerobic composting process.

FEEDSTOCK CHARACTERISTICS

Feedstock characteristics directly affect digestion performance, as well as the properties of the humus end-product. The physical, chemical, nutrient characteristics and biodegradability of the feedstocks were determined and are described below.

Physical Characteristics

The physical characteristics of interest include total solids (TS), volatile solids (VS), particle size, and bulk density. Representative physical characteristics for each waste substrate are reported in Table 4-1.

Table 4-1
Physical characteristics of the feedstocks used in the anaerobic composting process

Organic waste	Total solids, % wet weight	Volatile solids, % TS	Particle size, cm	Bulk density, kg/m^3
Newsprint	94	98	2 - 5	80
Office paper	96	95	2 - 5	80
Yard waste	80 - 90	78	2 - 20	50
Food waste	20 - 30	95	5 - 20	400
Manure	15 - 20	85	1 - 20	990
Mixed BOF/MSW[a]	70 - 80	90	1- 20	180
Raw primary sludge [b]	7	70	<2	1020
Thickened activated sludge[b]	5	40	<2	1000
Digested sludge[b]	2	70	<1	1000

[a] Typical BOF/MSW is comprised of 54% office paper, 18% newsprint, 11% food waste, and 17% yard waste (dry weight basis).
[b] Typical bulk density values from Tchobanoglous et al. (1992).

Table 4-2
Chemical characteristics of the WWTP sludges and BOF/MSW used as feedstock in the pilot-scale anaerobic composting process

	Unit	Sludge type: Primary sludge	Digested sludge	Activated sludge	BOF/MSW[a]
Alkalinity	mg/L as $CaCO_3$	1340	4000	1370	N/A
Ammonia	mg/L as N	170	950	550	N/A
Elemental analysis (dry basis)					
Aluminum, Al	ppm	1340	1400	1380	1980
Arsenic,As	ppm	17.1	24.8	15.0	0.59
Barium, Ba	ppm	202	120	175	ND
Boron, B	ppm	45	43	46	13.67
Cadmium, Cd	ppm	1.83	5.38	2.69	0.13
Calcium, Ca	%	0.78	1.31	0.65	1.08
Carbon, C	%	44.27	37.8	44.0	45.7
Chlorine, Cl	%	0.32	0.82	0.38	0.21
Chromium,Cr	ppm	24.4	73.9	65.3	3.4
Copper, Cu	ppm	303	631	424	1.0
Iron, Fe	%	0.87	1.43	1.05	0.07
Lead, Pb	ppm	19.8	31.9	19.4	5.31
Magnesium, Mg	%	0.23	0.44	0.33	0.05
Managese, Mn	ppm	434	1060	1270	11.61
Mercury, Hg	ppm	1.09	0.89	0.41	ND
Molybednum, Mo	ppm	5.0	14.6	11.9	1.05
Nickel,Ni	ppm	22.8	55.4	37.2	0.25
Nitrogen,N	%	3.80	4.28	7.04	0.89
Phosphorus,P	%	0.43	0.78	0.75	0.09
Potassium, K	%	0.17	0.55	0.51	0.38
Sodium, Na	%	0.23	0.45	0.38	0.28
Sulfur, S	ppm	2420	3660	3050	1100
Tungsten, W	ppm	0.29	0.26	0.15	0.13
Zinc, Zn	ppm	452	851	468	67.1
C/N ratio[b]		11.65	8.84	6.25	51.3

[a] Typical BOF/MSW is comprised of 54% office paper, 18% newsprint, 11% food waste, and 17% yard waste (dry weight basis).
[b] C/N ratio is reported based on total carbon and nitrogen.

Chemical Characteristics

The chemical characteristics of interest include alkalinity, ammonia, elemental composition, and C/N ratio. Typical chemical characteristics of the each waste are reported in Table 4-2.

Nutrient Characteristics

The nutrient characteristics of typical BOF/MSW, WWTP sludges, and dairy manure are reported in Table 4-3. Based on the nutrient concentrations of the various substrates and the feedstock ratios used, a commingled feedstock nutrient loading can be developed.

Biodegradability of the Feedstocks

The nature of the organic constituents in the feedstock materials varies widely. The digestable material within the wastewater sludges includes fecal material, cell material, and highly soluble paper products (such as toilet paper). The fecal material contains primarily polysaccharides and lipids. The lipids are easily degraded and it is estimated that they contribute the greatest proportion to the total digestion gas production (Hobson & Wheatley, 1993). Of the three sludges investigated, the primary sludge contains high levels of fecal material and soluble papers, while the activated sludge has large proportion of cell material. The digested sludge may be considered to have little or no readily degradable organic material.

The BOF/MSW, in contrast, is primarily a lignocellulosic substrate, containing cellulose, hemicellulose, and lignin as the three major components. Because lignocellulosics maintain the structure of plant cell walls, they have a complex organic structure and are more resistant to biodegradation. Consequently, the hydrolysis rate of

Table 4-3
Nutrient characteristics of typical BOF/MSW, wastewater treatment plant sludges, and dairy manure used as feedstocks.

	Nutrient concentration (mg/kg)								
Substrate	C/N	C/P	C/K	Co	Fe	Mo	Ni	Se	W
Mixed paper [a]	295	890	745	0.10	9	0.86	0.10	<0.10	0.13
Yard waste	22.8	178	30	0.10	903	0.97	0.10	0.10	0.15
Food waste	15.6	625	60	0.30	163	1.88	0.94	0.10	0.10
Mixed BOF/MSW[b]	50.5	500	115	0.13	740	1.03	0.26	0.10	0.12
Digested sludge	9.0	49.8	68.8	10.0	14300	14.6	55.4	ND	0.26
Activated sludge	6.3	58.7	86.3	9.0	10500	11.9	37.7	ND	0.41
Primary sludge	11.7	103.0	260.5	7.0	.8700	5.0	22.8	ND	0.29
Dairy Manure[c]	20.1	64.5	21.0	0.1	1000	6.0	23.0	ND	ND

[a] 75% office paper, 25% newsprint.
[b] Typical BOF/MSW is comprised of 54% office paper, 18% newsprint, 11% food waste, and 17% yard waste (dry weight basis).
[c] Based on ASAE (1992) average manure values.

lignocellulosics typically limits the overall conversion rate during digestion (Rivard et al., 1993).

In addition, the various lignocellulosic materials of the BOF/MSW substrates have large variations in biodegradability. Lignin content and biodegradable fractions for all substrates used in the investigation, including BOF/MSW, manure, and sludges, are presented in Table 4-4. Long term batch studies performed by Kayhanian et al. (1991b) have confirmed the biodegradability estimates. It is important to note that estimating the WWTP sludge biodegradability from lignin content is not appropriate given the nature of the sludge organics. However, for the purposes of calculating organic loading rates, the sludge degradabilities were conservatively estimated as 60, 40, and 20 percent VS (primary, activated, and digested sludge, respectively). Because the sludge organics make up a small fraction of the total feedstock organic content, variances in the assumed sludge biodegradability will have minimal effects on digester organic loading rates.

RESULTS OF THE LAB-SCALE BATCH STUDY

The results of the lab-scale batch digestion study are shown in Figure 4-1. As shown, the percent of feedstock BVS converted to biogas is plotted over the digestion period for different concentrations of digested sludge. Because the ultimate biodegradability of the feedstocks is known (See Table 4-4), the BVS removal efficiencies can be calculated from the subsequent reactor weight losses. The weight loss of reactor 8 (100 percent effluent) was used to account for the effluent contribution to reactor weight loss. As can be seen from Figure 4-1, digestion performance at 20 days varied from about 40 percent BVS removal with the reactor having 11.8 percent digested sludge (dry basis) to about 7 percent BVS removal for the reactor with no digested sludge added. Negligible weight loss was measured from Reactor 7 (100 percent digested sludge).

PERFORMANCE OF THE PILOT-SCALE ANAEROBIC DIGESTION PROCESS

The performance of the pilot-scale anaerobic digestion process is organized and reported as (1) digestion performance for the different sludge types, and (2) digestion performance for different nutrient supplements.

Digestion Performance for the Different Sludge Types

The performance of the high-solids anaerobic co-digestion of BOF/MSW and the three different WWTP sludges is presented in Table 4-5. As shown, the performance data

Table 4-4
Biodegradability of the feedstocks used in the anaerobic composting process.

Organic waste	Lignin content %VS	BVS fraction, %VS[a]
Newsprint	21.9	22
Office paper	0.35	83
Yard waste	4.07	72
Food waste	0.35	83
Manure	13.6	45
Mixed BOF/MSW[b]	5.35	68
Primary sludge		60
Activated sludge		40
Digested sludge		20

[a] Computed using Eq. [3-1]. Sludge BVS fractions are estimated.
[b] Typical BOF/MSW feedstock is comprised of 54% office paper, 18% newsprint, 17% yard waste, and 11% food waste (dry weight basis).

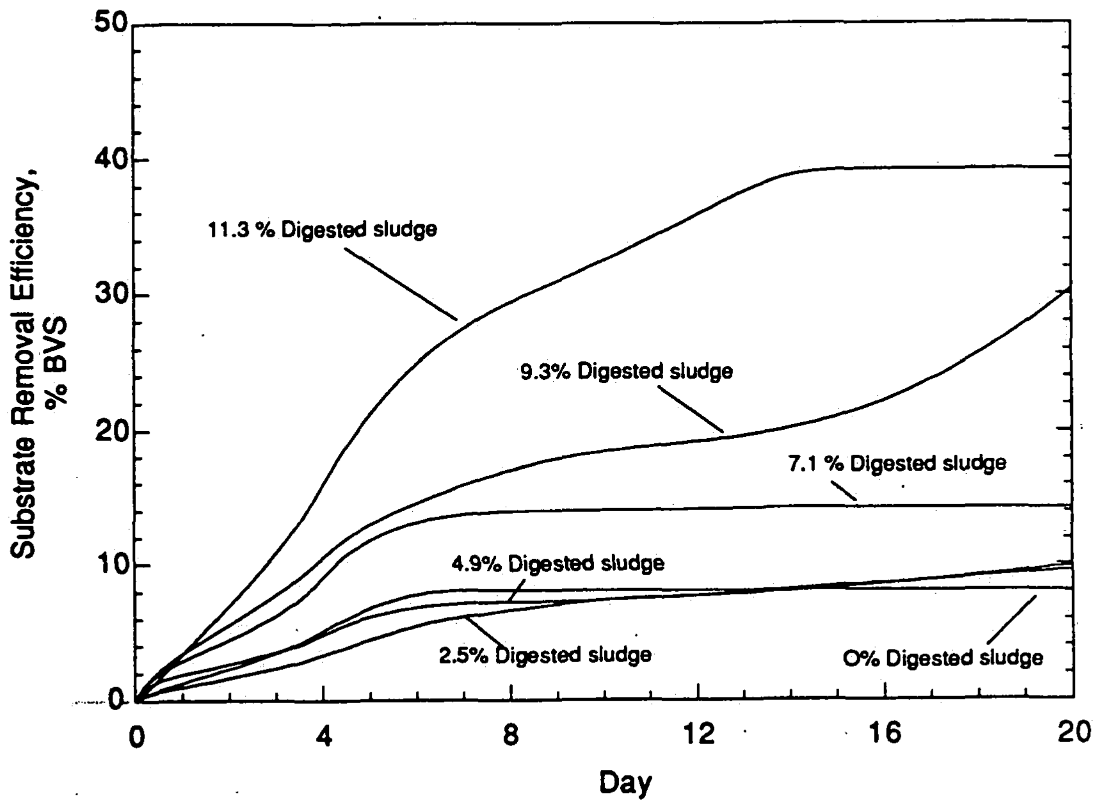

Figure 4-1.
Substate removal efficiency over time for varying concentrations of digested sludge using a batch digestion study.

Table 4-5
Performance of the high-solids anaerobic co-digestion of BOF/MSW and three different wastewater treatment sludges.

Item	Unit	Average values[a]	
		Range	Typical
Digested sludge and BOF/MSW			
Alkalinity	mg/L as $CaCO_3$	13,000 - 16,300	14,000
BF of alkalinity	%	50-60	60
Ammonia	mg/L	760- 1115	940
Biogas production rate	m3 /kg BVS added·d	0.38 - 0.70	0.66
Biogas production rate	V/ active reactor V·d	2.0- -4.5	4.3
Methane concentration	%	48-52	50
pH		6.75- 7.15	6.96
Solids removal rate	g BVS /kg ARM[d]·d	2.1 - 5.3	5.1
Solids removal efficiency	% BVS removed	60 - 85	79
VFA	mg/L as acetic acid	11,000 - 16,000[e]	13,500
Activated sludge and BOF/MSW			
Alkalinity	mg/L as $CaCO_3$	13,000 - 16,500	14,500
BF of alkalinity	%	50-60	60
Ammonia	mg/L as N	840- 1115	1020
Biogas production rate	m3 /kg BVS added ·d	0.40 - 0.75	0.68
Biogasproduction rate	V/ active reactor V·d	2.1- 4.6	4.4
Methane concentration	%	48 - 52	50
pH		6.7 - 7.2	7.0
Solids removal rate	g BVS /kg ARM·d	2.8 - 5.8	5.3
Solids removal efficiency	% BVS removed	60 - 87	82
VFA	mg/L as acetic acid	11,000 - 16,000	14,000
Primary sludge and BOF/MSW			
Alkalinity [b]	mg/L as $CaCO_3$	13,000 - 16,500	15,500
BF of alkalinity[c]	%	50-60	60
Ammonia	mg/L as N	860 -1230	1150
Biogas production rate	m^3 /kg BVS added ·d	0.41 - 0.85	0.73
Biogas production rate	V/ active reactor V·d	2.5 - 5.2	4.7
Methane concentration	%	48-52	50
pH		7.0 - 7.28	7.2
Solids removal rate	g BVS /kg ARM·d	3.0 - 6.0	5.5
Solids removal efficiency	% BVS removed	60 - 95	85
VFA	mg/L as acetic acid	11,000 - 16,000	14,000

[a] The reported values are based on an organic loading rate of approximately 6.5 g BVS / kg active reactor mass, an input C/N ratio of 20 - 30, and a nominal mass retention time of 30 days.
[b] Alkalinity values are based on the total alkalinity (to pH 4.5).
[c] Bicarbonate fraction (BF) of alkalinity represents the portion of alkalinity used in bicarbonate buffering. Bicarbonate fraction is determined by a double titration to pH 5.1 then pH 4.5.
[d] ARM = Active Reactor Mass.
[e] The values reported for VFA are for comparison only, may be non-representative of values measured by the isothermal GLC method.

used to monitor the digestion process includes: alkalinity, ammonia-nitrogen, gas production rates, biogas methane concentration, pH, solids removal efficiency and rate, and VFA concentrations. For each sludge feedstock, the reactor was maintained at a constant BVS organic loading rate of about 6.5 g/kg active reactor mass. Dairy manure was occasionally added as a nutritional supplement.

Digestion Performance with Different Nutrient Supplements

The performance of the high-solids anaerobic digestion process when fed different types of nutrient supplements is presented in Table 4-6. As shown, the digestion performance is given for four different feedstocks: (1) BOF/MSW and water, (2) BOF/MSW and WWTP sludges, (3) BOF/MSW, WWTP sludges, and diary manure, and (4) BOF/MSW, WWTP sludges, and synthetic nutrient solutions.

PERFORMANCE OF THE AEROBIC BIODRYING PROCESS

The performance of the aerobic biodrying process is determined by evaluating the characteristics of the humus material. Important physical, chemical, and biological characteristics of the humus are summarized in Table 4.7.

Table 4-6
Performance of the high-solids anaerobic process during four experiments using (1) a typical BOF/MSW and fresh water, (2) a commingled BOF/MSW and wastewater treatment plant sludges, (3) a commingled BOF/MSW, wastewater treatment plant sludges, and dairy manure, and (4) a commingled BOF/MSW, wastewater treatment plant sludges, and synthetic chemical solutions.

Item	Unit	Average values[a]		Remarks
		Range	Typical	
EXPERIMENT 1				
Alkalinity [b]	mg/L as $CaCO_3$	10,800 - 14,200	12,500	Digester prone
BF of alkalinity[c]	%	50 - 60	60	to upsets.
Ammonia	mg/L as N	600 - 2000	750	High fluctuations in
Biogas production rate	m^3 /kg BVS added ·d	0.33 - 0.65	0.55	VFA and reactor pH.
Biogas production rate	V/ active reactor V·d	1.5 - 3.8	3.6	In addition, ammonia
Methane concentration	%	48 - 52	50	inhibition occurred at
pH		6.5 - 7.2	6.8	concentrations
Solids removal rate	g BVS /kg ARM[d]·d	2.3- 5.0	4.5	greater than 1000
Solids removal efficiency	% BVS removed	55 - 80	70	mg/L.
VFA	mg/L as acetic acid	11,000 - 16,000[e]	12,500	

Continued on following page

Table 4-6, continued

Item	Unit	Average values[a] Range	Typical	Remarks
EXPERIMENT 2				
Alkalinity	mg/L as $CaCO_3$	13,000 - 16,300	14,500	Similar performance
BF of alkalinity	%	50 - 60	60	for all types of
Ammonia	mg/L as N	740 - 1230	1040	WWTP sludges
Biogas production rate	m^3 /kg BVS added ·d	0.38 - 0.73	0.67	evaluated.
Biogas production rate	V/ active reactor V·d	2.1- 4.5	4.3	Increased process
Methane concentration	%	48 - 52	50	stability due to
pH		6.8 - 7.2	6.9	higher alkalinity.
Solids removal rate	g BVS /kg A.R.M[d]. ·d	2.7- 5.5	5.0	Operated at higher
Solids removal efficiency	% BVS removed	60 - 85	77	ammonia and VFA
VFA	mg/L as acetic acid	11,000 - 16,000	13,000	concentrations.
EXPERIMENT 3				
Alkalinity	mg/L as $CaCO_3$	13,000 - 16,900	16,200	Enhanced gas
BF of alkalinity	%	50 - 60	60	production rates
Ammonia	mg/L	900 - 1260	1100	and greater stability.
Biogas production rate	m^3 /kg BVS added ·d	0.50 - 0.85	0.73	Typical ammonia
Biogas production rate	V/ active reactor V·d	3.0 - 5.2	4.7	and VFA levels
Methane concentration	%	48 - 52	50	would be inhibitory
pH		6.8 - 7.2	7.15	in Exp. 1.
Solids removal rate	g BVS /kg A.R.M. ·d	3.0 - 6.0	5.5	No noticeable
Solids removal efficiency	% BVS removed	75 - 95	85	changes using
VFA	mg/L as acetic acid	11,000 - 16,000	14,000	autoclaved manure.
EXPERIMENT 4				
Alkalinity	mg/L as $CaCO_3$	13,000 - 16,500	16,000	Stable digestion.
BFof alkalinity	%	50 - 60	60	Unable to replicate
Ammonia	mg/L	900 - 1230	1050	Exp. 3 enhanced
Biogas production rate	m3 /kg BVS added ·d	0.50 - 0.70	0.68	gas rates.
Biogas production rate	V/ active reactor V·d	3.0 - 4.5	4.4	After 2 weeks of
Methane concentration	%	48 - 52	50	nutrient solution
pH		6.8 - 7.2	7.0	supplements,
Solids removal rate	g BVS /kg A.R.M. ·d	3.2 - 5.4	5.1	effluent became
Solid removal efficiency	% BVS removed	60 - 85	78	"slimy", inhibiting
VFA	mg/L as acetic acid	11,000- 16,000	13,000	digestion.

a The reported values are based on an organic loading rate of approximately 6.5 g BVS / kg active reactor mass, an input C/N ratio of 20 - 30, and nominal mass retention time of 30 days.

b Alkalinity values are based on the total alkalinity (to pH 4.5).

c Bicarbonate fraction of alkalinity represents the portion of alkalinity used in bicarbonate buffering. Bicarbonate fraction is determined by a double titration to pH 5.1 then pH 4.5.

d ARM = Active Reactor Mass.

e The values reported for VFA are for comparison only, may be non-representative of values measured by the isothermal GLC method.

Table 4.7
Characteristics of the humus produced by the anaerobic composting of BOF/MSW and wastewater sludge.

Characteristic/ Description	Unit	Range	Typical
Physical Characteristics			
Bulk density	kg/m^3	550 - 600	560
Odor			no offensive odor detected
Particle size	mm	<1-10	0.8
Total solids (TS)	%	30 - 40	35
Volatile solids (VS)	% of TS	55-65	59
Chemical Characteristics			
Nutrient analysis			
C/N		15 - 20	17
K	%	0.3 - 1	0.73
N	%	1 - 2	1.9
Total P	%	0.1 - 0.5	0.23
NO_3-N	ppm	5 - 50	8
PO_4-P	ppm	50 - 200	170
SO_4-S	ppm	300 - 800	547
Metal analysis[a]			
As	ppm	<1 - 2	ND
Cd	ppm	<1 - 5	0.44
Cr	ppm	5 - 35	27.2
Cu	ppm	18 - 248	53.2
Hg	ppm	<1	ND
Mo	ppm	1 - 20	2
Ni	ppm	2 - 186	4.9
Pb	ppm	5 - 43	18
Se	ppm	<1	0.067
Zn	ppm	98 - 376	195
Energy content	MJ/kg	13 - 15	14.8
pH		8.1 - 8.4	8.2
Biological Characteristics			
Biodegradable fraction	% of VS	5 - 10	8.8
Bacterial indication			
Total coliform	MPN/100mL		Not detected[b]
Fecal coliform	MPN/100mL		Not detected[b]
Streptococcus and Enterococcus	MPN/100mL		Not detected[b]

[a] Selected pollutant metals shown. Values based on BOF/MSW and digested sludge feedstock.
[b] Detection limit is 0 to 6 organisms/10 mL at a 95 percent confidence level.

FEEDSTOCK MASS AND VOLUME REDUCTION USING THE ANAEROBIC COMPOSTING PROCESS

To evaluate anaerobic composting as a sludge dewatering/ waste reduction process, it is important to compare process performance with conventional dewatering/ management practices. Therefore, as a basis for comparison, the anaerobic composting process is compared to both sludge and MSW as placed in a well compacted sanitary landfill.

The weights and volumes of MSW fractions used as feedstock in the anaerobic composting process are presented in Table 4-8. As shown, the feedstcok volume as fed to the reactor is decreased by a landfill compaction factor, producing a volume of the each waste fraction as would be found in a well-compacted landfill. From the weight ratios of input feedstock, a commingled compacted density of the BOF/MSW is determined. While municipal sewage sludges cannot be "compacted", sewage sludges are required to be dewatered to at least 50 percent solids before placement in sanitary landfills, as dictated by the California Integrated Waste Management Board (CIWMB).

As a result of these physical transformations of the wastes, there are two possible representations of the combined sludge and BOF/MSW in the landfill. First, if it is assumed that the sludge cake fills the intersticies of the compacted MSW, the compacted MSW would retain the same volume in the landfill but have additional weight from the sludge cake. Second, if the sludge cake is assumed to remain unmixed with the compacted MSW in the landfill, both the weight and volume of the combined wastes would change. These two possible representations would produce different combined landfill waste densities. The example calculations below describe the computation of the possible combined sludge and BOF/MSW densities in the landfill. These densities are used as a basis of comparison for evaluating the anaerobic composting process as a dewatering/ waste reduction practice.

The substrate volume reduction using the anaerobic composting process is presented in Table 4-9. As shown, volume reduction through the process is compared to similar quantities of BOF/MSW and sludge as would be found in a well-compacted California landfill. Two possible representations of the wastes in the landfill are used: (1) assuming the BOF/MSW and sludge are mixed together, and (2) assuming the BOF/MSW remain layered in the landfill. Computation of the resulting combined landfill densities is outlined below.

Table 4-8.
Computation of the compacted density of the BOF/MSW feedstock as placed in a well compacted landfill.[a]

Item	Weight of organic feedstock, kg	Volume as fed to reactor, m^3	Landfill compaction factor[b]	Volume in compacted landfill, m^3	Compacted density, kg/m^3
Newsprint	5	0.06	0.15	0.009	540
Office paper	10	0.13	0.15	0.018	560
Yard waste	4	0.08	0.20	0.016	250
Food waste	8	0.02	0.33	0.007	1200
Combined	27			0.050	540[c]

[a] Adapted from Kayhanian et al., 1991a.
[b] Source: Tchobanoglous et al., 1993
[c] Combined weight of feedstock divided by combined compacted volume: 27 kg/0.050 m^3 = 540 kg/m^3.

Example Calculation

Cas e 1: Sludge cake fills the interstices of the compacted MSW in the landfill.

1. Assumptions

   a. Input feedstock ratio (wet): 60 % sludge to 40 % BOF/MSW
   b. Density of compacted MSW = 540 kg/m^3
   c. Sludge total solids = 5 %

2. Determine the amount of sludge required for the anaerobic composting process

   For every unit volume of BOF/MSW (540 kg of MSW) added:
   540 x (60/40) = 810 kg of sludge at 5% solids is required.

3. Determine the corresponding mass of sludge dewatered to 51% solids

   Dewatering the sludge to 51% solids would reduce the sludge wight to:
   810 kg x (51/5) x 0.01 = 82.6 kg dewatered cake at 51% solids

4. Determine the combined weight of the MSW and sludge solids

   Combined weight of MSW and sludge cake = 540 + 82.6 kg = 622.6 kg

5. Determine the density of the combined MSW and sludge

   Assuming no change in MSW volume (1 m^3),
   the combined density = 622.6 kg/m^3

Example Calculation, continued

Case 2: Sludge cake remains unmixed from compacted MSW in landfill.

1. Assumptions

   a. Input feedstock ratio (wet): 60 % sludge to 40 % BOF/MSW
   b. Density of compacted MSW = 540 kg/m^3
   c. Sludge total solids = 5 %
   d. Density of sludge cake at 51% solids = 1240 kg/m^3

2. Determine the amount of sludge required for the anaerobic composting process

   For every unit volume of BOF/MSW (540 kg of MSW) added:
   540 x (60/40) = 810 kg of sludge at 5% solids is required.

3. Determine the corresponding mass of sludge dewatered to 51% solids

   Dewatering the sludge to 51% solids would reduce the sludge wight to:
   810 kg x (51/5) x 0.01 = 82.6 kg dewatered cake at 51% solids

4. Determine the combined weight of the MSW and sludge solids

   Combined weight of MSW and sludge cake = 540 + 82.6 kg = 622.6 kg

5. Determine the combined volume of the MSW and sludge
   a. Volume of sludge = 82.62 kg / 1240 kg/m^3 = 0.07 m^3
   b. Volume of MSW = 1 m^3
   c. Combined volume = 0.07 m^3 + 1.0 m^3 = 1.07 m^3

6. Determine the combined density of the MSW and sludge (unmixed)

   Combined density = 622.6 kg/1.07 m^3 = 583 kg/m^3

Table 4.9
Substrate volume reduction before anaerobic digestion, after anaerobic digestion, and after aerobic biodrying. Relative volumes based on the volume of wastes as placed in a well compacted landfill requiring sludge to be dewatered to 51 percent solids.

		Average values				
		Input feedstock			After anaerobic digestion	Humus after aerobic biodrying
Parameter	Unit	BOF/MSW	Sludge	Combined		
Total solids	%	80	5	34	25	65
Relative wet mass		0.40	0.60	1.0	0.78	0.30
Bulk density	kg/m^3	178[a]	1010[b]		1009	560
Density as placed in a well compacted landfill						
Mixed	kg/m^3	540[c]	1240[d]	620[e]		
Layered	kg/m^3	540[c]	1240[d]	580[f]		
Relative volume[g]						
Mixed[h]	m^3			0.00161	0.00077	0.00054
Layered[i]	m^3			0.00172	0.00077	0.00054
Volume reduction[j]						
Mixed[h]				1.0	0.52	0.66
Layered[i]				1.0	0.55	0.69

a Bulk density of the BOF/MSW as fed to the digester.
b Typical sludge value
c Based on the compacted volume of the waste (see Table 4-8).
d Dewatered sludge cake at 51% TS, as required by California standards for wastewater sludge placed in landfills (CIWMB). If specific gravity (sg) of sludge solids = 1.6, then $1/sg_{cake}$= 0.51/1.6 + 0.49/1.0, sg_{cake} = 1.24. Cake density = 1000 kg/m^3 x 1.24= 1240 kg $/m^3$.
e See Case 1 calculation above.
f See Case 2 calculation above.
g Relative volume = relative wet mass/bulk density.
h Relative volume based on the mixed density of the feedstocks as placed a well-compacted landfill, assuming the intersticies of the compacted BOF/MSW are filled with sludge cake (Case 1).
i Relative volume based on the combined density of the feedstocks as placed in a well-compacted landfill, assuming the sludge cake is layered (and not mixed) with the compacted BOF/MSW (Case 2).
j Volume reduction = (relative feedstock volume - relative volume)/(relative feedstcok volume).

5
DISCUSSION

The results of the high-solids anaerobic composting process are discussed in this chapter. The general topics covered include: (1) co-digestion of BOF/MSW and wastewater sludge: lab-scale batch study, (2) co-digestion of BOF/MSW and wastewater sludges: pilot-studies, (3) assessment of the nutrient requirements for high-solids digestion, (4) assessment of the humus material, (5) assessment of the anaerobic composting process for the reduction in sludge volume.

CO-DIGESTION OF BOF/MSW AND WASTEWATER SLUDGE: LAB-SCALE BATCH STUDY

The laboratory-scale batch digestion study was conducted as a preliminary investigation and the experimental setup was such that specific digestion parameters (gas conversion rates, total volatile solids destruction) are difficult to quantify. However, the batch study does indicate two important aspects of the co-digestion of BOF/MSW and wastewater sludge. First, as shown in Figure 4-1, an increase in digested sludge concentrations resulted in increased feedstock BVS removal. Second, enhanced digestion with higher concentrations of sludge is due primarily to the nutrients contained in the sludge. This conclusion is based on the facts that digested sludge does not contribute to the degradables in the reactor (the control reactor with 100 percent sludge experienced no weight loss), all reactors were buffered with sodium bicarbonate, and equal amounts of acclimated "seed" (effluent) were added to each reactor. The results of the batch study provided a frame of reference for the pilot-scale investigations.

CO-DIGESTION OF BOF/MSW AND WASTEWATER SLUDGES: PILOT-STUDIES

A summary of digestion performance for the three types of wastewater sludge used as feedstock is presented in Table 4-5. As shown, all three sludges gave similar digestion performance when commingled with the BOF/MSW, with optimum digestion performance associated with the primary sludge feedstocks. Typical gas production rates were 0.66, 0.68, and 0.73 m^3/kg BVS added·d for digested sludge, activated sludge, and primary sludge, respectively. At these gas production rates, solids removal efficiencies varied from 79 percent with digested sludge to 82 percent with activated sludge to 85 percent with primary sludge feedstocks.

Typically, higher gas production rates indicated a more stable digestion process. Process stability may be readily measured from reactor pH and alkalinity. Although anaerobic digestion may sustain pH values in the range of 6.8 to 7.2, pH values above 7.0 generally indicate balanced production/consumption of acids and a healthy digestion process. As shown in Table 4-5, typical reactor pH for the different sludge feedstocks were 6.96 for digested sludge, 7.0 for activated sludge, followed by 7.2 for primary sludge. Similarly, reactor alkalinity, representing the buffering capacity of the process, was found to be the highest with primary sludge feedstocks (typically 15,500 mg/L as $CaCO_3$), followed by activated sludge (14,500 mg/L as $CaCO_3$), and digested sludge (14,000 mg/L as $CaCO_3$).

It appears that the higher gas production rates and reactor stability correspond with the higher wastewater sludge solids concentrations. The sludges were typically 2, 5, and 7 percent solids (digested, activated, primary, respectively). It is possible that the sludge solids provide a source of easily degradable material compared to the complex lignocellulosic organics of the BOF/MSW and effectively facilitate the overall reaction. But because the sludge organics typically comprised around 5 percent of the biodegradable material in the feedstock, it is believed that the nutrients, not the organics, contained in the sludges are the fundamental reason for changes in reactor performance. As shown in Table 4-3, compared to the BOF/MSW, the sludges are rich in a variety of mineral nutrients. Nickel, for example, was typically less than 1 ppm in the BOF/MSW while between 20 and 50 ppm for the different sludges. The feedstock using primary sludge had a higher proportion of nutrients (due to the higher total solids of primary sludge) than the other feedstock types. Additionally, the higher biodegradability of the primary sludge potentially allow the nutrients to be more readily available to the bacteria. It is important to note, however, that all sludge feedstock types could be digested at high solids levels (22 - 30 percent) with organic loading rates maintained between 6.5 to 7.2 g BVS / kg active reactor mass.

ASSESSMENT OF NUTRIENT REQUIREMENTS FOR HIGH SOLIDS DIGESTION

An evaluation of nutrient requirements for the high-solids digestion of BOF/MSW is discussed below. The topics considered include: (1) the effect of nutrient supplements on digester performance, (2) optimum nutrient concentrations for high-solids digestion of BOF/MSW, and (3) nutrient hierarchy.

Effect of Nutrient Supplements on the Digester Performance

As shown in Table 4-6, although all feedstocks were fed into the digester at similar organic loading rates and mass retention times, process performance varied with the different types of nutrient supplements commingled with BOF/MSW. The digestion of BOF/MSW and fresh water was shown to be the most sensitive to upsets, indicated by the large ranges in pH, ammonia-N, VFA, and gas production rates. Typically, a pH below 6.8 and/or ammonia-N concentrations above 1000 mg/L resulted in inhibited digestion.

Digestion of commingled BOF/MSW and wastewater treatment plant sludges showed increased process stability, as shown by higher reactor pH and alkalinity concentrations. Ammonia-N and VFA levels also increased, possibly indicating a more robust bacterial culture.

Digestion of commingled BOF/MSW, dairy manure, and wastewater treatment plant sludges showed not only stable digestion, but markedly enhanced gas production rates. Reactor pH was sustained above neutral, typically at pH 7.15. Reactor buffering capacity was indicated by higher alkalinity (typically 16,200 mg/L as $CaCO_3$) as well as the fact that the sustained ammonia and VFA concentrations (typically 1,100 mg/L and 16,200 mg/L as acetic acid, respectively) would have inhibited the digestion of BOF/MSW alone (Experiment 1). The use of autoclaved manure resulted in no noticeable differences in process performance.

The use of nutrient solutions also stabilized the digestion process effectively, but failed to duplicate the enhanced gas production achieved with combined manure and sludge supplements. Gas production rates were similar to those attained with the digestion of BOF/MSW and sludges.

For the purpose of comparison, the results of typical biogas production rates and the corresponding reactor pH for the different types of commingled feedstocks are shown in Figure 5-1. As can been seen, gas production rates were highly variable when BOF/MSW was used as feedstock. When the BOF/MSW was commingled with the various nutrient supplements, gas production rates somewhat stabilized. Optimum digestion was achieved with manure and sludge as nutritional supplements. The enhanced gas production rates and consistently higher pH values associated with sludge and manure additions indicates robust methanogenic activity and a healthy digestion process.

It is important to note that both manure and wastewater sludges have characteristics other than nutrients which may aid digestion such as: (1) potentially inoculating the system, (2) adding alkalinity to the system (directly), and (3) being a source of easily degradable organics. However, similar performance was achieved using autoclaved and non-autoclaved manure. Furthermore, the use of digested sludge (which presumably has high levels of anaerobic bacteria) produced no significant changes over the use of activated or primary commingled sludge feedstocks. The digested sludge had considerable alkalinity (4000 mg/L as $CaCO_3$) compared to the other sludges (600 mg/L as $CaCO_3$), but reactor alkalinity was essentially unchanged. Adding small quantities of the sodium bicarbonate (to duplicate the alkalinity of manure) in Experiment 4 also produced no significant effects. Additionally, the sludges and manure typically made up less than 10 percent of the biodegradable organic material in the commingled feedstock. It is possible, however, that the enhanced gas production rates associated with manure addition may be in part due to the fact that manure itself is a more concentrated form of many nutrients (i.e. nitrogen, phosphorus, potassium, and nickel) than the wastewater sludges. That is to say that with manure additions, the process may benefit from greater nutrient sufficiency as well as the higher digestion efficiencies associated with high-solids digestion.

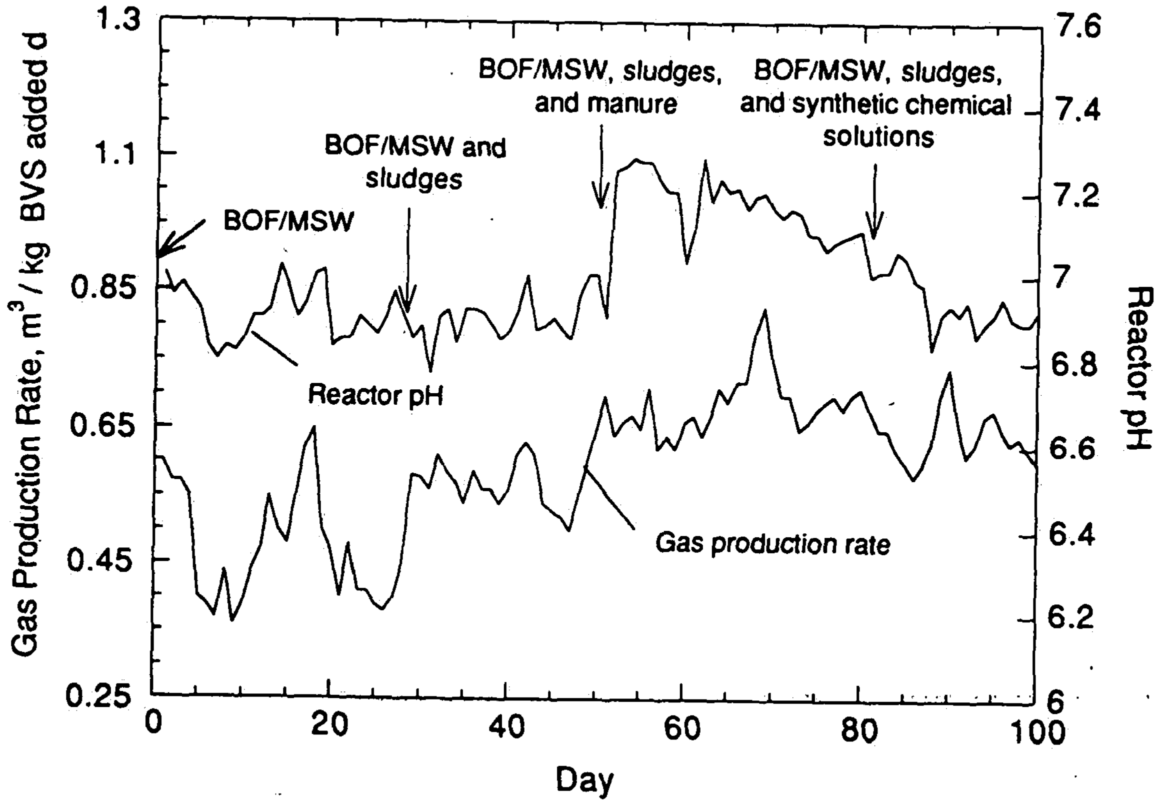

Figure 5-1
Gas production rates and reactor pH for different digester feedstocks.

Optimum Nutrient Concentrations for High-Solids Digestion of BOF/MSW

Based on typical feedstock nutrient concentrations during peak digestion (BOF/MSW + sludge + manure), the optimum commingled feedstock nutrient concentrations for high-solids digestion were calculated and are presented in Table 5-1. Additionally, Table 5-1 includes the reactor effluent nutrient concentrations during the same period of operation. As shown, there is a good correspondence between the feedstock nutritional characteristics of a desirable commingled feedstock and actual reactor nutrient concentrations during peak operation. It would be expected the nutrient concentrations be higher in the reactor due to the fact that some solids have been converted to biogas. Phosphorus, potassium, and nickel follow this trend, as indicated by the slightly higher effluent concentrations. The decrease in nitrogen concentration in the reactor effluent was presumably due to the bioconversion and subsequent volatilization of organic nitrogen to ammonia gas. Other micro-nutrients (Co, Mo, Se, W) were present in too small of concentrations to determine accurate trends. Iron (Fe) was assumed to be present in excess.

Table 5-1
Nutritional characteristics of the commingled feedstock and digester effluent at peak performance

		Average value (dry basis)		
		Commingled feedstock[a]		Reactor effluent
Nutrient	Unit	Range	Typical	Typical
C/N[b]		25-30	25	19
C/P[b]		150-300	180	120
C/K[b]		40 - 100	65	45
Co	ppm	<1 - 5	2	1
Fe	ppm	100 - 5000	1000	1800
Mo	ppm	<1 - 5	2	0.7
Ni	ppm	5-20	10	22
Se	ppm	<0.05	0.03	ND
W	ppm	<1	0.1	ND

[a] Desirable commingled feedstock nutrient characteristics.
[b] C/N, C/P, and C/K ratios are based on biodegradable organic carbon and total nitrogen, phosphorus, and potassium.

Although the use of soluble chemical solutions successfully stabilized the digestion process (Experiment 4), after 2 weeks the reactor effluent became slimy and digested solid/liquid separation occurred, inhibiting the digestion process. It is believed that although the chemicals were added to take the place of the nutrients in the manure, the highly soluble chemicals were much more bio-available and eventually artificially "spiked" the reactor. The slimy characteristics of the effluent are assumed to be from the complexation of the excess phosphorus with digested solids. The unknown bio-availability as well as the potential costs associated with the chemical solutions may make chemical addition a less attractive nutrient source for commercial applications.

Nutrient Hierarchy

It is believed that although all the macro and micro nutrients discussed in the paper have specific functions in the digestion process, nitrogen, phosphorus, potassium, and nickel deficiencies quickly result in process instability and decreased performance. These four nutrients are present in relatively high levels in dairy manure, and peak performance was observed during manure supplementation. The importance of the micro-nutrient nickel is also highlighted in Table 2-3, with the anaerobic treatment of most substrates experiencing stimulatory effects with nickel supplementation. The other micro-nutrients described are assumed to be present in sufficient trace concentrations within the BOF/MSW or their effect on the metabolism of anaerobic bacteria is not as pronounced.

ASSESSMENT OF THE HUMUS MATERIAL

The final humus produced using this process is a fine material with an energy content of 14.8 MJ/ kg (6360 BTU/lb), and a bulk density of 560 kg/m^3 (specific weight, 35 lb/ft^3). Based on preliminary combustion tests with a pilot-scale fluidized bed incinerator, it has been found that the humus material can be fired directly or mixed with other fuels for the production of energy (Kayhanian et al., 1994).

Alternatively, the humus material can be used as a soil amendment. The humus, however, would be categorized as a sludge-based product and regulated under the national Sewage Sludge Use and Disposal Regulation: Chapter 40 Code of Federal Regulations Part 503. This newly developed EPA rule (effective March 22, 1993) addresses many common use and disposal practices for sludge. In an attempt to promote the beneficial use of sludge, the rule sets national standards for sludge products that are land-applied, distributed or marketed. Part 503 contains limits for 10 metal pollutant concentrations, maximum pollutant loading rates, pathogen reduction requirements, and vector attraction reduction requirements. Other characteristics of the sludge products such as nutrient availability or phytotoxicity are assumed to be site-specific and selfimplementing. The effect of Part 503 on the use of the humus material applied to land is reported below and organized as: (1) humus pollutant concentrations, (2) pathogenic characteristics, and (3) vector attraction characteristics of the humus material

Humus Pollutant Concentrations

A comparison of the EPA limit, digested sludge concentration, and humus concentration for the 10 pollutants regulated in Part 503 is presented in Figure 5-2. Land application of sewage sludges or sludge-based products must meet the EPA pollutant concentration limit (shown in Figure 5-2) or cumulative or annual pollutant loading rates. The elemental analyses indicate that both the digested sludge and humus produced with digested sludge are below the EPA pollutant limits. However, the humus material is below limits by several orders of magnitude.

The relatively low humus pollutant concentrations are due to the commingling of the sludge with the BOF/MSW. Because the BOF/MSW is the primary substrate in the process, the sludges solids typically comprise around 5 percent of the input feedstock solids. Based on typical process performance and feedstock characteristics, it can be estimated by mass balance that humus pollutant concentrations are diluted to between 10 and 20 percent of the input sludge concentration. The dilution capacity of the process is confirmed in elemental analyses (Figure 5-2), although the differences in pollutant reduction may be due to sample variability. Overall, it appears that the anaerobic composting process effectively dilutes the metal pollutants contained in the sludge with the undigested solids of the BOF/MSW to environmentally safe levels.

Pathogenic Characteristics

Part 503 specifies two classes of pathogen reduction: Class A and Class B. Class A is intended to be equivalent to Process to Further Reduce Pathogens (PFRP) standards while Class B is intended to be similar to Process to Significantly Reduce Pathogens (PSRP) standards. Class A specifies one of six alternative pathogen reduction methods to be employed, including anaerobic digestion of the sludge between 15 days at 35 to 55 degrees Celsius and 60 days at 20 degrees Celsius. The indicator standard for Class A is less than 1,000 fecal coliforms per gram of dry solids.

The UC Davis anaerobic composting process may be considered an equivalent PFRP method. Both high-solids digestion and aerobic biodrying are maintained at thermophilic temperatures (55 degrees Celsius) and digestion is maintained at a 30 day

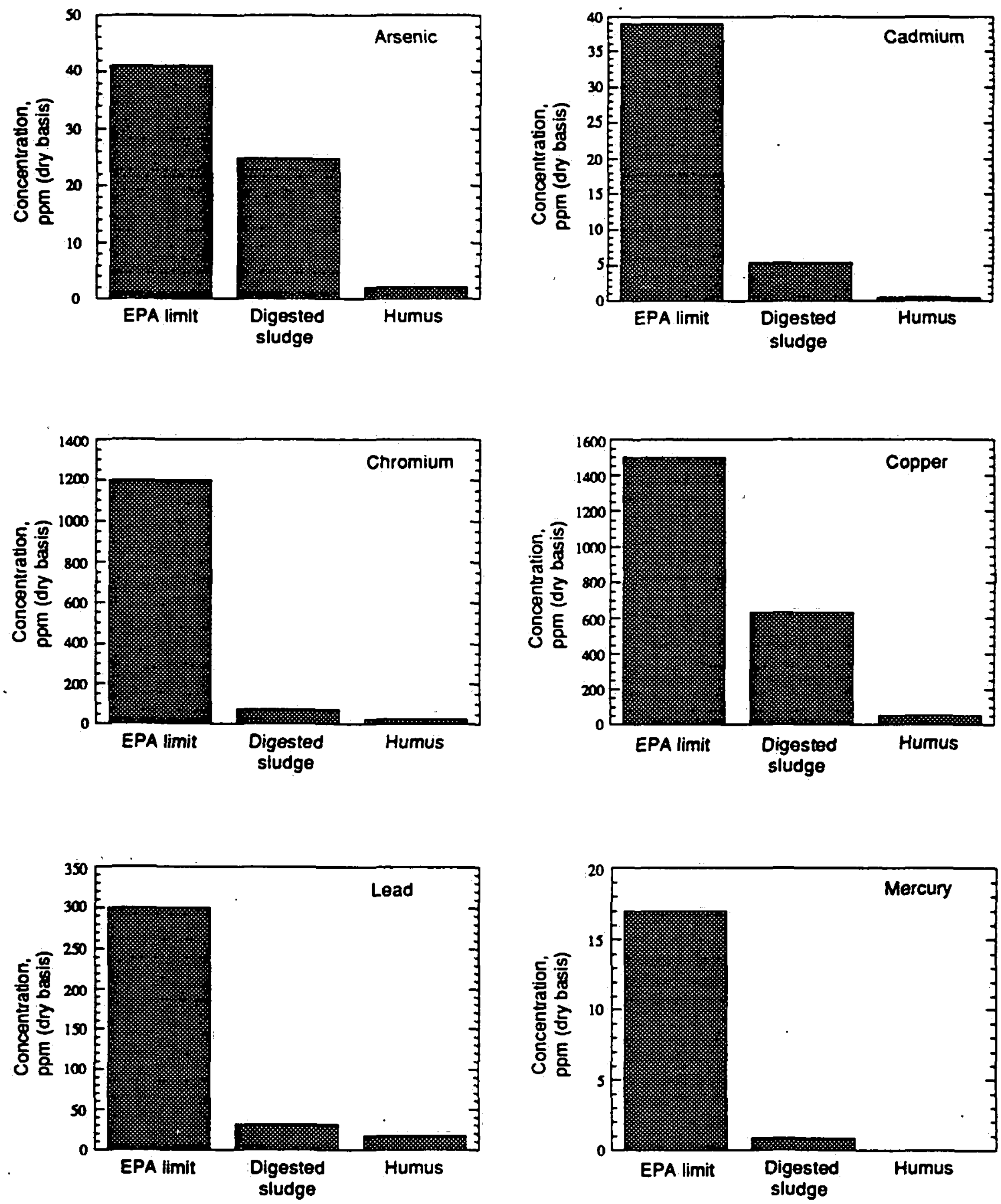

Figure 5-2
Comparison of the US EPA land application limits for ten metal pollutants to the metal concentrations found in digested sludge and in the humus produced with digested sludge.

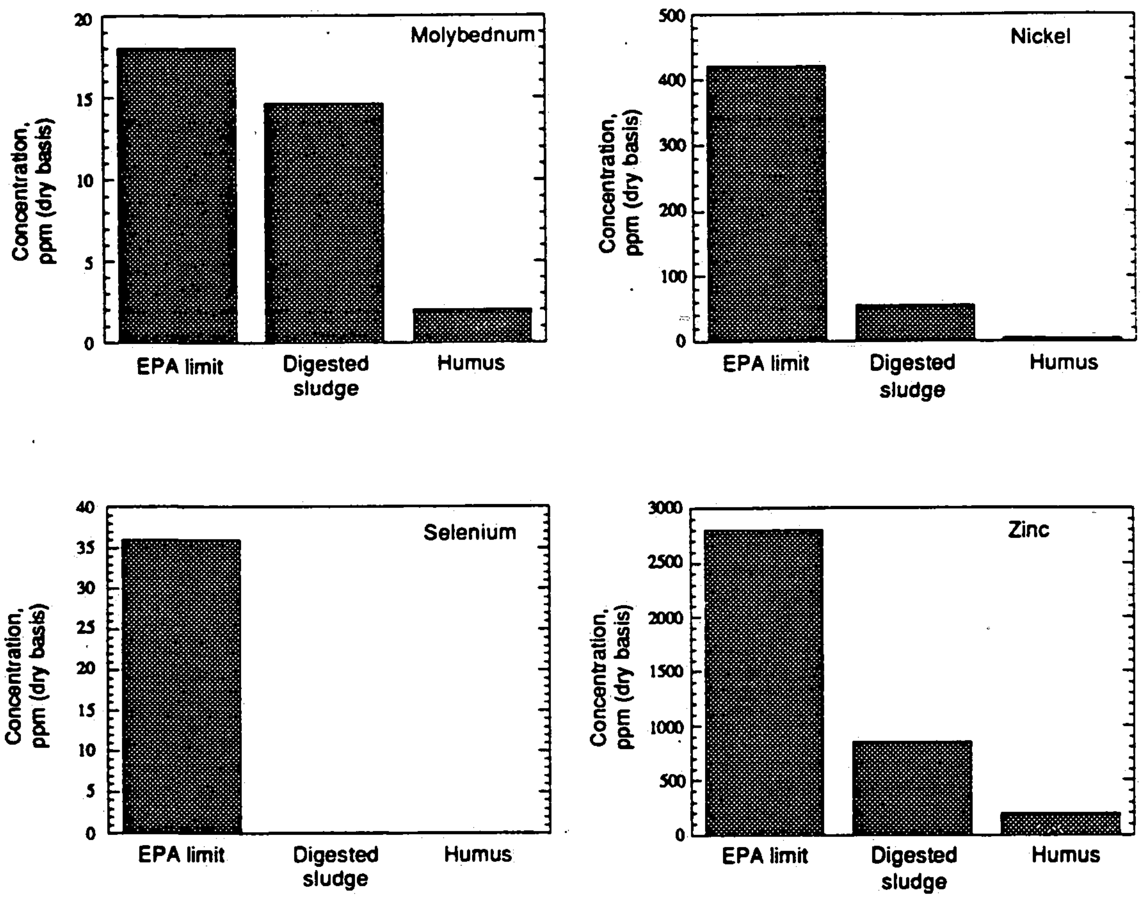

Figure 5-2, continued

nominal mass retention time. As shown in Table 4-7, no pathogenic indicators were detected in the final humus material. Therefore, sludge treated with this anaerobic composting process would meet a Class A pathogen reduction requirement.

Vector Attraction Characteristics

For vector attraction reduction, Part 503 requires one of 12 methods to be used, which focus on sludge volatile solids (VS) reduction or immobilization. Method 1, for instance, requires a 38 percent VS reduction. Since the high-solids anaerobic digestion process alone removes, on average, 80 percent of the biodegradable material in the feedstock (SeeTable 4-5), anaerobic co-composting may be considered to meet the Part 503 vector attraction reduction requirement. Furthermore, as shown in Table 4-7, the final humus is a fine, low moisture, non-putrescent material.

ASSESSMENT OF THE ANAEROBIC COMPOSTING PROCESS FOR WASTE VOLUME REDUCTION

The reduction in waste volume using the anaerobic composting process as compared to conventional sludge dewatering and waste compaction required in a typical California landfill is presented in Table 4-9. As shown, a volume reduction between 66 and 69 percent compared to conventional landfilling practices may be achieved, and therefore may potentially increase landfill life. Anaerobically composted humus would take up around 70 percent less volume than the compacted BOF/MSW and dewatered sludge. Moreover, because a high quality humus is produced, all the material could be diverted from the landfill and used as a beneficial product (i.e. soil amendment).

The conventional dewatering of sludge to at least 50 percent total solids before placement in a California landfill may be accomplished by a variety of means. Land-based practices include sludge composting and sludge drying beds and are both land intensive and a potential source of odors. Other processes, such as centrifugation or belting filter pressing or thermal treatment are also used to dewater the sludge. However, these processes are: (1) energy intensive, (2) typically require chemical conditioning, and (3) vary in effectiveness for different sludge types (i.e. biological sludges may be more difficult to dewater).

The anaerobic composting process appears to overcome these sludge dewatering shortcomings by essentially using the BOF/MSW as a source of energy and a bulking agent. Because the BOF/MSW is the primary substrate in the process, different sludge types will result in insignificant changes in process performance with respect to volume reduction. It is important to note that most of the sludge volume reduction occurs through evaporation during biodrying, thereby eliminating a liquid waste stream that would require further treatment.

6
SUMMARY AND RECOMMENDATIONS

This report is intended to serve as a feasibility study for anaerobic composting of the biodegradable fraction of municipal solid waste (BOF/MSW) and wastewater treatment plant sludges. A summary of this investigation and future research recommendations are described below.

SUMMARY

The high-solids anaerobic composting process has been used to co-manage the BOF/MSW and three types of wastewater treatment plant sludges. The process involves high-solids anaerobic digestion followed by aerobic biodrying. The BOF/MSW is comprised of a mixture of newsprint, office paper, yard waste, and food waste. The sludges investigated in this study represent the three general types of sludges produced during wastewater treatment: (1) primary sludge, (2) activated sludge, and (3) digested sludge. The BOF/MSW is the primary substrate in the high-solids digestion process, and the sludges are used to increase the moisture content of the BOF/MSW to appropriate levels for high-solids anaerobic digestion.

The pilot-scale digester was operated as a thermophilic semi-continuously fed and mixed reactor. The digester was maintained at organic loading rate of about 6.5 g BVS per kg active reactor mass, a 30 day nominal mass retention time, and an input C/N ratio between 22 and 30. For each of sludge type investigated, digestion was monitored for three months. The three sludge types had similar digester performance, with typical biogas production rates varying from 0.66 to 0.73 m^3 / kg BVS added· d and solids removal efficiencies ranging from 79 to 85 percent BVS removed. Commingled BOF/MSW and primary sludge was found to give the highest gas production rates and were least likely to have reactor upsets.

Sustained high-solids digestion of BOF/MSW requires nutrient supplementation. A lab-scale batch study and a series of pilot-scale nutrient availability digestion studies have confirmed that nutrient supplements in the form of wastewater sludges, dairy manure, and synthetic chemical solutions effectively stabilized the digestion process. The combined addition of wastewater sludges and diary manure also showed enhanced biogas production rates. Based on feedstock ratios and substrate nutrient concentrations, optimum nutrient concentrations for high-solids digestion of BOF/MSW have been determined and confirmed by analysis of the reactor effluent. It is believed that the digestion process is most sensitive to deficiencies of nitrogen, phosphorus, potassium, and nickel.

The humus material produced after aerobic biodrying is a fine, odorless material having a moisture content around 35 percent. The humus material complies with all aspects of the EPA's Part 503 federal regulation for sludge products that are land applied, distributed or marketed. Metal pollutants in the sludge are diluted with the digested solids of the MSW to between 10 and 20 percent of the original sludge concentration, allowing even high pollutant sludges to meet EPA pollutant limits. The humus also meets the Class A pathogen reduction and vector attraction reduction requirements

Overall, the anaerobic composting process appears to be an attractive alternative to conventional MSW and wastewater sludge management. The process is capable of achieving significant mass and volume reductions of the BOF/MSW and wastewater sludge. Using anaerobic composting process, the volume reduction relative to (1) dewatered sludge layered on the top of well compacted MSW, and (2) dewatered sludge mixed with a well compacted MSW in a landfill are 66 and 69 percent respectively. The biodegradable material in the substrates are converted to a biogas which may be used for the production of energy. The residual material may be used as an environmentally safe, nutrient/mineral-rich soil amendment or top-soil cover material, thereby diverting significant portions of the municipal waste stream from expensive and environmentally unattractive disposal practices such as landfilling or combustion. Anaerobic composting appears to be a feasible and an environmental benign technology.

RECOMMENDATIONS

A number of critical questions remain to be answered before this technology can be applied on a broader scale. To enhance the scope of an anaerobic composting process for commercial application, the following studies are recommended: (1) mitigation of the ammonia toxicity problem, (2) heavy metal mobility in the humus, (3) evaluation of humus characteristics, and (4) economics of the process. These research topics are briefly described below.

Mitigation of the Ammonia Toxicity Problem

Recent studies conducted at UC Davis indicate that when the organic fraction of MSW is mixed with nitrogen-rich organic substrates, digester performance may be reduced and that smaller amounts of biogas are produced as compared to the similar substrates with lower nitrogen contents. The lower gas production rate seems to be due to the fact that free ammonia, which at high concentrations inhibits methane formation, is formed during the anaerobic degradation of nitrogen-rich substrates. At present, a practical and reliable method to eliminate the ammonia toxicity problem in a high-solids anaerobic digestion process is not readily available. Further research on the ammonia toxicity problem would greatly enhance the scope of the application of high-solids anaerobic digestion for commercial use.

Heavy Metal Mobility in the Humus

If applied to land, the humus may increase the heavy metal concentrations of the soil, and potentially pose risks to plants, animals, and humans. Increases in metal concentrations, however, do not necessarily correlate with increased metal mobility and bioavailability. Based on preliminary observations, it appears that the lignin found in paper and yard wastes that does not biodegrade readily may serve to chelate, and potentially insolubilize, the heavy metals found in the wastewater sludges. If lignin chelation does occur , it may offer an alternative method that can be used for the management of metals in the land disposal of composted sludges.

Evaluation of Humus Characteristics

Preliminary characteristics of the humus have been determined by various physical, chemical, and biological analyses. The analyses indicate the humus may be an appropriate candidate for land application. Further studies of the humus would enhance the potential agricultural use of the humus. Additional research studies for the following topics would be appropriate: (1) evaluation of hazardous compounds within the humus, (2) field evaluation of the humus for agricultural use, and (3) presence of pathogenic bacteria such as Salmonella.

Economics of the Process

Anaerobic composting for the co-management of MSW and wastewater sludges has yet to be established on a commercial level in the United States, and economics of the process are relatively unknown. Based on UC Davis process performance and externalities such as landfill tipping fees, sludge treatment costs, and revenue from the compost and energy derived from biogas; a comparative cost analysis of anaerobic composting as a waste management alternative could be formulated.

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GLOSSARY

This glossary has been prepared to aid those readers of this report who may not be familiar with some of the terms used. Most of these terms are considered standard usage, with definitions that are well known and accepted in the field, while others are newly coined, based on recent developments in the field. It should be noted that the purpose of this glossary is not to standardize terminology, but to allow readers to understand any unfamiliar words that may be encountered in the report.

Acetogens

One of three types of bacteria which, together, anaerobically digest organic wastes. Also called acid-forming bacteria, these microorganisms convert the intermediate compounds made available by hydrolyzing bacteria into volatile fatty acids (VFA's), which are then consumed by methane-producing bacteria.

Acidity

The capacity of a liquid, slurry, or sludge to absorb alkali without a change in pH, usually due to minerals or compounds present in the liquid which react with the alkali to neutralize it. When the acidity, or buffering capacity, of a liquid is exceeded, the addition of alkali will cause a rise in pH.

Active Reactor Mass/Volume

Digester contents containing active bacteria, including feedstock, digestate, and bacterial mass.

Aerobic Biodrying

A mechanical drying process which allows a small degree of composting as the anaerobic digestate dries, but does not support complete composting.

Alkalinity

The capacity of a liquid, slurry, or sludge to absorb acid without a change in pH, usually due to minerals or compounds present in the liquid which react with the acid to neutralize it. When the alkalinity, or buffering capacity, of a liquid is exceeded, the addition of acid will cause a drop in pH.

Ammonia

An organic nitrogen, NH_3, which is released during anaerobic digestion as bacteria degrade nitrogen containing proteins. The name is usually used to refer to both the free ammonia and the ammonium ion concentrations, since analytical tests cannot distinguish between the two forms. The term free ammonia is used to distinguish it from ammonium. Free ammonia is more inhibitory to methanogenesis than ammonium.

Ammonium

An ionized form of ammonia, NH_4^+, ammonium is less inhibitory to methanogenesis than its unionized, parent compound. The relative ratios of ammonia to ammonium in a liquid or semi-solid depend upon pH. The lower the pH, the less free ammonia relative to ammonium. Therefore, ammonia toxicity depends on pH as well as the ammonia concentration.

Ammonia Toxicity

Free ammonia interferes with methanogenesis. If the interference is slight, it is referred to as ammonia inhibition. However, when the free ammonia level is too high, it can slow methanogenesis sufficiently to prevent the methane forming bacteria from consuming the acids formed by the acid forming bacteria in the anaerobic digestion process. This acid buildup further inhibits methanogenesis and the digester fails.

Batch Digestion/Digester

An anaerobic process in which a digester vessel is filled with feedstock and bacterial inoculum and then sealed and allowed to digest until the degradation process is complete.

Bicarbonate

An acid salt of carbonic acid containing the radical HCO_3^-. Bicarbonates add to the buffering capacity of liquids and sludges.

Biodegradable Carbon

The concentration of carbon contained in the biodegradable fraction of a material. Calculated by multiplying the carbon concentration by the biodegradable percentage of an organic material.

Biodegradable Volatile Solids

That portion of the volatile solids of a material that is biodegradable.

Biogas

The gas produced by anaerobic digestion process, usually containing about 50 percent methane (CH_4), 50 percent carbon dioxide (CO_2), and trace gasses, such as hydrogen sulfide (H_2S) and light hydrocarbons.

Biosolids

Term recently coined as a synonym for digestate or sludge. An inexact euphemism.

Buffering Capacity

see Alkalinity, Acidity

C/N Ratio

The ratio of carbon (C) to nitrogen (N) in a feedstock or digestate. Conventionally, the C/N ratio is calculated using the dry weights of carbon and nitrogen present in a material. However not all of the carbon in a complex feedstock is available for biotransformation. The C/N ratio is, therefore, calculated more accurately using the dry weight of nitrogen and the biodegradable dry weight of carbon, as determined using batch studies or lignin content.

Carbonate

An acid anhydride salt of carbonic acid containing the radical CO_3^{-2}. Carbonates add to the buffering capacity of liquids and sludges.

Co-digestion

The or digestion of two or more commingled wastes, such as MSW, wastewater sludge, and organic chemical waste. Wastes are sometimes mixed to provide digester microorganisms with complete nutrition.

Coliform bacteria

A group of bacteria typically found in the lower intestine of mammals. The presence of these organisms is taken as an indication that pathogens, which also are excreted in fecal matter, may be present.

Decomposition

The breakdown of organic wastes by biological or other means. Complete decomposition leaves only inorganic residue.

Digestate

Waste material that has been subjected to anaerobic digestion and from which, therefore, most of the biodegradable volatile solids have been removed. Digestate is also referred to as sludge or slurry.

Digestion, anaerobic

The conversion of wastes by bacterial metabolism under anaerobic conditions. Biogas is produced by this process.

Feedstock

The material fed into a biological process to provide nutrition to the microorganisms. A feedstock usually has both organic and inorganic components.

First Order Rate Constant

An empirically derived proportionality constant used to characterize the rate of biological activity.

Gas Production Rate

The rate at which bacteria convert an organic substrate to biogas (principally methane and carbon dioxide). Gas production rate may be expressed in terms of the volume of gas produced per active volume of the reactor per day or, alternatively, the volume of gas produced per mass of substrate fed per day.

Heavy Metals

Metals which are not in the elemental groups IA or IIA on the periodic table. Heavy metals of concern in anaerobic digestion and compost management include: copper (Cu), iron (Fe), chromium (Cr), cobalt (Co), nickel (Ni), zinc (Zn), molybdenum (Mo), lead (Pb), mercury (Hg), and others.

High-solids Digestion

Anaerobic digestion which occurs at a total solids content of 25 percent or more, usually at solids concentrations of between 25 and 32 percent.

Humus

A residue from the decomposition or digestion of organic wastes, resistant to further degradation. Humus is often a natural part of soils and can be used as a soil amendment.

Hydraulic Retention Time (HRT)

The volume of a vessel divided by the influent flow rate or rate of input volume. In a continuous flow digester, the HRT represents the average time that a given volume of input stays in the vessel.