Anaerobic Codigestion of Municipal, Farm, and Industrial Organic Wastes: A Survey of Recent Literature

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ABSTRACT: Codigestion of organic wastes is a technology that is increasingly being applied for simultaneous treatment of several solid and liquid organic wastes. The main advantages of this technology are improved methane yield because of the supply of additional nutrients from the codigestates and more efficient use of equipment and cost-sharing by processing multiple waste streams in a single facility. Many municipal wastewater treatment plants (WWTPs) in industrialized countries currently process wastewater sludge in large digesters. Codigestion of organic wastes with municipal wastewater sludge can increase digester gas production and provide savings in the overall energy costs of plant operations. Methane recovery also helps to reduce the emission of greenhouse gases to the atmosphere. The goal of this literature survey was to summarize the research conducted in the last four years on anaerobic codigestion to identify applications of codigestion at WWTPs. Because the solids content in municipal wastewater sludge is low, this survey only focuses on codigestion processes operated at relative low solids content (slurry mode). Semi-solid or solid codigestion processes were not included.

Municipal wastewater sludge, the organic fraction of municipal solid waste, and cattle manure (CAM) are the main wastes most often used in codigestion processes. Wastes that are codigested with these main wastes are wood wastes, industrial organic wastes, and farm wastes. These are referred to in this survey as *codigestates.* The literature provides many laboratory studies (batch assays and bench-scale digesters) that assess the digestibility of codigestates and evaluate the performance and monitoring of codigestion, inhibition of digestion by codigestates, the design of the process (e.g., single-stage or two-stage processes), and the operation temperature (e.g., mesophilic or thermophilic). Only a few reports on pilot- and full-scale studies were found. These evaluate general process performance and pretreatment of codigestates, energy production, and treatment costs. *Water Environ. Res.,* **78,** 607 (2006).

KEYWORDS: Anaerobic digestion, codigestion, organic wastes, digestibility, methane production.

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Introduction

Codigestion of organic wastes is a technology that is increasingly being applied for the simultaneous treatment of several solid and liquid organic wastes. The main advantages of this technology are improved methane (CH_4) yield because of the supply of additional nutrients from the codigestates and a more efficient use of equipment and cost-sharing by processing multiple waste streams in a single facility. Codigestion also allows for digestion of materials such as fat or protein wastes, which are poorly biodegradable and cannot be digested if not mixed with other, more degradable wastes.

Use of the spare capacity in anaerobic digesters at full-scale facilities potentially is an attractive option for codigestion. For example, in Germany, there are over 500 facilities for the anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) with a total capacity of approximately 8.4 million metric tons per year (Kübler et al., 2000). Full-scale facilities for anaerobic digestion of animal manure (i.e., cattle and hog manure) have also become common in Europe. Indeed, the first full-scale study on codigestion investigated the addition of bentonite-bound oil and/or size water (a waste from protein extraction from bone) to thermophilic digesters fed with cow manure (Ahring et al., 1992). Likewise, anaerobic digesters at municipal wastewater treatment plants (WWTPs) potentially are available for codigestion of organic wastes. For example, the City of Los Angeles Bureau of Sanitation (California) currently operates two WWTPs (Hyperion and Terminal Island) that process municipal wastewater sludge (MWS) in large digesters (Iranpour et al., 2003; 2004a, b; 2005; 2006; Oh et al., 2005; Shao et al., 2002). The methane produced during anaerobic digestion is recovered and used for heating of the digesters and for electricity production. Enhancement of methane production by codigestion would provide considerable savings in the energy costs of these plants or could even add an income to the process. In general, methane recovery from organic industrial wastes is the most economic alternative for handling of these types of wastes (Nielsen et al., 2002).

Codigestion of organic wastes with manure has been investigated in Denmark since the late 1980s (Danish Energy Agency, 1995). Earlier works also include the codigestion of OFMSW with MWS (Mata-Alvarez and Cecchi, 1990), while, in recent years, many studies on the codigestion of MWS, OFMSW, and other organic wastes have been published (Ahring and Angelidaki, 1997; Demirekler and Anderson, 1998; Griffin et al., 1998; Poggi-Varaldo et al., 1997). Although most works have demonstrated the advantages of codigestion, only few full-scale applications have been implemented for MWS (Hartmann et al., 2003; Mata-Alvarez et al., 2000).

The goal of this literature survey was to summarize the research conducted in the last four years on anaerobic codigestion. The focus was on digestion of waste mixtures with relatively low solids content (“slurry mode of operation”) to use the data for future implementation of codigestion processes with MWS at WWTPs. Hence, semi-solid or solid codigestion processes were not included in this survey. Particular attention was paid to the codigestion of fat, oil, and grease (FOG) materials and OFMSW because disposal of these two wastes is an important environmental issue in urban areas.

Survey Approach

This survey focused on laboratory and pilot- and full-scale studies published in scientific journals and conference proceedings over the past four years. Research conducted before this period has been reviewed by Mata-Alvarez et al. (2000) and De Baere (2000). Many studies in this survey were presented at the 9th World Congress on Anaerobic Digestion held in Belgium in 2001.

Codigestion research covers a wide range of topics, and the assessment of each process requires evaluation of great number of parameters. To provide detailed information in an easily accessible manner, all quantitative data have been categorized in the following tables:

- Tables 1 to 3: Laboratory batch assays for the preliminary evaluation of the digestibility of codigestates and the methane production potential of codigestates and mixtures of wastes.
- Table 4: Laboratory bench-scale studies using a single stage.
- Table 5: Laboratory bench-scale studies using two stages.
- Table 6: Pilot-scale studies that mostly focus on verification of parameters and process criteria obtained from bench-scale studies.
- Table 7: Full-scale applications of codigestion with performance evaluation by monitoring of, for example, pH, alkalinity, volatile fatty acids (VFAs), volatile solids (VS) destruction, and the gas or methane production.

Results

The three major waste streams identified by this literature survey were MWS, OFMSW (also referred to as the putrescible fraction of municipal solid waste), and cattle manure, also referred to as cattle slurry or cattle dung (CD). Some studies used a combination of two or three of these major wastes. Wastes most often used for codigestion (codigestates) with the major wastes were agricultural materials such as energy crops and woody materials, industrial wastes such as confectionery byproducts and enzyme industry wastes, farm wastes such as chicken manure (CM) and waste milk (WM), and municipal wastes such as food and vegetable waste (FVW). Some studies also specified the bacterial inoculum used in the experiments. These were, in general, obtained from anaerobic digesters containing one of the three main wastes.

Laboratory Studies

Laboratory studies using batch assays are summarized in Tables 1 to 3. The main goal of these studies was to screen individual wastes and waste mixtures for the potential of methane production (Table 1). The methane production potential is generally measured as the specific methane yield (SMY). In some studies, the SMY was based on the amount of volatile solids added (VS_{in}), while in others this was based on the amount of volatile solids destroyed (VSD). Additional issues addressed in batch assays included (a) the codigestion of wastes of low biodegradability; (b) the effect of pretreatment and temperature on codigestion; (c) kinetic studies (Table 2); (d) toxicity of wastes on codigestion (Table 3). If available from the reviewed studies, Tables 1 to 3 include the quantitative composition of the codigestates. Tables 4 and 5 summarize laboratory-scale digesters studies using one or two stages, respectively. The topics frequently addressed in these studies were optimization of the composition of the waste mixtures, the organic loading rate (OLR), the hydraulic retention time (HRT) and parameters for monitoring digester instability. Laboratory studies often combined batch assays with single-stage digester studies. These are, therefore, discussed together in the "Batch Assays and Single-Stage Process" section. Two-stage bench-scale digester studies are separately discussed in the "Two-Stage Processes" section.

Batch Assays and Single-Stage Processes. *Municipal Wastewater Sludge. Woody and Agricultural Wastes with High Content of Cellulose.* Converti et al. (1997) studied the benefits of chemical prehydrolysis for solubilizing hemicellulose and lignocellulose in wood chips and corn waste before anaerobic codigestion with MWS. Batch digestion assays were performed with dilutions of a mixture of MWS and the waste hydrolyzates at a chemical oxygen demand (COD) loading ranging from 0.8 to 6.1 g/L (0.6 to 4.5 kg $VS/m^3 \cdot d$). Methane production was maximal at a COD concentration of 3.8 g/L, but declined at higher concentrations (Table 1). Likewise, a stable and efficient fed-batch process was established at a COD loading of 2.2 g $COD/L \cdot d$ (Table 4). However, the codigestion efficiency was lower than what is generally observed for the sole digestion of MWS. This was probably because of inhibition by furfurals (released from hemicellulose during acidic pretreatment) that were measured in significant amounts in the hemicellulose hydrolyzates. The inhibitory effect of furfurals on methanogenesis has been reported by Azhar et al. (1981). Another inhibitory factor could have been the presence of phenolic compounds that are released from lignin during caustic pretreatment. Nearly complete inhibition of methanogenesis has been observed at phenol concentrations over 8 mM (Watson-Craick et al., 1993).

Converti et al. (1999) conducted kinetic studies of the thermophilic anaerobic digestion of the lignocellulosic matrix present in vegetable wastes (VW). Batch assays demonstrated that the hydrolysis of cellulose was the rate-limiting step in the anaerobic digestion of the lignocellulosic matrix (Table 2). However, the biodegradability of VW in fed-batch reactors was not significantly improved by hydrolytic pretreatment (Table 4). Converti et al. (1999) also compared mesophilic and thermophilic codigestion (37 and 55°C) of VW with MWS. The methane content of the biogas was 10% higher at 55°C and the residence time could be reduced by 25 to 35%, while still achieving the same performance as at 37°C.

Aircraft Deicing Fluid. Aircraft deicing fluid (ADF) is a propylene glycol-based fluid that is sprayed in large amounts on aircrafts to prevent ice formation. Zitomer et al. (2001) recently evaluated the methane production potential of ADF with and without the addition of acetate to assess the toxicity of ADF to aceticlastic methanogens (Table 3). The methane yield was over 80% of the stoichiometric maximum at an ADF dose of up to 2.2 g COD/L, but severe toxicity was observed at an ADF dose of 8.94 g COD/L. These results suggested that codigestion of ADF with MWS would be feasible, as was confirmed in bench-scale experiments. The SMY increased from 0.74 m^3/kg VSD during sole digestion of MWS to over 2.8 m^3/kgVSD during codigestion of diluted ADF (OLR of 2.7 g COD/L per day). It is important to note that ADF has been anaerobically codigested in Taarnby, Denmark, at a full-scale WWTP for approximately 10 years (personal communications).

Carbohydrate-Rich Food Waste. To compare several parameters commonly used as indicators of process performance, Björnsson et al. (2000) conducted a study using three bench-scale digesters fed with MWS (Table 4). After stable operation, the OLR of the digesters was increased by addition of carbohydrate-rich food waste. One digester received a pulse load by increasing the OLR from 1.6 to 3.6 kg $VS/m^3 \cdot$ day. Partial alkalinity and pH decreased and VFA levels increased while the total alkalinity remained constant. In the other two digesters, the OLR was stepwise increased. Signs of overloading were observed at 5.9 kg VS/m3 · day in one digester and at 5.3 kg VS/m^3 · day in the other digester. In both cases, changes in process monitoring parameters were similar to those observed during the pulse load. The authors concluded that partial alkalinity and VFA levels were reliable parameters for monitoring. The pH was a less reliable parameter because of possible variations of the buffering capacity.

Municipal Wastewater Sludge and the Organic Fraction of Municipal Solid Waste. Industrial Organic Wastes. Einola et al. (2001) evaluated the codigestion of paper mill wastewater sludge and enzyme industry waste with OFMSW and MWS. Methane yields from the sole digestion of individual wastes and from codigestion of waste combinations were measured (Table 1). Good digestibility was observed when paper mill wastewater sludge and enzyme industry waste were present at relatively low contents of 10 to 20%. Codigestion in bench-scale digesters was stable at an OLR of up to 7 kg VS/m^3 · day with mixtures containing 10 or 30% paper mill wastewater sludge and 20% enzyme industry waste. Digester instability was observed at 30% enzyme industry waste or more. Accumulation of toxic intermediates such as VFAs and toxic byproducts such as ammonia or other unknown inhibitory compounds was suggested as factors potentially destabilizing the digesters.

Cattle Manure. Waste Milk. Callaghan et al. (1997) determined the maximum concentration of waste milk that could be codigested with cattle manure without adversely affecting the gas production. Waste milk was added at different COD loadings (Table 1). Immediately after addition, the gas production rate transiently increased from 0.3 L/day to a maximum of 1.46 L/day in the digesters receiving the highest loading of 29.3 kg COD/m^3. Free ammonia and ammonium levels increased in all tests. The results suggested that upscaling of codigestion of waste milk with cattle manure would be feasible, but that inhibition by ammonia was a factor to be considered.

Fish Offal, Brewery Sludge, Dissolved Air Flotation Sludge, and Fruit and Vegetable Waste. Callaghan et al. (1999) studied the codigestion of various industrial and farm wastes with cattle manure (Table 1). Methane yields increased when codigesting fish offal or brewery sludge, but decreased when codigesting FVW or dissolved air flotation sludge. The dissolved air flotation sludge came from a unit used to reduce the solid's load on an activated sludge plant treating the waste from a yogurt manufacturing facility. Decreasing methane yields with the latter codigestates were probably caused by high free ammonia concentrations.

Fruit and Vegetable Waste and Chicken Manure. Callaghan et al. (2002) conducted bench-scale digester studies of the codigestion of FVW and chicken manure with cattle manure (Table 4). Increasing the FVW load caused higher methane yields, but the VFA-to-alkalinity ratio (VFA/alkalinity) increased to the range of 0.4 to 0.8, pointing to possible digester instability (Switzenbaum et al., 1990; Zickerfoose and Hayes, 1976). When increasing the cattle manure load, both the SMY and the VS destruction decreased, but the VFA/alkalinity was still below the range of 0.4 to 0.8. In the latter case, the low digester performance could be ascribed to the toxicity of high levels of free ammonia ($>$100 mg/L).

Molasses, Chicken Manure, Sheep and Goat Manure, Fruit and Vegetable Waste, and Waste Activated Sludge. Misi and Forster (2001) examined the use of a response surface method for optimizing the digestion of three- and five-component waste mixtures. This method is a mixture design mathematical technique, commonly used in pharmacy and chemistry (Cornell, 1981 and 1990) to evaluate whether the ingredients of a mixture produce an additive response or whether the response is synergistic or antagonistic. Misi and Forster (2001) measured the SMY and VSD as functions of the waste mixture composition. In the three-component trials, the addition of molasses to chicken manure, cattle manure, or a mixture of chicken manure and cattle manure enhanced the methane yield (Table 1). The five-component trial indicated that digestion of cattle manure was enhanced when FVW and cattle manure were added. The response surface method appeared to be able to predict the optimum composition of waste mixtures for codigestion. However, it was also concluded that mixing of wastes in optimal ratios at full-scale facilities may not be feasible because waste supply rates to the facility are likely to be in a different ratio.

Poultry Waste, Fruit and Vegetable Waste, and Thickened Waste Activated Sludge. Misi and Forster (2002) investigated the codigestion of mixtures with different ratios of poultry waste and thickened waste activated sludge (TWAS) with 15% FVW and 15% cattle manure in bench-scale digesters. None of the mixtures caused process instability, and increasing the poultry waste contents increased the methane yields from 0.162 (at 0% poultry waste) to 0.25 (at 75% poultry waste), as shown in Table 4. However, the VSD decreased from 52% (at 0% poultry waste) to 40% (at 70% poultry waste). The authors did not provide a clear explanation for these inconsistent results, but they suggested the presence of an organic constituent in the poultry waste with a "high potential for methane production". Their overall results indicated that, although poultry waste has a good potential for enhancing methane production, further investigation is needed to determine if increasing levels of free ammonia, observed at increasing percentage of poultry waste, were responsible for the decrease in VS destruction or if other unknown factors were affecting performance process.

Agricultural and Industrial Wastes. Kaparaju et al. (2001) evaluated the methane production potentials of energy crops (clover, grass, hay, and oats) and confectionery byproducts (chocolate, black candy, and confectionery raw materials) using digested cattle manure as inoculum (Table 1). Methane yields from confectionery byproducts were, on average, 65% higher than from energy crops. Full-scale codigestion tests of these wastes with cattle manure are presented in the "Other Main Wastes" section.

Hog and Poultry Waste. Magbanua et al. (2001) conducted a feasibility study of the codigestion of various ratios of diluted liquid hog and poultry wastes in batch assays (Table 1). Methane production during sole digestion of poultry waste was very low, but addition of hog waste enhanced the performance. The SMY was the highest at 40 to 80% (v/v) hog waste in the mixture. Levels of ammonia (total and free) were far below those reported as inhibitory because both wastes were diluted, which reduced the ammonia loading and promoted digestion stability.

Two-Stage Processes. The use of two-stage anaerobic codigestion processes is generally recommended for treating highly biodegradable wastes because these processes allow higher OLR. A few laboratory studies have been performed over the past four years, which are summarized in Table 3.

Municipal Wastewater Sludge. Confectionary Waste. Lafitte-Trouqué and Forster (2000) evaluated a two-stage process for codigesting confectionary waste with MWS. The first-stage consisted of a thermophilic acid phase (55°C, 4 h HRT). Three HRTs (8, 12, and 15 days) were tested in the second stage for gas production, which was operated at 35°C (Table 5). An HRT of 12 days in the second stage was the most effective with respect to the stability of the pH and the SMY. Volatile solids destruction, however, was approximately the same at

Table 1—Laboratory batch assays.

		Codigestate or codigestate mix					
			Quality				
Author or location	**Main waste and inoculum**	**Type**	**TS**	**VS**	**Nitrogen**	**ALK**	**pH**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Converti et al. (1997) Genoa, Italy See Table 2 for bench digester study	Municipal wastewater sludge (MWS): Primary and excess sludges Inoculum: mesophilic anaerobic digested MWS	a) Wood hydrolyzates: acidic hydrolysis of wood chips (mainly oak) to release hemicellulose sugars. The residue was treated with caustic solution for lignin and cellulose solubilization. b) Corn starch hydrolyzate (CSH): enzymatic hydrolysis of starchy residues from corn overproduction and cultivation wastes.					
Einola et al. (2001)	MWS		%	%	Kjeldahl-N (g/kg)		
Jyvaskyla, Finland	OFMSW	a) MWS	13	8	8.0		
See Table 2 for bench digester study	Inoculum: mesophilic anaerobic digested MWS (11 g VS/L)	b) OFMSW	30	26	5.5		4.5
		c) Enzyme industry waste	27	13	12		5.1
		d) Paper mill waste	16	12	5.9		7.0
		Mix 1: a, b, c, d	19	13	7.0		5.9
		Mix 2: a, b, c	21	15	6.9		5.9
		Mix 3: a, b, c, d	19	13	7.0		6.5
		Mix 4: a, c	17	9	7.6		7.1
		Mix 5: b, c	29	21	8.1		5.9
		Mix 6: a, b	19	14	5.7		5.9

ALK: alkalinity; COD: chemical oxygen demand; CSH: corn starch hydrolyzate; MWS: municipal wastewater sludge; Kjeldahl-N: nitrogen (Kjeldahl); OFMSW: organic fraction of municipal solid waste; SMY: specific methanogenic yield; TS: total solids; VFA: volatile fatty acids. VS: volatile solids; VSD: volatile solids destruction; VSin: volatile solids influent.

Callaghan et al. (1997) Birmingham, United Kingdom	Cattle slurry (CD) Inoculum: digested cattle slurry	WM		g COD/L 190			
Callaghan et al. (1999)	CD Trial 1: 100 g/L TS; 70 g/L VS; pH 8.1; 1040 g/L NH_3-N		g/L	g/L	NH_3-N (mg/L)		
Birmingham, United Kingdom		a) Dissolved air flotation sludge	50	38	<10		5.5
	Trial 2: 137 g/L TS; 107 g/L VS; pH 7.8	b) Brewery sludge	41	29	1000		8
		c) Fish offal	490	481	<10		6.7
		d) Fruit and vegetable waste (FVW)	167	156	<10		4.2
		Chicken manure	300	219	12,800		7.3

ALK: alkalinity; CD: cattle slurry; COD: chemical oxygen demand; FVW: food and vegetable waste; NH_3-N: nitrogen (ammonia); SMY: specific methanogenic yield; TS: total solids; VS: volatile solids; VSD: volatile solids destruction; WM: waste milk.

Table 1—(Extended)

Batch assay conditions				Performance		
Mixture composition	Temp °C	Organic load	pH	VSD %	CH_4 or gas production	Remarks
9	10	11	12	13	14	15
Mixture of: MWS (1.00 liter), wood hydrolyzate (0.682 L) and CSH (0.301 L) diluted with tap water up to the COD in column 11	37	g/L COD			mmol CH_4/L Remark 1	1. Molar methane production per unit reactor volume. 2. Ultimate SMY of 0.103 m^3/kg VSD at 3.8 g/L COD. 3. Ultimate SMY of oak hydrolyzates was lower than those of OFMSW, sorted leaves, and grass (0.27, 0.123, and 0.209 m^3/kg VSD, respectively), but higher than those of softwood or yard waste (0.01 to 0.06 and 0.05 to 0.09 m^3/kg VSD, respectively).
		1.2			1.1	
		1.5			2.4	
		1.8			5.1	
		2.9			8.8	
		3.8 Remark 2			11.5	
		6.1			7.4	
		g VS/L			SMY m^3/kg VSin	1. Codigestion of mixtures with higher proportions of enzyme industry waste and paper mill sludge resulted in the accumulation of VFA and lower methane yields. Both wastes could be codigested when present in low proportions.
Sole digestion	35	10–12			0.430 ± 0.055	
″	″	10–12			0.550 ± 0.037	
″	″	3.3–6.6			0.620 ± 0.035	
					0.510 ± 0.050	
″	″	10–12			0.180 ± 0.007	
% wet weight						
a) 30%; b) 20%; c) 20%; d) 30%	″	10–12			0.370 ± 0.066	
a) 50% b) 30%; c) 20%	″	″			0.460 ± 0.016	
a) 50%; b) 20%; c) 20%; d) 10%	″	″			0.410 ± 0.033	
a) 70%; c) 30%	″	″			0.320 ± 0.056	
b) 60%; c) 40%	″	″			0.570 ± 0.018	
a) 60%; b) 40%	″	″			0.370 ± 0.060	
Mixtures of CD and inoculum (50% by volume) were prepared with initial CODs of 69 to 89 kg/m^3. After 14 days incubation, a pulse load of WM was added at the organic loads indicated in column 11.		kg/m^3 COD			Gas/CH_4 L/day (% CH_4) Remark 1	1. Reported values for gas and methane production correspond to the 4th day after WM addition. Reported methane content correspond to the lowest value observed after WM addition. 2. WM addition caused higher gas and methane production, but lower methane content in the gas, indicating that some stress occurred. The decrease of methane content, was only temporarily.
		9.6			0.90 gas 0.43 CH_4 (44% CH_4)	
	35	19.7			1.10 gas 0.64 CH_4 (35% CH_4)	
		29.3			1.46 gas 0.74 CH_4 (33% CH_4)	
Trial 1 (% by weight)		g VS/L			SMY m^3/kg VSD	1. TS content of some wastes was adjusted before addition to codigestion mixture as follows: fish offal 8.7%; fruit and vegetable waste 9.2%; chicken manure 7.5 % (mix 1) and 15% (mix 2). 2. Codigestion of fish offal and brewery sludge slightly improved the SMY. 3. Addition of chicken manure with 15% TS caused a lower SMY, probably because of high ammonia concentrations.
Control: 100% CD	35	68	8.1	31.1	0.3	
70% CD; 10% inoculum; 20% codigestate	″	56.6	7.8	45.2	0.27	
″	″	54.8	8.0	33.9	0.31	
″ (Remark 1)	″	79.2	7.7	47.3	0.38	
″ (Remark 1)	″	72.8	7.7	52.1	0.22	
Trial 2 Same as in trial 1, but with a different batch of cattle slurry						
	35	96.3	7.6	51.8	0.15	
Mix 1 (Remark 1)	″	84.4	7.3	48.9	0.16	
Mix 2 (Remark 1)	″	93.8	7.2	81.0	0.12	

Table 1—(Continued)

		Codigestate or codigestate mix					
			Quality				
Author or location	Main waste and inoculum	Type	TS	VS	Nitrogen	ALK	pH
1	2	3	4	5	6	7	8
Misi and Forster (2001) Birmingham, United Kingdom	No main waste. See column 3. Inoculum: mesophilic digested wastewater (20% by volume)	Trial A: Mixture composition (% TS). Remark 1	g/L	g/L	NH_3-N (mg/L)	TAlk (mg/L)	
		Mix 1: 100% molasses	35.0	21.8	421	9651	8.1
		Mix 2: 100% CM	41.0	24.7	1757	16 477	7.9
		Mix 3: 100% CD	50.5	35.2	419	8788	7.7
		Mix 4: 50% CD, 50% CM	42.0	28.3	1135	11 063	7.5
		Mix 5: 50% CM, 50% molasses	40.5	25.0	1177	9442	7.2
		Mix 6: 50% CD, 50% molasses	47.0	31.2	349	7899	7.0
		Mix 7: 33.3% each CD, CM, and molasses	44.0	25.0	827	10 095	7.3
		Trial B: Mixture composition (% TS). Remark 1: Each mixture contained fruit and vegetable waste (15 % TS), cattle slurry (15% TS), and					
		Mix 1: 70% WAS	46.0	25.8	271	7350	7.1
		Mix 2: 70% CM	41.5	26.9	996	9950	7.3
		Mix 3: 70% SGM	48.0	34.8	267	7000	7.2
		Mix 4: 35% SGM, 35% CM	41.5	28.7	640	8350	7.3
		Mix 5: 35% CM, 35% WAS	43.0	26.3	623	8875	7.2
		Mix 6: 35% SGM, 35% WAS	46.0	30.2	259	7700	7.0
		Mix 7: 33.3% SGM, CM, WAS	42.0	27.3	515	8125	7.2
Kaparaju et al. (2001) Jyvaskyla, Finland See Table 5 for full-scale digester study.	No main waste. See column 9 Inoculum: mesophilic digested cow manure	Energy crops	%	%	Total N (mg/L)		
		a) Clover (vegetative)	18.7	16.9	3100		7.8
		b) Clover (flowering)	13.5	11.9	3800		7.8
		c) Grass hay	25.9	23.6	1700		7.9
		d) Oat	60.2	55.9	1600		7.6
		Confectionary byproducts					
		a) Chocolate	97.5	93.7			7.2
		b) Black candy	84.6	78.3			8.2
		c) Raw material	89.1	89			6.1

ALK: alkalinity; CD: cattle slurry; CM: chicken manure; SGM: sheep and goat manure; SMY: specific methanogenic yield; TS: total solids; VS: volatile solids; VSD: volatile solids destroyed; VSin: volatile solids influent; WAS: waste activated sludge.

Magbanua et al. (2001) MISSISSIPPI, USA	Hog liquid waste Poultry liquid waste Inoculum: No inoculum was added. Remark 1	Each waste was mixed and filtered through 6 mm mesh	g/L	g/L	NH_3-N g/L		
		Hog liquid waste: SCOD: 3.38 g/L TSS: 6.30 g/L VSS: 6.10 g/L	9.75	9.40	0.220		
		Poultry liquid waste: SCOD: 7.81 g/L TSS: 14.60 g/L VSS: 10.50 g/L	17.4	14.6	1.500		

ALK: alkalinity; NH_3-N: nitrogen (ammonia); SCOD: soluble chemical oxygen demand; SMY: specific methanogenic yield; TS: total solids; TSS: total suspended solids; VS: volatile solids; VSD: volatile solids destruction; VSS: volatile suspended solids.

Table 1—(Extended)

Batch assay conditions				Performance		
Mixture composition 9	**Temp °C 10**	**Organic load 11**	**pH 12**	**VSD % 13**	**CH_4 or gas production 14**	**Remarks 15**
Trial A: mixtures as indicated in column 3 (80% by volume) and inoculum (20% by volume)					SMY m^3/kg VSin	1. A mathematical technique (response surface method) was used to optimize the composition of waste mixtures. 2. In trial A, molasses showed the highest SMY, followed by chicken manure and cattle slurry. 3. In trial B, chicken manure showed the highest SMY, followed by sheep and goat manure and waste activated sludge.
	35	See column 5		70.0	0.224	
	″	″		28.5	0.098	
	″	″		14.5	0.067	
	″	″		23.3	0.140	
	″	″		46.9	0.228	
	″	″		41.8	0.229	
				30.7	0.250	
Trial B: mixtures as indicated in column 3 (80% by volume) and inoculum (20% by volume)	35	See column 5		30.6	0.13	
	″			41.8	0.24	
	″			34.1	0.14	
	″			36.4	0.20	
	″			38.8	0.18	
	″			36.1	0.13	
	″			35.9	0.18	
Individual wastes were assayed at the VS content indicated in column 11.	°C	g VS/L			SMY m^3/kg VSin	1. The effect of particle size on CH_4 yield was tested. No effect was observed for oats.Optimum yield was observed at 1 cm particle size for clover and hay. 2. Stage of the energy crop influenced CH_4 yield. Clover harvested at vegetative stage produced higher CH_4 yield than clover harvested at flowering stage.
	35	51	7.4 to 7.7		0.21 Remark 1&2	
	″	″	″		0.14 Remark 1&2	
	″	″	″		0.27 Remark 1	
	″	″	″		0.25 Remark 1	
	35	25.8	7.4 to 7.5		0.37	
	″	—	″		0.39	
	″	—	″		0.32	
Serum bottles (125 mL) were used for the test. Five replicates were prepared.	35	VS mg/L		%	SMY m^3/kg VSD	1. Hog waste was collected from a drainage sump that may have harbored methanogenic bacteria. 2. Initial pH of 5 and 6 for hog and poultry waste, respectively, dropped to 4.5 for the first 15 to 20 days, but eventually stabilized at 6 for sole hog waste and 7 in the other mixtures. 3. Free ammonia initially increased with addition of hog waste, up to 0.025 g/L. Then, levels of free ammonia decreased at higher hog waste ratios.
Hog liquid and poultry liquid waste were mixed in various ratios (hog:poultry)						
100:0		700	5.0	40	0.080	
80:20		800	5.5	57	0.130	
60:40		950	6.0	57	0.110	
40:60		1150	—	57	0.100	
20:80		1300	6.0	70	0.070	
0:100		1450	6.0	55	0.005	
Assay lasted up to 113 days						

Table 2—Laboratory batch assays (kinetic study).

						Performance			
		Codigestates	Batch conditions						
Author or location	Main waste and inoculum	Type	Mixture composition	Temp °C	Organic load	Methane production rate constant	% Yield	% CH_4 in biogas	Remarks
1	2	3	4	5	6	7	8	9	10
Converti et al. (1999) Genoa, Italy See Table 2 for bench digester Study.	No main waste. See column 4. Inoculum: meso or thermophilic anaerobic digested wastewater sludge.		Individual hydrolyzates were assayed at the COD content indicated in column 6.		COD (g/L)	L/h g VSS	Remark 1		1. Percent yield was calculated by comparing the experimental yield with a theoretical yield. The theoretical yield was estimated by assuming simplified reactions for conversion of monosaccharides to gas and considering 15.6 mmoles CH_4 per gram of COD. 2. Hemicellulose hydrolyzate was more readily degradable, whereas nonhydrolyzed VW/EWS mixture was more recalcitrant. This indicated that the hydrolysis of hemicellulose was the rate limiting step during digestion. 3. Thermophilic digestion of hemicellulose hydrolyzate was not affected by an increase in organic load from 1.4 to 2.8 g COD/L, while methane content of biogas from starch hydrolyzate decreased from approximately 50 to 30%, indicating acidification of the process. 4. Higher methane production rate from digestion of hemicellulose hydrolyzate occurred at mesophilic conditions. However, higher methane yield and methane content was obtained at thermophilic conditions. 5. Percent yield hardly exceeded 80%, even under the most favorable conditions, indicating possible presence of recalcitrant substances, such as toxic hydrolysis byproducts. Low percent yields may also be because of the simplifying assumptions introduced in the calculations of the theoretical yield.
		Hemicellulose acid hydrolyzate		55	1.4	8.8×10^{-3}	77.8	53	
					2.8	8.0×10^{-3}	86.8	60	
				37	1.4	10.4×10^{-3}	48.1	46	
					2.8	10.1×10^{-3}	23.0	43	
		Starch enzymatic hydrolyzate		55	1.4	6.7×10^{-3}	78.3	50	
					2.0	6.7×10^{-3}	48.5	35	
					3.0	6.6×10^{-3}	23.3	30	
		Nonhydrolyzed VW and EWS		55	1.5	4.0×10^{-3}	69.3	61	
					5.0	4.1×10^{-3}	20.4	46	

COD: chemical oxygen demand; EWS: excess wastewater sludge; VW: vegetable waste.

Table 3—Laboratory batch assays (toxicity study).

		Batch conditions			Performance	
Author or location	**Main waste and Inoculum**	**Mixture composition**	**Temp °C**	**Organic load**	**% CH_4 Yield remark 2**	**Remarks**
1	2	3	4	5	6	7
Zitomer (2001) Milwaukee, Wisconsin	ADF containing propylene glycol.	Trial A: Methane production potential ADF at the COD content indicated in column 5		COD of ADF mg/L		1. Forty milliliters of ADF-unacclimated (7.85 g TVS/L) or ADF-acclimated (16.6 g TVS/L) anaerobic digested wastewater sludge were used as inoculum. Unacclimated digested sludge was obtained from conventional high-rate anaerobic digesters at a wastewater treatment plant. Acclimated digested sludge was obtained from laboratory bench-scale digesters treating ADF. 2. % CH_4 yield is defined as CH_4 produced divided by the theoretical CH_4, based on stoichiometric ratios. 3. ADF toxicity on aceticlastic methanogens was tested. Calcium acetate was added to prevent a substrate- limited condition.
	Inoculum: anaerobic digested mesophilic wastewater sludge. Remark 1.	Unacclimated biomass (Remark 1)	35	520	94	
			”	980	81	
			”	2200	93	
			”	5370	53	
			”	10 140	41	
		Acclimated biomass (Remark 1)	”	520	98	
			”	980	105	
			”	2200	94	
			”	5370	75	
			”	10 140	7	
		Trial B: ADF toxicity assays ADF at the COD content indicated in column 5 plus 12 000 mg COD/L of calcium acetate. (Remark 3)				
		Unacclimated biomass (Remark 1)	35	0	76	
			”	460	79	
			”	878	77	
			”	1940	82	
			”	4700	68	
			”	8940	28	
		Acclimated biomass (Remark 1)	”	0	89	
			”	460	87	
			”	878	92	
			”	1940	86	
			”	4700	68	
				8940	3	

ADF: aircraft deicing fluid; COD: chemical oxygen demand; TVS: total volatile solids.

the three HRTs tested in the second stage. The advantage of using a two-stage over a one-stage process was demonstrated by a parallel experiment with a single-stage mesophilic digester. The performance of this digester operated at a HRT of 20 days was similar to that of the two-stage process, but operated at a HRT of only 12 days in the second stage.

Municipal Wastewater Sludge and Organic Fraction of Municipal Solid Waste. Schmit and Ellis (2001) compared the performance of temperature-phased anaerobic digestion (TPAD; thermophilic gas phase followed by mesophilic gas phase) and two-phase anaerobic digestion (2PAD; thermophilic acid phase followed by mesophilic gas phase) for digestion of mixtures of MWS and OFSMW. The TPAD outperformed 2PAD in terms of methane production and VS reduction at 0, 20, and 40% OFMSW, but performance of both systems was similar at 60 and 80% OFMSW (Table 5). The performance of either process was in general improved by adding OFMSW to MWS.

Organic Fraction of Municipal Solid Waste. Poultry Manure, Food and Kitchen Refuse, and Contents of Grease Separators. Maibaum and Kuehn (1999) studied two-stage codigestion of a multi-component mixture with OFMSW as the main waste. The first stage was an acidogenic digester at 15°C. The second stage (gas phase) was operated at 35 or 55°C to compare mesophilic and thermophilic codigestion as a function of HRT. Thermophilic VSS destruction and methane yields were higher than those at mesophilic temperatures at a HRT ranging from 4 to 20 days (Table 5). Pulse loads applied to the second-stage digesters indicated that thermophilic operation was more reliable and had more capacity to absorb abrupt variations in the OLR than mesophilic operation.

Pilot-Scale Studies

Only two pilot-scale studies were found during the survey period (Table 6). One used MWS as the main waste. Both studies focused mainly on optimization of operational parameters.

Stomach Contents and Slaughterhouse Residues. Rosenwinkel and Meyer (1999) investigated the codigestion of stomach

Table 4—Single-stage bench-scale digester studies.

			Operation parameters			
Author or location	**Main waste(s)**	**Codigestion system and codigestates characteristics**	**Temp °C**	**HRT days**	**Mixture composition**	**OLR**
1	2	3	4	5	6	7
Converti et al. (1997) GENOA, ITALY See Table 1 for batch assays.	MWS: mixture of primary and excess sludges	Setup: single stage process; 3- and 2-L glass vessels; gently mixing for 2 minutes after feeding; batch fed once per day. Startup: no description of the startup was provided. A set of digesters were operated at different OLR by feeding fixed volumes of waste mixture with increasing COD values (column 7). Waste mixture: feeds were prepared by mixing 1.0 L of MWS, 0.682 L of wood hydrolyzate, and 0.301 Lof corn starch hydrolyzate, followed by dilution with tap water to the desired COD. The COD/VS ratio was kept near to 1.34 to simulate the average composition of hydrolyzed municipal and agroindustrial solid wastes. Waste pretreatment: Wood hydrolyzate: wood chips (mainly oak) were acid hydrolyzed to release hemicellulose sugars. The residue was treated with caustic solution to release sugars from the ligninic fraction. Corn starch hydrolyzate: starchy residues from corn overproduction and cultivation wastes were enzymatically hydrolyzed to increase the sugar content of the feed.	37	20	Column 3	g COD/L · d 0.8 1.4 2.2 3.4 4.6 6.1
Converti et al. (1999) Genoa, Italy See Table 1 for batch assay.	MWS: primary and EWS VW	Setup: four 3-L digesters. Feed once a day. After feeding, digesters were gently mixed for 2 minutes (static digesters) Startup: not available. Waste mixtures: Each digester received a sole substrate at variable COD loads. – Hemicellulose acidic hydrolyzate (HH): 1.4 to 2.8 g COD/L – Starch enzymatic hydrolyzate (SH): 1.4 to 3.0 g COD/L – Hydrolyzed mixture of MWS/VW: 1.5 to 5.0 g COD/L – Nonhydrolyzed mixture of MWS/VW:1.5 to 5.0 g COD/L	55	20	Sole HH Sole SH MWS/VW nonhydrolyzed MWS/VW hydrolyzed	g COD/L · d up to 6 up to 2.8 up to 5 up to 5
Björnsson et al. (2000) Lund, Sweden See Table 5 for full-scale study.	MWS: primary and EWS.	Setup: Three 0.5-L jacketed glass reactor. Feed with pump once a day. Startup: during the startup period of 40 days, 1.5 kg VS/m^3 day was applied to three reactors, with a sludge composition similar to the average composition in the full-scale plant. Then each reactor was operated as follows. Reactor operation: Reactor 1 was maintained at the startup conditions for six months as a reference. Towards the end of the experimental period, a pulse of the carbohydrate-rich sludge of 3.6 kg VS/m^3 · day was pumped into the reactor to mimic Monday pulse load in full-scale plant. Reactor 2 was operated at increasing OLRs (stepwise fashion) until the process became overloaded. Reactor 3 was operated similarly to reactor 2, but the feed composition was changed after the startup period to a higher percentage of the carbohydrate-rich waste (44%), imitating a higher contribution from the food processing factory. Waste mixture: CRW, PWS, and EWS mixture composition is indicated in column 6. Note that reactors 1 and 2 have the same composition. Reactor 3 has a slightly higher percentage of CRW.	35		% vol (%VS) Reactor 1: CRW: 36% (72%); PSS: 11% (9%); EWS: 53% (19%). Reactor 2: CRW: 36% (72%); PSS: 11% (9%); EWS: 53% (19%). Reactor 3: CRW: 44% (80%); PSS: 9% (6%); EWS: 47% (14%).	kg VS/m^3 · day Before pulse: 1.6 Pulse: 3.6 Before overload: Variable OLR Overload: 5.9 Before overload: Variable OLR Overload: 5.3

ALK: alkalinity; COD: chemical oxygen demand; HRT: hydraulic retention time; MWS: municipal wastewater sludge; OLR: organic loading rate; SMY: specific methanogenic yield; VFA: volatile fatty acids; VOA: volatile organic acids; VS: volatile solids; VSD: volatile solid destruction.

ALK: alkalinity; CRW: carbohydrate-rich food processing waste; EWS: excess wastewater sludge; HH: hemicellulose acidic hydrolyzate; HRT: hydraulic retention time; MWS: municipal wastewater sludge; OLR: organic loading rate; PWS: primary wastewater sludge; SH: starch hydrolyzate (enzymatic); SMY: specific methanogenic yield; VFA: volatile fatty acids; VOA: volatile organic acids; VSD: volatile solid destruction; VW: vegetable waste.

Table 4—(Extended)

		Operation performance			
pH	**ALK**	**VSD %**	**VOA or VFA**	**CH$_4$ or gas production**	**Remarks**
8	**9**	**10**	**11**	**12**	**13**
				SMY m^3/kg VSD	1. The loading rate threshold for optimumrate of solid destruction was 4.6 g COD/L · d corresponding to 3.4 g VS/L · d. 2. Maximum biogas and methane production rates (0.319 and 0.142 L/L · drespectively) were also obtained at 4.6 g COD/ L · d. 3. The loading rate threshold for maximum methane yield, methane content in biogas, and VS removal was 2.2 g COD/L · d (1.6 g VS/ L · d). 4. An OLR of 2.2 g COD/ L · d was the best compromise between obtaining maximum degradation, satisfactory methane content of biogas, and a reasonable rate of solids breakdown.
		10.8		0.479	
		14.5		0.450	
		14.7		0.483	
		12.4		0.428	
		12.5		0.335	
		7.5		0.299	
			Stable methanogenesis		1. Hemicellulose hydrolyzate ensured both the highest CH$_4$ productivity, 60 mmol/ L · d, and CH$_4$ content, 60%, at a OLR threshold of 6 g COD/L · d. 2. Unbalance towards acidogenic phase occurred at lower OLR, 2.8 g COD/ L · d, with starch hydrolyzate. 3. An intermediate OLR threshold (5g COD/L · d) was observed for the non- hydrolyzed mixture of MWS/VW. 4. Prehydrolysis of the MWS/VW mixture did not show any significant effect on the ORL threshold and CH$_4$ productivity increase was marginal (<10%). Based on these results hydrolytic pretreatment of the MWS/VW mixture was not justified.
			Acidogenesis prevailed		
			Stable methanogenesis		
			Stable methanogenesis		
	mg/L Partial (Total)		VFA mg/L Remark 1	L/L$_{reactor}$ day gas	1. Individual VFA were measured: A, acetic; P, propionic; N-B, n-butyric; I-B, iso-butyric; N-V, n-valeric; I-V, iso-valeric. 2. In reactor 2, the concentration of the iso- butyrate was dominant over the normal form after overload. Ratio iso/ normal may be used as indicator of imbalance, but caution should be exercised in evaluating each case separately because small changes in composition can change the ratio. 3. Gas composition was not a reliable parameter of performance: Reactor 1: gas composition was constant at 67% CH$_4$, 30% CO$_2$ Reactors 2 and 3: overload at 5.9 and 5.3 was not reflected in the methane concentration until after other process parameters exhibited severe signs of overload.
7.3	1,930 (2,340)		A: 0; P: 0	0.0	
7.0	1,600 (2,400)		A: 195; P: 175	0.9	
7.0	1,500 (2,000)		Remark 2 A: 0	2.6	
5.2	0 (1,500)		P: 0	0.5	
			N-B: 0		
			I-B: 0		
			N-V: 0		
			I-V: 0		
			A: 1650		
			P: 2000		
			N-B: 800		
			I-B: 2250		
			N-V: 1000		
			I-V: 1000		
6.8	1,000 (1,500)		A: 200	2.6	
5.2	0 (1,500)		P: 500	0.5	
			N-B: 0		
			I-B: 0		
			N-V: 0		
			I-V: 0		
			A: 800		
			P: 1500		
			N-B: 380		
			I-B: 50		
			N-V: 200		
			I-V: 110		

Table 4—(Continued)

Author or location	Main waste(s)	Codigestion system and codigestates characteristics	Operation parameters			
			Temp °C	HRT days	Mixture composition	OLR
1	2	3	4	5	6	7
Einola et al. (2001) Jvaskyla, Finland See Table 1a for batch assays	MWS OFMSW	Setup: single stage process; 5-L digesters; CSTR; semi-continuous feeding. Startup: digesters were started with a loading of 2 kg VS/m^3 · d of the particular mixture to be tested. When stable methane production was observed, load was increased to 4 and then to 7 kg VS/m^3 · d. For digesters with performance problems, the feeding was interrupted until COD levels decreased to below 5 g/L. Waste mixtures: ratios as indicated in column 6. a) MWS b) OFMSW c) enzyme industry waste d) paper mill sludge	35	14	% wet weight See column 3.	kg VS/m^3 · d
					Mix 1: a) 30%; b) 20%; c) 20%; d) 30%	7
					Mix 2: a) 50% b) 30%; c) 20%	7
					Mix 3: a) 50%; b) 20%; c) 20%; d) 10%	7
					Mix 4: a) 70%; c) 30%	4
					Mix 5: b) 60%; c) 40%	2
					Mix 6: a) 60%; b) 40%	7
					Mix 7: c) 100%	1
Callaghan et al. (2002) Birmingham, United Kingdom	CD	Setup: single stage process; 18-L digesters; CSTR; batch fed. Startup: digesters were operated for four months on CD alone (7.6% VS; 3.62 kg VS/m^3 · day; 21 days HRT) Waste mixtures: OLRs tested as indicated in column 7; CD/FVW, CD/CM. Mixture composition is indicated in column 6. Waste quality: CD: pH 7.8; 100 to 137 g TS/L; 70 to 107 g VS/L; 1040 to 1925 mg NH_3-N /kg. CM: pH 7.3; 300 to 450 g TS/L; 150 to 220 g VS/L; 7000 to 12 800 mg NH_3-N /kg. FVW: pH 4.2; 167 g TS/L; 156 g VS/L; <10 mg NH_3-N /kg.	35	21	% (wet weight) CD:FVW	kg VS/m^{3}d
					100:0	3.62 ± 0.15
					80:20	4.22 ± 0.10
					70:30	4.52 ± 0.11
					60:40	5.22 ± 0.10
					50:50	5.01 ± 0.07
					CD:CM	
						3.19 ± 0.14
					100:0	3.83 ± 0.19
					70:30	
					50:50	3.97 ± 0.26
					25:75	4.44 ± 0.21
					10:90	4.75 ± 0.42

ALK: alkalinity; CD: cattle slurry; CM: chicken manure; CSTR: complete stirred reactor tank; FVW: fruit & vegetable waste; HRT: hydraulic retention time; MWS: municipal wastewater sludge; NH_3-N: nitrogen (ammonia); OFMSW: organic fraction municipal solid waste; OLR: organic loading rate; SMY: specific methanogenic yield; VFA: volatile fatty acids; VOA: volatile organic acids; VSD: volatile solid destruction.

Misi and Forster (2002) BIRMINGHAM, UK	TWAS Poultry waste (PW)	Setup: single-stage process; glass digesters; 15 L; 6.2-L headspace; CSTR. Startup: each of the two digesters was started with an inoculum of digested sludge which had been predigested until no more biogas was produced. It was fed initially with WAS and a mixture of other wastes (Mix 1 or 2; see column 6). The reactors were fed batch on daily bases. The initial ratio of WAS to Mix 1 or 2 was 3:1. The proportion of WAS gradually decreased to zero volume over a period of 10 days. Reactor operation: after startup, each digester (A or B) was operated under different fed phases. In each phase, composition of the waste mixture changed. Digester A was consecutively fed with Mix 1, 3, and 5, and digester B with Mix 2, 4, and 6. Mixtures compositions are described in column 6. Each phase lasted for at least two retention times, and there was a resting period of one retention time, when no feed was added, between each phase. Waste mixtures: mixtures of FVW, CD, PW, and TWAS were prepared at the ratios indicated in column 6. Amount of FVW and CD was constant in all mixtures (15% TS). Ratios of PW to TWAS were variable.	35	20	% TS (PW:TWAS) Remark 1	kg VS/m^{3}day (digester A or B)
					Mix 1 (digester A): 17.5% PW; 52.5% TWAS (25:75)	1.85 (digester A)
					Mix 2 (digester B): 35% PW; 35% TWAS (50:50)	1.80 (digester B)
					Mix 3 (digester A): 52.5% PW; 17.5% TWAS (75:25)	1.57 (digester A)
					Mix 4 (digester B): 70% PW; 0% TWAS (100:0)	1.51 (digester B)
					Mix 5 (digester A): 0% PW; 70% TWAS (0:100)	1.86 (digester A)
					Mix 6 (digester B): 17.5% PW; 52.5% TWAS (25:75)	1.89 (digester B)

ALK: alkalinity; CD: cattle slurry; FVW: fruit and vegetable sludge; HRT: hydraulic retention time; OLR: organic loading rate; PW: poultry waste; SMY: specific methanogenic yield; TAlk: total alkalinity; TWAS: thickened waste activated sludge; VFA: volatile fatty acids; VOA: volatile organic acids; VSD: volatile solid destruction; WAS: waste activated sludge.

Table 4—(Extended)

			Operation performance		
pH	**ALK**	**VSD %**	**VOA or VFA**	**CH$_4$ or gas production**	**Remarks**
8	**9**	**10**	**11**	**12**	**13**
			VOA	SMY m^3/kg VSin	
			high	0.300	Mix 1: stable digester performance. High initial levels of VFA were controlled by buffering and pH adjustment.
				0.380	Mix 2: stable digester performance.
				0.280	Mix 3: stable digester performance.
high			high	0.180	Mix 4: moderate digester performance; buffer added; high ammonia.
high			high	0.330	Mix 5: poor digester performance; buffer added; high ammonia.
				0.380	Mix 6: stable digester performance.
high			high	0.500	Mix 7: poor digester performance; buffer added; high ammonia.
			VOA mg/l	SMY m^3/kg VSin	1. Levels of free ammonia (mg/L) were as follows: sole digestion of CD: 40 to 85; codigestion with FVW: <100; and codigestion with CM: >100.
		53.0 50.0	2,202±357 2,752±229	0.240 0.380	
		30.0 49.0	7,458±1118 5,320±813	0.340 0.375	
		47.0	7,994±913	0.440	
		49.0 51.0	2,192±342 2,723±380	0.100 0.110	
		32.0 28.5	7,990±625 9,272±154	0.040 0.045	
		29.0	6,369±598	0.060	
	mg/l TAlk (mean)		mg/l VFA (VFA/TAlk) (max. values)	SMY m^3/kg VSin	1. All mixtures contained 15% of FVW and 15% of CD. The remaining 70% was PW and TWAS. 2. None of the feeds caused process instability as indicated by the process pH, VFA:alkalinity ratio, and methane content (63.8 to 69.2%). 3. SMY increased with decreasing OLR, that is, with increasing amounts of PW. 4. An increase in the amount of free ammonia (from 58.2 to 147.6 mg/L) and a decrease in VSD from 56 to 40% were observed at higher percentage of PW. 5. Maximum concentration of free ammonia observed during digestion of Mix 4 (147.6 g/L) was above the proposed toxic threshold (138 mg/L).
7.52	5678		1572 (0.24)	0.192	
7.43	6598		1779 (0.24)	0.190	
7.57	6366		440 (0.06)	0.245	
7.64	7484		486 (0.06)	0.250	
7.42	7304		816 (0.14)	0.162	
7.35	8.038		2271 (0.36)	0.163	

Table 5—Two-stage bench-scale digester studies.

Author or location	Main waste(s)	Codigestion system and codigestates characteristics	Operation parameters			
			Temp °C	HRT days	Mixture composition	OLR
1	2	3	4	5	6	7
Lafitte-Trouqué and Forster (2000) Birmingham, United Kingdom	WAS	Set up two-stage system: First-stage: acid phase (TAND 55); 55°C; 5-L; CSTR; 4 h HRT				kg VS/m^{3}d Remark 1
	Confectionery waste, mainly syrups.	Second-stage: gas phase; 35°C; 5-L, CSTR; two second digesters were operated as follows:	55 TAND 55	0.17 (4 h)		—
		Phase 1: DUAL 55-8: HRT of 8 days DUAL 55-12: HRT of 12 days	35 DUAL 55-8 Phase 1	8		0.631
		Phase 2: at day 70 (Remark 3) DUAL 55-15: DUAL 55-8 was increased to 15 days HRT. DUAL 55-12: DUAL 55-12 was kept at 12 days HRT				
		Setup single-stage system (SS-20): 35°C; 10-L; CSTR; 20 days HRT	35 DUAL 55-15 Phase 2	15		0.408
		Waste mixture: WAS and confectionary waste at ORL indicated in column 7	35 DUAL 55-12 Phase 1	12		0.422
			35 DUAL 55-12 Phase 2	12		0.422
			35 SS-20 Phase 1	20		0.333
			35 SS-20 Phase 2	20		—

COD: chemical oxygen demand; CSTR: completely stirred tank reactor; DUAL: mesophilic second-stage (gas-phase); HRT: hydraulic retention time; OLR organic loading rate; SMY: specific methanogenic yield; SS: single-stage system; TAND: thermophilic first stage (acid-phase); VFA: volatile fatty acids; VOA: volatile organic acids; VSD: volatile solids destruction; WAS: waste activated sludge.

Schmit and Ellis (2001)	PWS			Remark 1	OFMSW: PWS (%W/W)	
Iowa		Setup TPAD First-stage: gas phase (TPAD1); 55°C	55 TPAD 1	3 5	0:100 20:80	Remark 2
	Synthetic	Second-stage: gas phase (TPAD2); 35°C			40:60	
	OFMSW: 50% office paper, 10% newspaper, 26% grass clipping, and 14% dog food.	Set-up two-phase anaerobic digester 2PAD First-stage: acid phase (2PAD1); 55°C			80:20	
		Second-stage: gas phase (2PAD2); 35°C	35 TPAD 2	10 10	0:100 20:80	Remark 2
		Digesters volume was not reported; digesters were mixed every 10 min for 30 seconds			40:60 60:40 80:20	
		System operation: Both systems were operated initially at a system HRT of 13 days. Individual stage HRT were: TPAD1, 3 days; TPAD2, 10 days 2PAD1, 3 days; 2PAD2, 10 days	55 2PAD1	3 3	0:100 20:80 40:60 60:40	Remark 2
		On day 120, the HRT of TPAD1 was increased to 5 days to avoid washout of methanogens. Both systems were subsequently operated at a system HRT of 15 days. Individual stage HRT were: TPAD1, 5 days; TPAD2, 10 days 2PAD1, 3 days; 2PAD2, 12 days			80:20	

Table 5—(Extended)

Stage performance					
pH	ALK	VSD %	VOA or VFA	CH_4 OR gas production	Remarks
8	9	10	11	12	13
	mg/L		mg/L VFA Remark 2	SMY m^3/kg VSin	1. Loading rates for two-stage systems was based on overall retention time. 2. Individual acids were measured: A, acetic; P, propionic; B, butyric. 3. At an HRT of 8 days, the second-stage digester (DUAL 55-8) was not able to assimilate high VOA concentrations and low pH values from first stage digester; This was probably because of the HRT being too short to keep methanogenic populations. Increase to 15 days HRT helped to stabilize the process (DUAL55-15). 4. An HRT of 12 days in the second-stage digester (DUAL 55-12) appeared to give the best performance in terms of stability, VS destruction, and CH_4 yield.
3/4	0 to 500	—	—		
5/7		51	491 (A) 611 (P) 4,347 (B)	0.12	
7	1000 to 1500	41	981 (A) 381 (P) 713 (B)	0.31	
6/7	1000 to 2100	52	436 (A) 301 (P) 89 (B)	0.34	
—		51	—	0.30	
—	—	28	642 (A) 1149 (P) 177 (B)	0.36	
—	—	50	—	0.28	
			VOA mg/L	SMY m^3/kg VS_{in}	1. HRT of individual digesters were changed on day 120, as explained in system operation in column 3. 2. OLR for individual reactors was not provided. OLR for the systems was variable, ranging from 0.25 to 4 kg/m^3day. 3. Thermophilic gas phase (TPAD1) contribution to the total CH_4 production was almost comparable to the contribution from the mesophilic gas phase (TPAD2). 4. Acid phase (2PAD1) was adjusted to pH 5.6, which was found optimal for cellulose hydrolysis in previous studies. 5. Contribution of the acid phase (2PAD1) to the total methane production was minimal in comparison to the contribution from the gas phase (2PAD2).
7.6		43.8 ± 4.4	529 ± 130	0.226 ± 0.007	
6.9		19.9 ± 4.6	3,269 ± 80	0.134 ± 0.008	
7.1		38.5 ± 5.9	3,560 ± 460	0.180 ± 0.008	
7.0		27.3 ± 7.8	3,030 ± 480	0.163 ± 0.014	
7.3		45.7 ± 5.5	3,130 ± 70	0.199 ± 0.013	
7.6		NA	147 ± 27	0.098 ± 0.006	
7.5			167 ± 64	0.245 ± 0.011	
7.3			170 ± 32	0.238 ± 0.010	
7.2			934 ± 507	0.172 ± 0.013	
7.4			166 ± 27	0.093 ± 0.007	
5.6		21.2 ± 3.4	3,280 ± 60	0.021 ± 0.002	
5.6		—	5,560 ± 140	0.017 ± 0.001	
				0.020 ± 0.011	
				0.023 ± 0.005	
				0.025 ± 0.005	
5.6		14.4 ± 3.7	5,230 ± 480	0.265 ± 0.014	
5.6		6.5 ± 5.9	4,650 ± 370	0.316 ± 0.013	
5.6		16.5 ± 5.4	4,060 ± 200	0.313 ± 0.011	
7.3		NA	141 ± 27	0.296 ± 0.020	
7.4			143 ± 20	0.253 ± 0.013	
7.2			216 ± 48		
7.0			278 ± 144		
7.1			717 ± 248		

Table 5—(Continued)

Author or location	Main waste(s)	Codigestion system and codigestates characteristics	Operation parameters			
			Temp °C	HRT Days	Mixture Composition	OLR
1	2	3	4	5	6	7
		Waste Mixtures: several OFMSW/PWS ratios were tested as indicate in column 6. Initially, systems were fed with sole PWS (0:100 ratio). Then the OFMSW/PWS ratio was changed on days 36, 171, 315, and 383 to increasing amounts of OFMSW, as indicated in column 6.				

2PAD: two-phase anaerobic digester; HRT: hydraulic retention time; OFMSW: organic fraction municipal solid waste; OLR organic loading rate; PWS: primary wastewater sludge; SMY: specific methanogenic yield; TPAD: temperature-phase anaerobic digester; VFA: volatile fatty acids; VOA: volatile organic acids; VSD: volatile solids destruction.

Maibaum and Kuehn (1999) Dresden, Germany	OFMSW Poultry manure	Setup two-stage system: First-stage: acid phase; 15°C; 50-L digester; CSTR Second-stage: gas phase; 6-L digester, CSTR; batch fed once a day; two digesters were operated in parallel at 35 and 55°C, at different HRT (see column 5).	35	4 6 8 10 12 20	See Remark 1	
		Waste mixture. Raw substrate from a biogas plant with an average composition (by weight) as follows: poultry manure, 28.1%; OFMSW 45.5%; kitchen refuse, 3.9%; contents of grease separators, 8.7%; food refuse, 3.5%; and Other, 10.3%.	55	4 6 8 10 12 20		
		Waste mixture quality: N-org: 1.9 to 4.0 g/L; NH_3-N: 0.4 to 1.7 g/L; COD: 50 to 170 g/L; VS: 18 to 99 g/Ll; VSS in % of VS: 50 to 83%; VFA: 2.3 to 15.4 g/L.				

COD: chemical oxygen demand; HRT: hydraulic retention time; OLR organic loading rate; ALK: alkalinity; VS; volatile solids; VSD: volatile solids destruction; VSS: volatile suspended solids; VOA: volatile organic acids; VFA: volatile fatty acids; N-org: nitrogen (Kjeldhal); NH_3-N: nitrogen (ammonia); SMY: specific methanogenic yield; OFMSW: organic fraction municipal solid waste.

Table 5—(Extended)

		Stage performance			
pH	ALK	VSD %	VOA or VFA	CH_4 OR gas production	Remarks
8	9	10	11	12	13
		Overall system performance			
		TPAD % OFMSW	% VSD	SMY m^3/kg VSin	6. The TAPD system outperformed the 2PAD system in terms of CH_4 production and VS destruction at OFMSW/PWS ratios of 0:100, 20:80, and 40:60. At higher ratios, 60:40 and 80:20, there was no significant difference in the performance. 7. Levels of VOA in TPAD1 were high, but smaller than levels in 2PAD1, indicating efficient removal of VOA through CH_4 production in TPAD1.
		0	47.5 ± 3.2	0.325 ± 0.010	
		20	58.2 ± 3.1	0.377 ± 0.011	
		40	69.8 ± 3.0	0.418 ± 0.014	
		60	65.1 ± 4.4	0.335 ± 0.018	
		80	71.6 ± 2.9	0.299 ± 0.017	
		2PAD % OFMSW			
		0	39.6 ± 3.8	0.283 ± 0.014	
		20	48.6 ± 3.3	0.331 ± 0.013	
		40	59.3 ± 3.2	0.332 ± 0.011	
		60	65.1 ± 4.4	0.312 ± 0.019	
		80	69.3 ± 2.7	0.281 ± 0.013	
		%VSS destr.	mg/L VFA	SMY m^3/kg VSSin	1. The composition of each waste was subjected to seasonal and weekly variations. 2. CH_4 yield increased with increasing HRT. This effect was more pronounced under mesophilic conditions. However, methane yield and VSS destruction at thermophilic operation were higher than at mesophilic operation at all HRT tested. 3. At short HRT (4 and 6 days) mesophilic process was overloaded and VFA levels increased up to 4500 mg/L, while the respective value was 1500 mg/L for the thermophilic process. 4. Digested sludge obtained under thermophilic operation is significantly less dewaterable than that obtained under mesophilic operation.
		23	—	0.230	
		30	4000	0.290	
		33	—	0.505	
		37	—	0.400	
		43	<1000	0.510	
		45	—	0.510	
		37	—	0.455	
		48	1500	0.540	
		44	—	0.560	
		40	—	0.410	
		55	1000	0.590	
		42		—	

Table 6—Pilot-scale digester studies.

Author or location	Main waste	Codigestion treatment	Treatment mode				Performance				Remarks
			Temp °C	HRT (days)	Feed	OLR	pH	VOA or VFA	VSD	SMY and (% CH_4)	
1	2	3	4	5	6	7	8	9	10	11	12
Rosenwinkel and Meyer (1999) Hannover, Germany See Table 4 for full-scale study	Raw sludge Waste quality: pH: 6.9 %TS: 2.4 %VS: 69 mg/L VSS: 16.1 COD: 37.8 TKN: 1.41 $N\text{-}NH_4$: 112 P_{tot}: 730 Acetic ac: 658 Propionic ac: 265	Setup: 2-m^3 digester; jacket heater; mixing by stirrer and circulator gas; continuous pH adjustment of stomach content with NaOH. Waste mixture: see Remark 1. Step 1: Raw sludge with stomach content (% v/v),		(Phase of experiment)	Once a day	kg TS/$m^3 \cdot d$		mg/L VOA		m^3/kg TSin CH_4	1. Different combinations of raw sludge and stomach content (Step 1) or slaughter flotation tailings (Step 2) were tested.
		Reactor 1: 100% stomach content; pH: 3.7; %TS 17.4; %VS 82; COD (mg/L) 232; TKN (mg/L); 4.1; P (mg/L) 783.	37	44 (1) 25 (2)	100% ″	3.2 5.8	7.0	10 480 —		0.064 (40%) 0.009 (17%)	Reactor 1: digester becomes acidified an digestion of 100% stomach content failed.
		Reactor 2: 30% and 25% stomach content.	37	20 (1) 25 (2) 17 (3)	30% 25% ″	3.1 2 2.9		5314 4619 —		0.112 (44%) 0.168 (48%) 0.227 (52%)	Reactor 2: successful codigestion of 25% stomach content at 17 d HRT and 2.9 kgTS/$m^3 \cdot d$ loading. No pH control.
		Reactor 3: 12.5% and 0% stomach content	37	20 (1) 25 (2) 25 (3) 17 (4)	0% ″ 12.50% ″	1.3 1.2 1.3 2	7.0 mg/L	1863 1544 1730 —		0.278 (57%) n.a. (55%) 0.401 (41%) 0.122	Reactor 3: codigestion of 12.5% stomach content was possible at 25 d HRT days. Digester becomes acidified at 17 days HRT.
		Step 2: Raw sludge with slaughter flotation tailings (% v/v).									
		Reactor 1: 100% flotation tailings pH 6.9; %TS 5.6; %VS 68; COD (mg/L) 87; TKN (mg/L) 3.9; $N\text{-}NH_4$ (mg/L) 75; P (mg/L) 658; acetic ac. (mg/L) 187; propionic ac. (mg/L) 84.	37	44 (1) 30 (2) 25 (3)	100% ″ ″			— 22 6,678		0.373 (66%) 0.331 (66%) 0.353 (62%)	Reactor 1: digester becomes acidified and digestion of 100% flotation tailings failed.
		Reactor 2: 25% flotation tailings.	37	25 (1) 20 (2) 15 (3)	25% ″ ″	0.68 0.99 1.67		— 240 300		0.434 (66%) 0.382 (66%) 0.412 (66%)	Reactor 2: successful codigestion of 25% flotation tailings at HRT = 15 days and 1.67 kgTS/$m^3 \cdot d$ loading.

Table 6—(Continued)

Author or location	Main waste	Codigestion treatment	Treatment mode				Performance				Remarks
			Temp °C	HRT (days)	Feed	OLR	pH	VOA or VFA	VSD	SMY and (% CH_4)	
1	2	3	4	5	6	7	8	9	10	11	12
		Reactor 3: 12.5% flotation tailings. The loading was increased, keeping the % composition constant and reducing HRT.	37	25 (1) 20 (2) 15 (3)	12.50% ″ ″	0.63 0.94 1.46		— 210 90		0.338 (67%) 0.307 (67%) 0.322 (66%)	Reactor 3: successful codigestion of 12.5% flotation tailings at 15 d HRT and 1.46 kgTS/$m^3 \cdot$ d loading
Hernandez, et al. (2001) Los Angeles, California	Organic fraction of Los Angeles Airport restaurant solid waste Waste quality: Moisture: 73% VS: 89.3 to 94.9%	Set-up: 5.3-m^3 digester; TS/day: 6.3 kg/d; Q: 0.261 m^3/d.			3 times per week	kg VS/d		mg/L	%	m^3/kgVSD CH_4	
		Waste: Sole thermophilic digestion of restaurant waste was conducted as a test run for future application as a codigestate with municipal wastewater sludge.	54	16.5–20.8	0.22 to 0.37 m^3/d	3 to 5	6.6 to 7.3	182 to 534	72 to 83	0.04 to 0.07 (50 to 58)	

HRT: hydraulic retention time; OLR: organic loading rate; SMY: specific methanogenic yield; VFA: volatile fatty acids; VOA: volatile organic acids; VSD: volatile solid destruction.

contents or slaughterhouse flotation tailings with MWS in anaerobic digesters of 2 m^3 at 37°C (Table 6). The loading rate, HRT, and feed composition were varied to optimize full-scale implementation of the process at the municipal WWTP of Rheda, Germany (discussed in the "Municipal Wastewater Sludge" section under "Full-Scale Studies"). Sole digestion of stomach contents was not successful because of a low SMY and production of high concentrations of VFAs. A stable process, however, was obtained during codigestion with MWS, although the addition of stomach contents had a negative effect on the digestion of MWS. Digesters for the sole digestion of flotation tailings also became acidified. However, unlike stomach contents, the addition of flotation tailings at 12.5 to 25% significantly improved the digestion of MWS.

Organic Fraction of Restaurant Solid Waste. The Environmental Engineering Division of the City of Los Angeles, California, performed a pilot study of thermophilic (54°C) anaerobic digestion of organic fraction of restaurant solid waste collected at the Los Angeles airport (Hernandez et al., 2001). The objective was to evaluate the potential of codigestion of organic fraction of restaurant solid waste in thermophilic digesters at the Hyperion Treatment Plant (Los Angeles, California). The VS destruction during sole digestion of organic fraction of restaurant solid waste was 72 to 83%, which indicates that organic fraction of restaurant solid waste is an easily biodegradable material. However, the methane yield was relative low (0.04 to 0.07 m^3/kg VSD). Future experiments will focus on the codigestion of organic fraction or restaurant solid waste with MWS.

Full-Scale Studies

Full-scale codigestion applications are summarized in Table 7.

Municipal Wastewater Sludge. *Slaughterhouse Residues.* Rosenwinkel and Meyer (1999) investigated mesophilic codigestion of slaughterhouse residues (stomach contents and flotation tailings) at a municipal WWTP in Rheda, Germany (Table 7). The digester operation was based on results obtained with a pilot-scale study, presented in the "Pilot-Scale Studies" section. Full-scale digesters achieved a specific gas production of 0.470 m^3/kg TS_{in} at a loading rate of 1.26 kg TS/$m^3 \cdot$ d. The gas production rate increased to 2800 m^3/day, representing an increase of 60%, as compared to sole digestion of MWS. Operational problems, such as clogging, deposits, and poor dewaterability were not encountered.

Organic Fraction of Municipal Solid Waste. The municipal WWTP in Frutigen, Switzerland, codigested OFMSW with MWS in two mesophilic digesters operated in series (Edelman et al., 2000; Table 7). Before codigestion, MWS was pasteurized by thermophilic aerobic digestion. The OFMSW was supplied by supermarkets and local hospitals. Feed of OFMSW at 20% of the total OLR resulted in an increase of the gas production rate of 27%. The SMY remained the same at 0.55 m^3/ kg VS_{in}.

Fat, Oil, and Grease. The City of Oxnard, California, collects FOG from grease interceptors at 150 restaurants for codigestion in three mesophilic anaerobic digesters at the Oxnard municipal WWTP (Machuzak, 1997, Table 7). The FOG was fed at 0.6 to 2.7% VSS loading, causing an increase of gas production ranging from 1.5 to +21%.

Carbohydrate-Rich Food-Processing Waste. Björnson et al. (2000) evaluated a 3500 m^3 digester at a municipal WWTP during

Table 7—Full-scale digester studies.

			Operation parameters		Operation performance		
Author or location	**Treatment facility characteristic and main waste(s)**	**Codigestates parameters**	**OLR**	**Temp °C**	**VSD**	**SMY or SGY**	**Remarks**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Rosenwinkel and Meyer (1999) Hannover, Germany	Municipal wastewater treatment plant. Digester volume: 5000 m^3; 18 days HRT. Raw sludge at 277 m^3/d.	a) Slaughter flotation tailings: 37 m^3/day (13.4% by volume); 5.6% TS. b) Stomach content: 50 m^3/week (2.6% by volume); 17% TS. Pretreatment: stomach content was added after passing through grit chamber, macerator, and mixer.	Loading Rate kg TS/m^{3}day 1.26	37	NA	m^3/kg TS$_{in}$ 0.47 SGY	1. Codigestion increased gas production from 1700 to 2800 m^3/d. 2. Addition of codigestate increased the OLR from 0.78 to 1.26 kg TS/m^{3}day, reducing HRT from 21 to 18 days.
Edelman et al. (2000) Frutigen, Switzerland	Municipal wastewater treatment plant. Digester volume 240 m^3; 20 days HRT. Two mesophilic digesters in series: main digestion (D1) and post-digestion (D2). Mixture of primary and secondary sludge was hygienized (thermophilic/aerobic) before anaerobic digestion. Total feed of hygienized sludge was 10 to 14 m^3/day.	Kitchen and food waste from hospitals and supermarkets. Digesters were initially operated on sole digestion of wastewater sludge (control period) followed by codigestion (test period). During codigestion, the organic loading rate increased about 20%. Pretreatment: Delivery and weighing waste; storage of fresh wastes; sorting out of metal and plastic materials; chopping to particles of 2 cm, maceration; suspending in MWS to 6.4% TS and 91% organic matter; and storing and mixing before pumping to digestion system.	NA	Meso	NA	Gas production m^3/day 0.162 (control D1) 0.016 (control D2) 0.178 (control, total) 0.219 (test D1) 0.009 (test D2) 0.227 (test, total) SMY m^3/kg VS$_{in}$ 0.550 (control, total) 0.569 (test, total)	1. Increase gas production of 27% by codigestion. 2. Fiber content in digester 1 increased three-fold by adding codigestate. 3. Digester 1 was tested for tomato weed recycling showing 99 % weed inactivation after 7 days exposure. 4. The energy for pretreatment and digestion was 35 kWh for electricity and 50 kWh for heat per ton of waste. 5. Approximately 20% of the Swiss wastewater treatment capacity could be converted into codigestion plants without major investment.

Table 7—(Continued)

Author or location	Treatment facility characteristic and main waste(s)	Codigestates parameters	Operation parameters		Operation performance		Remarks
			OLR	Temp °C	VSD	SMY or SGY	
1	2	3	4	5	6	7	8
Machuzak (1997) Oxnard, California	Wastewater treatment plant sludge. Digester volume: 9400 m^3. No data Available on the MWS feed.	FOG from restaurant grease trap: pH 4.5 to 9.6; 0.1 to 51.8 %TS; 33 to 99 %VS. Pretreatment: FOG was added using a chopper pump which is able to handle solid-laden waste slurries without clogging, though a combination of chopping and pumping both built into one piece of equipment.	Percent increase in load: 0.6% to 2.7% VSS loading	Meso		Increase in gas production from 1.5 to 21% (Remark 1)	1. Sometimes, decrease in gas production was observed. 2. No scum blanket was observed. 3. No significant change in volatile acids.
Björnsson et al. (2000) Lund, Sweden See Table 2 for bench-scale digester study.	Municipal wastewater treatment plant Digester volume: 3500 m^3; 20 days HRT Two reactors in series. Excess sludge (28% VS; addition of 64% by volume).	Carbohydrate-rich food processing waste (72 % VS; addition of 36% by volume).	kg VS/m^3 · day 1.4 Four-month monitoring at constant load	35	Remark 1	n/a, Remark 1	1. Operation performance was evaluated by measuring pH, total and partial alkalinity, and VFA composition. 2. After the pulse load, partial alkalinity and VFA significantly changed. Stable performance was, however, recovered after 2 to 3 hours. 3. pH also changed after load pulses. However, changes were very minor because of the buffering capacity of digester contents.
			Two load pulses: 0.5 kg VS/m^3, 4.5 h interval		Remark 1	n/a, Remark 1	

FOG: fat, oil, and grease; HRT: hydraulic retention time; OLR: organic loading rate; SGY: specific gas yield; SMY: specific methane yield; TSin: total solids influent; VFA: volatile fatty acids; VSD: volatile solid destruction.

Table 7—(Continued)

Author or location	Treatment facility characteristic and main waste(s)	Codigestates parameters	Operation parameters		Operation Performance		Remarks
			OLR	Temp °C	VSD	SMY or SGY	
1	2	3	4	5	6	7	8
Yoneyama and Takeno (2001) Joetsu, Japan	Codigestion plant Digester volume: 900 m^3; 22 days HRT. Septic tank and night soil sludge, feed 75 m^3/day.	Domestic kitchen waste (10 m^3/day).	NA	55	42	m^3/kg VS$_{in}$ 0.12–0.2 SMY	1. Gas generation (m^3/day): 755 (average); 54 to 1610 (range); mean methane concentration 60%. 2. Phosphorus in feeding sludge was coagulated with aluminum sulfate and polymer. 3. Generation from digester gas yielded 600 to 1200 kWh/d.
Kübler et al. (2000) Bavaria, Germany	Codigestion plant digester volume not reported. HRT decreased through the testing period, May 1996 to October 1997 from 15.4 to 7.5 days. OFMSW; feed 911 to 1462 ton/month during the 9-month testing period.	a) food waste: 8.7 to 15 ton/month (7 months of the testing period). b) rumen content (RC): 4.5 to 9 ton/month (four months of the testing period). Wet digestion process (BTA technology). Digester was completely mixed by biogas injection.	kg VS/m^3/day 3.0 to 6.1 May 1996 to October 1997 (Remark 1) 3.0 May 1996 (Remark 3)	Meso	64 to 37 (Remark 2) 54 (Remark 3)	m^3/kg VS 0.548 to 0.334 SGY 0.342 to 0.21 SMY Remarks 1 and 2 0.464 SGY 0.288 SMY Remark 3	1. Variable amounts of OFMSW co-digested with food waste, and RC were fed during the 9-month testing period increasing the organic loading. 2. A decrease in both VS removal and standard gas production was associated with a decrease in HRT during the testing period. 3. Two periods were compared, May 1996 (sole digestion of OFMSW, HRT 15.4 days) and April 1997 (codigestion with food waste and RC, HRT 14.6 days). Codigestates did not adversely affect the process. Indeed, a modest increase in VS removal and gas/CH_4 production was observed.

Table 7—(Continued)

Author or location	Treatment facility characteristic and main waste(s)	Codigestates parameters	Operation parameters		Operation Performance		Remarks
			OLR	Temp °C	VSD	SMY or SGY	
1	2	3	4	5	6	7	8
		Pretreatment (wet): a) pulpers to sort contaminants by rake and heavy fraction. b) pasteurization (70°C, 30 min), is integrated in pulper c) stones, glass fragments, and split are separated out of pulp by a hydrodynamic grit removal system, that also disintegrates the pulp. Then, pulp is pumped to digester.	3.7 April 1997 (Remark 3)		64 (Remark 3)	0.548 SGY 0.342 SMY (Remark 3)	4. Cogenerators convert 36% of the biogas energy into electricity and 33% into used heat. 5. Optimized operation of the facility resulted in a surplus energy production of 1700 MJ/t OFMSW.
Rintala and Järvinen (1996) Stormossen, Finland	Codigestion plant. Digester volume: 1400 m^3 HRT variable: 21.8 to 36.8 days Putrescible fraction of municipal solid waste and thickened wastewater sludge. Total feed: 38 to 64 m^3/day Feeding cycle: weekdays: once a day; no feeding on weekends.	Equal volumes of: a) Putrescible fraction of municipal solid waste (45 %TS, 34% VS). b) Thickened sewage sludge (14 %TS, 8 %VS). c) Supernatant of dewatered digested material.	kg VS/m^{3}day 2.5 to 4.1	37	NA	m^3/kgVS$_{in}$ day 29.7 to 64.2 CH_4, (Remark 1)	1. During the feeding cycle, the specific methanogenic activity increased, suggesting that the process was substrate- limited, caused by nonfeeding over the weekend. 2. Other digester performance parameters were: pH 7.6; alkalinity, 7600 mg/L; organic acids, 285 mg/L.

HRT: hydraulic retention time; OFMSW: organic fraction municipal solid waste OLR: organic loading rate; RC: rumen content; SGY: specific gas yield; SMY: specific methane yield; TSin: total solids influent; VFA: volatile fatty acids; VSD: volatile solid destruction.

Kumke and Lanhans (2000) Behringen, Germany	Codigestion plant. Two digesters, 797 m^3 liquid volume. Slow mixer. Coil-pipe heat exchanger. OLR: 6.4 kg VS/m^3 tank; HRT: 26 days. Storage vessels	a) Liquid dairy cow manure: 35 000 kg/d feed rate; 9% TS; 2527 kg VS/d. b) Emulsified fats and oil: 20 000 kg/d feed rate; 26% TS; 4836 kg VS/d. c) Bentonite clay (fat and oil): 5000 kg/d feed rate; 905 TS; 2700 kg VS/d.		57		m^3/kg VSD 0.769 CH_4	1. Methane content: 68%. 2. Two generators were used, each with 450 Kw electrical capacity and 750 Kw thermal energy.

FOG: fat, oil, and grease; HRT: hydraulic retention time; OLR: organic loading rate; SGY: specific gas yield; SMY: specific methane yield; TSin: total solids influent; VFA: volatile fatty acids; VSD: volatile solid destruction.

Table 7—(Continued)

Author or location	Treatment facility characteristic and main waste(s)	Codigestates parameters	Operation parameters		Operation Performance		Remarks
			OLR	Temp °C	VSD	SMY or SGY	
1	2	3	4	5	6	7	8
	Cow manure: storage tank (DO1) Fat and oil: first pasteurized (DO3) and then stored at storage tank (DO4). Bentonite and piggery manure stored in a concrete base, then fluidized and stored (DO2). Storage tanks equipped with mixer, vent and biofilter. Effluent stored in 4 tanks, each 1890 m^3. Effluent storage volume is sufficient for winter storage when application to land is not possible.	d) Piggery manure (added as substitute for bentonite): 10 000 kg/d feed rate; 38% TS: 2264 kg VS/d. Typical feed composite: 60 000 kg/d feed rate; 21% TS; 10 064 kg VS/d. Variable component feed to get maximum biogas production.					3. Typical electric production, 650 Kw. Heat rejected by generator was used for heating digesters and animal confinement. 4. Approximately 30% of electricity was consumed for the facility. The remaining was sold to industry at 8¢ / kwH (75% of mean market price). 5. 10% of the biogas supply to engines comes from storage tanks. 6. Effluent TS was 9% with 3.5% of TS available as total nitrogen. 7. Capital cost of the facility: $3.8 million. 8. Interest and depreciation, plus operation and maintenance (O&M) annual average: 440,000 with O&M costs representing approximately 55%. 9. Average annual income: $480,000. 10. Sole codigestion of cow manure would produce 20% of codigestion biogas.

Table 7—(Continued)

Author or location	Treatment facility characteristic and main waste(s)	Codigestates parameters	Operation parameters		Operation Performance		Remarks
			OLR	Temp °C	VSD	SMY or SGY	
1	2	3	4	5	6	7	8
Kaparaju et al. (2001)	Codigestion plant 150 m^3 digester. Cow manure.	Test 1: sole digestion of cow manure; 6 m^3/day. Test 2: codigestion of cow manure (6 m^3/day) and confectionary byproducts: black candy, chocolate, and confectionary raw materials (50 to 200 kg/day). Test 3: codigestion of cow manure (6 m^3/day) and energy crops: clover, grass hay, and oats (50 to 400 kg/day). Particle size reduced to 2.0 cm.		35/37		m^3/kg Tsin CH_4 0.22 0.28 0.21	1. Gas production increased 60%, from 85 m^3/day (sole digestion of cow manure) to 150 m^3/day (codigestion with confectionary byproducts. 2. In codigestion with confectionary byproducts and energy crops, approximately 40 to 50% of VS were destroyed with 0.6 to 1.7 g/l N-NH_4.

HRT: hydraulic retention time; OLR: organic loading rate; SGY: specific gas yield; SMY: specific methane yield; TSin: total solids influent; VFA: volatile fatty acids; VSD: volatile solid destruction.

codigestion of carbohydrate-rich food processing waste (Table 7). The experiments focused on digester stability after pulse loads of the codigestate, rather than on general performance of codigestion. These experiments demonstrated that pulse loads caused declines of the partial and total alkalinity, which can tentatively be attributed to increased production of VFAs and other acids. Changes of the pH, however, were small and within the standard error of measurement because of the high buffering capacity of the digester content.

Other Main Wastes. *Human Waste (Main Waste) and Domestic Kitchen Waste (Codigestate).* As part of a resource recovery program, a full-scale sludge treatment facility was constructed in Joetsu, Japan. The objective was to codigest domestic kitchen waste (12% by volume) with mixtures of coagulated night soil and septic tank sludges in a thermophilic (55°C) anaerobic digester of 900 m^3 (Yoneyama and Takeno, 2001; Table 7). Gas was produced at an average rate of 755 m^3/day with a methane content of 60%. The volatile solids destruction was 42%. It was observed that the SMY increased with higher VS content in the kitchen waste. Overall, the digester operation was stable over a five-month period and the electrical power generated from the produced biogas was equivalent to approximately 7% of the total power consumption of the plant.

Organic Fraction of Municipal Solid Waste (Main Waste), Food Waste, and Rumen Content (Codigestates). Kübler et al. (2000) reported an 18-month study of a biogas plant in Bavaria, Germany (Table 7). Codigestion of food waste and rumen content with OFMSW resulted in a VS destruction ranging from 37 to 64% and a methane yield from 0.210 to 0.342 m^3/kg VS. The total gas production rate was 1.4 to 2.2 $m^3/m^3 \cdot d$. Codigestion performance was slightly better than that of sole digestion of OFMSW. The cogenerators at the plant converted biogas into electricity and heat with an overall efficiency of 66%. Energy production exceeded the plant's demand by 1700 MJ/ton OFMSW.

Organic Fraction of Municipal Solid Waste and Municipal Wastewater Sludge. Rintala and Järvinen (1996) investigated a full-scale anaerobic biogas digester in Stormossen, Finland, for codigestion of equal volumes of MWS, OFMSW, and centrate from solids dewatering (Table 7). A 1400-m^3 digester was fed once a day for five days per week. The gas production rate increased over the five-day feeding period, indicating that the process was substrate-limited, especially during weekends without feeding. The methane yield was 90% of the theoretical yield. Consequently, semi-continuous feeding instead of once per day was suggested to make better use of the digester capacity at higher loading rates.

Farm Manures and Industrial Fatty Wastes. Thermophilic (57°C) codigestion of farm manures (cow and pig) and industrial fatty wastes was evaluated by Kumke and Lanhans (2000) in a plant in Behringen, Germany. The key waste streams and feed rates are listed in Table 7. A SMY of 0.769 m^3/kg VSD and methane content of 68% were achieved. The produced biogas was used for power generation (650 kW) and for heating of the digesters and animal confinements. The anaerobic digester effluent was used for land application.

Cow Manure (Main Waste), Confectionary Byproducts, and Energy Crops. Semicontinuous mesophilic codigestion of cow manure with either confecionary byproducts or energy crops was evaluated in a farm biogas plant (Kaparaju et al., 2001). The specific methane yield of sole digestion of cow manure was, on average, approximately 0.22 m^3/kg VS_{in}. The codigestion of confectionary byproducts with cow manure increased the specific methane yield to approximately 0.28 m^3/kg VS_{in} (a 27% increase), whereas with energy crops the methane yield was similar to that obtained from cow manure alone. Addition of codigestates resulted in 40 to 50% VS destruction, 100 to 200 mg/L of VFAs, and 0.6 to 1.7 g/L of ammonium nitrogen.

Discussion

Laboratory Studies. *Batch Assay Studies. Methane Formation Potential.* A large variability of the SMY for a given waste was observed. This was because of the effect of several factors on methanogenesis. For example, methane yields from OFMSW varied with the type of sorting being used, e.g., manual at the source or mechanical at a sorting facility. Likewise, methane yields from cattle manure varied with the diet of the livestock (e.g., winter or summer diet). In the case of energy crops, particle size and maturation stage of the crop influenced the methane yield. It is, therefore, important to use caution when comparing specific methane yields from wastes. Also, the lack of standard conditions in SMY assays may have contributed to the variability in SMY. Nevertheless, the results presented in Table 1 allow for a general comparison. Confectionary wastes and enzyme industry waste had a high SMY (0.32 to 0.62 m^3 CH_4/kg VS_{in}). Wastes with an intermediate SMY were paper mill sludge, fish offal, clover (vegetative stage), molasses, oat, and grass hay (0.180 to 0.270 m^3 CH_4/kg VS_{in}). Chicken manure, brewery sludge, dissolved air flotation sludge, fruit and vegetable waste, and clover (flowering stage) had a relatively low SMY (0.098 to 0.14 m^3 CH_4/kg VS_{in}). In general, degradability of the waste by codigestion, as measured by stable methane production and VSD, was directly correlated to the SMY. Exceptions to this observation were enzyme industry waste and paper mill sludge with a high and intermediate SMY, respectively. In codigestion with OFMSW, both wastes showed good degradability, but only at low codigestate loadings. This may indicate the presence of an unknown antagonistic effect at high loadings.

Inhibitory Factors. The methane formation potential obviously depends on the presence of compounds inhibitory to methanogenesis. Inhibition of anaerobic digestion by ammonia has been widely investigated and has been related to the presence of the unionized form of ammonia (Angelidaki and Ahring, 1993; De Baere et al., 1984; Hansen et al., 1998). The actual concentration of ammonia (NH_3), also referred to as unionized or free ammonia, during digestion depends on the pH and the temperature. Inhibition of digestion by free ammonia has been observed at concentrations ranging from 80 to 250 mg/L (De Baere et al., 1984; Kapp, 1992; Webb and Hawkes, 1985). Wastes with high free ammonia concentrations are manures and, in general, other wastes from livestock. These wastes would need to be diluted before codigestion or fed to digesters at a relatively low rate.

Hydrolytic pretreatment to enhance the biodegradability of wood waste and other agricultural wastes may, at the same time, cause inhibition of digestion. Although hydrolysis of lignin and cellulose improve the availability of these polymers to digestion, toxic compounds such as furfurals and phenols may be released, depending on the type of hydrolytic pretreatment being used (Converti et al., 1997). On the other hand, anaerobic conditions and an excess of electron donors may, in general, enhance biological processes for removal of xenobiotic compounds such as reductive dechlorination of pentachlorophenols (PCP) (Hendriksen and Ahring, 1992). Detoxification has been demonstrated by codigestion of pharmaceutical waste with manure, which reduced the levels of aniline and trichloroethylene (Ahring et al., 1996).

Bench-Scale Digester Studies. Organic Loading Rate. The OLR is one of the main parameters in optimizing digester performance. Many bench-scale studies showed that the production of VFAs increased with the OLR. This may cause inhibition of digestion if the alkalinity is not sufficient to prevent a decline of the pH. Acidification probably is the single most reported result of digester failure both on a laboratory and larger scale. However, the presence of high VFA concentrations as such is probably not inhibitory (Ahring et al., 1995). Wastes with a high alkalinity, such as manures, can contain up to 8 g/L VFAs during digestion but without an apparent effect on VS destruction and/or methane production (Callaghan et al., 2002). Consequently, relatively high volumetric loading rates (up to 5 kg VS/$m^3 \cdot$ day) can be fed when the alkalinity of the waste mixture is sufficiently high. Likewise, stable codigestion of chicken manure with TWAS has been reported, albeit at a maximum OLR of approximately 1.5 kg VS/$m^3 \cdot$ day (Misi and Forster, 2002). This lower maximum for the OLR may have been caused by a lower alkalinity of the TWAS and chicken manure mixture or by inhibition by ammonia from chicken manure. Similarly, a high OLR may cause inhibitory concentrations of other components, such as furfurals (Converti et al., 1999) or propylene glycol (Zitomer et al., 2001), depending on the type of waste being codigested.

The study by Björnsson et al. (2000) on the effect of reactor overloading revealed that laboratory-scale processes could be safely operated at a three to four times higher OLR than full-scale processes. Although the reason for this discrepancy was not clear, it is important to emphasize that laboratory-scale studies are not very predictive and that a large safety factor should be taken when designing full-scale processes on basis of performance parameters obtained in laboratory-scale processes. Contrary to this study, full-scale experiments at the Veggar Biogas Plant in Denmark showed that very high organic loading rates of up to 10 kg VS/$m^3 \cdot$ d can be used without any process problem when codigestates such as bentonite-bound oil or size water (a waste from protein extraction of bone) were added to thermophilic digesters with cow manure as the main waste (Ahring, 1995; Mathrani et al., 1994).

Digester Performance. In the bench- and full-scale experiments conducted by Björnsson et al. (2000), digester overloading caused changes in the partial alkalinity, the pH, and the VFA concentration. Although the decrease of the pH was within the standard deviation during normal operation, the changes of the partial alkalinity and VFA concentration were significant. Gas or methane production rate and gas composition are parameters that may also be used for monitoring digester performance, although, in the study by Björnsson et al. (2000), the responses of the gas production and composition were delayed. The type of volatile acids may be another important parameter for monitoring digester performance. Björnsson et al. (2000) observed in the bench-scale study that the concentration of propionic acid was highest during digester overloading.

Temperature. The few studies that directly compared the effect of the temperature on codigestion indicated that reaction kinetics were more favorable at a thermophilic temperature (Converti et al., 1999; Maibaum and Kuehn, 1999). This has been attributed to an increase of the hydrogenotrophic methanogenic activity of thermophilic archaea (Converti et al., 1999).

Two-Stage Processes. Two-stage processes, in general, outperform single-stage processes (Lafitte-Trouqué and Forster, 2000). Separation of the process into an acidogenic and a methanogenic stage would allow for optimization of each stage without interference with the other stage, which also allows for a higher OLR. Several designs for two-stage processes have been evaluated for codigestion. Temperature-phased anaerobic digestion generally demonstrated better performance than two-phase anaerobic digestion (Schmit and Ellis, 2001). This has been attributed to the first stage of the TPAD process having a greater specific rate of polymer hydrolysis and VS destruction than the first stage of the 2PAD process. In addition, the second stage of the TPAD process may have a higher ability to compensate for fluctuations occurring in the first stage.

Pilot-Scale Studies. Codigestion facilities often operate on an empirical basis. Pilot-scale studies can, therefore, play an important role in optimizing full-scale applications regarding digester operation and waste feed composition. In addition, pilot-scale studies can provide an indication of process performance.

The main operational parameters of a codigestion process are temperature, HRT, feed composition, and loading rate. The HRT has a significant effect on harmonizing acidogenic and methanogenic processes occurring during codigestion. Because methanogens are known to have a long mean generation time (Wilkie and Colleran, 1998), the HRT should be long enough to maintain a methanogenic population in a sufficiently high density in the digester. Acidogens prevail at a relatively short HRT, causing accumulation of VFAs, acidification, and instability of the process.

The pilot-scale studies of Rosenwinkel and Meyer (1999) demonstrated the importance of the waste composition in optimizing the HRT. They found that digesters for the sole digestion of slaughterhouse residues became acidified at HRT times as long as 44 days. However, when the residues were codigested (25% by volume) with MWS, a stable process was achieved at an HRT of only 25 days.

The pilot study of thermophilic sole digestion of organic fraction of restaurant solid waste of the Los Angeles airport was not focused on parameter optimization, but on the degradability of organic fraction of restaurant solid waste (Hernandez et al., 2001). This study proved that implementation of codigestion of this waste stream with municipal sludge at Hyperion WWTP could be possible without foreseeable major problems.

Pilot studies have also provided valuable information regarding the pretreatment of codigestates. Rosenwinkel and Meyer (1999) reported that a considerable amount of stomach contents was not degraded, although stomach contents were reduced in size in a macerator. Most of the macerated material, mainly straw, was present as a floating layer. Hence, systems for suspending or removing these floating layers should be recommended for full-scale applications if the waste is difficult to suspend. For digestion of food waste, Hernandez et al. (2001) reported that this waste did not contain grits. However, it needed grounding to provide a fluidized slurry that can easily be fed and to enhance anaerobic digestion.

Full-Scale Studies. Important issues discussed in full-scale studies included the enhancement of gas production and codigestate pretreatment, the conversion of digester gas to energy, and economic evaluations.

Enhancement of Gas Production. Several codigestates have been found to increase gas production in full-scale digesters. Rosenwinkel and Meyer (1999) reported that codigestion of slaughterhouse wastes with MWS increased the gas production by approximately 60%. Codigestion of kitchen and food waste with primary MWS increased gas production by 27% (Edelmann et al., 2000). Similarly, Kübler et al. (2000) reported an 18% increase in gas production during the codigestion of food waste and rumen content with OFMSW in a biogas plant. In all cases, the increase in gas production correlated with the higher organic loading because of the addition of the codigestate. The SMY, in all cases, was only slightly higher than that of the sole digestion of the main waste. This would indicate that codigestion does not improve the biodegradability of wastes. However, codigestion of FOG (2.7% VSS loading) with primary MWS caused an increase of the gas production of up to 21% (Machuzak, 1997). Although Machuzak (1997) did not provide data of the SMY, these results seem to indicate that codigesting FOG with MWS increased overall biodegradability.

Codigestate Pretreatment. Pretreatment of solid codigestates is, in general, required to reduce the size of waste particles and to facilitate waste transport through pipes and pumps. This requires additional equipment, not only for reducing the particle size, but also additional storage vessels. These drawbacks are, at least partly, counterbalanced by an increased biodegradability observed after particle size reduction (Kaparaju et al., 2001). This can probably be related to a higher particle surface-to-volume ratio.

Laboratory studies with wastes containing cellulose and lignin demonstrated that hydrolytic pretreatment and lignin removal increased the digestibility (Converti et al., 1997). However, full-scale applications for the codigestion of cellulose and lignin-containing wastes have not been reported over the past four years.

Digester Gas Conversion to Energy. One of the main advantages of codigestion is that increasing the methane production also increases the amount of energy obtained from converting methane to electricity and/or power. Kübler et al. (2000) reported that optimized operation of a codigestion plant resulted in an energy surplus of approximately 80.5 kWh/ton of treated waste. Before codigestion, the energy surplus was approximatley 72.2 kWh/ton. The energy balance of the codigestion process investigated by Edelman et al. (2000), which included pasteurization of MWS and indicated an energy surplus of 65 kWh (electricity) and 166 kWh (heat)/ton. Without pasteurization, the surplus would have been over 70kWh/t (electricity) and 210 kWh/t (heat). No data on energy surplus before codigestion was provided by Edelman et al. (2000). Biogas generated by a codigestion plant described by Kumke and Lanhans (2000) is supplied directly to engine-generator sets to produce electrical power and thermal energy. Approximately 30% of the electrical energy was used to satisfy the requirements of the codigestion and adjacent facilities used for animal confinement. The remainder was supplied to the local utility energy grid, providing revenue of approximately 8 cents per kilowatt-hour. Yoneyama and Takeno (2001) reported that the biogas produced by codigestion in a sludge recovery plant provided for approximately 7% of the plant's total energy demand. In this case, energy recovery from biogas was not sufficient to meet the demand of other plant operations, which included denitrification and aeration of the liquid fraction of wastes and gasification and ash melting of the biosolids cake. The codigestion processes described by Kumke and Lanhans (2000) and Yoneyama and Takeno (2001) were implemented in plants that used codigestion from the start. Therefore, these plants had no data on the energy surplus before codigestion.

Economic Evaluations. Only two reports provided insight in the economics of codigestion. Machuzack (1997) reported that codigestion of FOG in digesters at an existing wastewater treatment facility required $81,650 USD in capital costs and $22,500 USD per year for operation and maintenance (O&M). Storage equipment was not required because FOG was pumped directly from the delivery truck to the digester. The biogas was used in a cogeneration plant to compensate for operation costs.

Kumke and Lanhans (2000) reported a capital cost of $3.8 million USD for construction of a turnkey codigestion plant in 1995, treating approximately 260 ton/day of a waste composite of liquid manure and fat and oil residues. The total annual cost, which included depreciation, loans, and O&M, was $440,000, with O&M cost comprising for approximately 55% of the total costs. The average annual income because of the sale of electrical energy and payment for processing of industrial organic wastes was approximately $480,000.

Conclusions

(1) Certain wastes may contain constituents that are toxic and that may cause a decline in the performance of anaerobic digesters. Wastes containing high ammonia concentrations are of particular concern.

(2) Although most studies were conducted at mesophilic temperatures, a few studies indicated that codigestion at a thermophilic temperature would probably improve performance.

(3) Most codigestion processes have been single-stage at mesophilic temperatures. The few data available (laboratory, bench-scale) indicated that a similar performance will be obtained with two-phase codigestion, but performance might improve when using temperature-phase codigestion.

(4) Successful codigestion of several wastes in pilot- and full-scale applications has been demonstrated. Increases in the gas production ranging from 18 to 60% have been reported, while in the past even larger increases have been reported (e.g., Ahring, 1995; Mathrani et al., 1994).

(5) Gas enhancement production occurred mainly because of the increase in organic loading because of codigestate addition. Only in one case, when FOG was codigested with municipal wastewater sludge, gas enhancement production seems to be associated with an overall increase in the biodegradability of the waste mixture.

(6) Codigestion generally results in production of surplus energy.

(7) The pH alone is not a reliable parameter for monitoring digester performance. Partial alkalinity and/or the VFA concentrations better predict early stages of digester instability.

NOTATION

PARAMETERS

ALK	Alkalinity
COD	Chemical oxygen demand
Kjeldahl-N	Nitrogen (Kjeldahl)
NH_3-N	Nitrogen (ammonia)
OLR	Organic loading rate
PAlk	Partial Alkalinity
SCOD	Soluble chemical oxygen demand
SGY	Specific gas yield
SMY	Specific methane yield
TAlk	Total alkalinity
TEMP	Temperature
TS	Total solids
TS_{in}	Total solids influent
TSS	Total suspended solids
VFA	Volatile fatty acids (gas chromatography assay)
VOA	Volatile organic acids (distillation/titration assay)
VS	Volatile solids
VSD	Volatile solids destruction
VS_{in}	Volatile solids in influent
VSS	Volatile suspended solids
VSS_{in}	Volatile suspended solids influent
WW	Wet weight

WASTES

ADF	Aircraft deicing fluid
CAM	Cattle manure
CD	Cattle slurry or cattle dung
CM	Chicken manure
CRW	Carbohydrate-rich food processing waste
CSH	Corn starch hydrolyzate
ESS	Excess wastewater sludge
FOG	Fat, oil, and grease
FVW	Fruit and vegetable waste
HH	Hemicellulose acidic hydrolyzate
MWS	Municipal wastewater sludge
OFMSW	Organic fraction of municipal solid waste
PSS	Primary wastewater sludge
PW	Poultry waste
RC	Rumen content
SGM	Sheep and goat manure
SH	Starch hydrolyzate (enzymatic)
TWAS	Thickened waste activated sludge
VW	Vegetable waste
WAS	Waste activated sludge
WM	Waste milk

DIGESTER CONFIGURATIONS

2PAD	Two-phase anaerobic digestion system
CSTR	Completely stirred tank reactor
DAD	Dual anaerobic digestion system
DUAL	Mesophilic second-stage (gas phase)
SS	Single-stage system
SSAD	Single-stage anaerobic digestion system
TAND	Termophilic first stage (acid phase)
TPAD	Temperature-phased anaerobic digestion system

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