# Anaerobic Processes in Waste Treatment

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Anaerobic digestion is a biochemical conversion technology that can substantially destroy complex organic matter in wastes. When used in a fully engineered system, anaerobic digestion not only provides pollution prevention, but also allows for sustainable energy and nutrient recovery. As the technology continues to mature, anaerobic digestion is becoming a key method for both waste reduction and recovery of a renewable fuel and other valuable co-products. The main objective of this article is to provide an overview of the recent research on the anaerobic digestion of agricultural, industrial, and municipal wastes. Information of the recent development in anaerobic microbiology and mathematical modeling is also covered in the article.

## 1 General

Celis-Garcia et al. (2004) evaluated the granular sludge and biofilm for their susceptibility to sulfide and dissolved oxygen. It was found that both sulfate reduction and methanogenesis in attached biomass exhibited a better tolerance to high concentrations of total sulfide and dissolved oxygen than those in granular sludge. The better performance of biofilm was attributed to the selective attachment of biomass. Rulkens and Biens (2004) summarized the existing sludge treatment processes with a focus on the valuable use of organic carbon compounds as an energy source. Lahav and Morgan (2004) reviewed the titration measurement of volatile fatty acids (VFA) and carbonate alkalinity concentrations for monitoring of anaerobic digestion processes. Jordao and Volschan (2004) summarized the cost-effective solutions, particularly chemical enhanced primary treatment and upflow anaerobic sludge bed (UASB) process, for sewage treatment in Brazil. Angenent et al. (2004) reviewed the biological processing strategies that can produce bioenergy or biochemicals while treating industrial and agricultural wastewater. Yin et al. (2004) reviewed the dewaterability and the ultrasound pretreatment of bio-sludge. Yadvika et al. (2004) reviewed the different techniques that could be used to enhance the gas production rate from solid substrates. Rulkens (2004) presented a survey of the sludge treatment options that can eliminate the risks for environment and recover the valuable compounds in the sludge. Brief assessment was also given of the specific future technological development. Odegaard (2004) reviewed the sludge minimization technologies including mechanical, chemical, physical, and biological methods. Azbar et al. (2004) reviewed treatment and disposal alternatives of olive oil mill wastes.

## 2 Application of Anaerobic Digestion

### 2.1 Sewage Sludge Treatment

Park et al. (2004) investigated the effects of pretreatment of secondary sludge by microwave irradiation on anaerobic digestion. The microwave pretreated sludge contained higher concentration of soluble chemical oxygen demand (COD). Anaerobic digestion of the pretreated sludge achieved higher volatile solid (VS) reduction, biogas production, and COD removal rate than that of untreated sludge. High-powered ultrasound was applied to waste activated sludge (WAS) to rupture the cellular material and reduce the particle size (Hogan et al. 2004). Increased biogas production from sonicated WAS and better solids reduction was achieved in anaerobic digestion. The digested sludge also had improved dewatering characteristics. Mao et al. (2004) studied the ultrasound treatment of primary and secondary sludges. It was indicated that secondary sludge had a more remarkable improvement after sonication than the primary sludge. Optimal solids concentration range for optimum sonication was proposed. Rai et al. (2004) investigated the influence of pressure pulses produced by an ultrasonic homogenizer on the disintegration of the sludge. It was found that the degree of disintegration, as indicated by COD and protein release, increased significantly when the energy intensity applied with the ultrasonic homogenizer was increased. Yoon et al. (2004) developed an MBR-US system by incorporating an ultrasonic cell disintegration process to a conventional membrane bioreactor. The results showed that sludge production was completely prevented using the hybrid system. However, the effluent quality of MBR-US slightly deteriorated due to the return of disintegrated sludge. Onyeche (2004) integrated sewage sludge homogenization into anaerobic digestion. More energy generation and sludge reduction was achieved during the following anaerobic digestion process. Sievers et al. (2004) investigated the ozonation of industrial and sewage sludge. Sludge liquefying by release of 110 and 160 mg COD/g total suspended solid (TSS) had been reached at specific ozone consumption of 0.03 and 0.06 kg $O_3$/kg TSS. The subsequent biological treatment reached a mass reduction of 19% for the anaerobic stabilization. Goel et al. (2004) investigated the treatment of a mixture of primary and secondary municipal sewage sludge with an anaerobic digester coupled with ozonation process. Due to sludge ozonation and long solids residence time (SRT), high VSS degradation efficiency of approximately 80% was achieved at a reactor solid concentration of 6.5%. The high inorganic content in the digested sludge resulted in better sludge dewaterability. Meeroff et al. (2004) conducted laboratory and pilot tests to investigate the use of ionizing radiation in the sludge treatment. Radiation caused permanent effects in measured sludge parameters including solids content, COD, ammonia-nitrogen, specific surface area, resistance to filtration, pH, organic acid production, and digester gas evolution. Vlyssides and Karlis (2004) investigated the thermal-alkaline solubilization of WAS as a pretreatment stage for anaerobic digestion. At pH 11 and a temperature of 90°C the concentration of the volatile suspended solid (VSS) was 6.82%, the VSS reduction reached 45% within ten hours. The total efficiency for methane production was 0.28 l $CH_4$/g of VSS loading. Chu and Lee (2004) studied two sludge pretreatment techniques: ultrasonication and alkaline treatment. Both treatments released a marked amount of insoluble organic matter in soluble form. Alkaline treatment was proved to be more efficient than the ultrasonication. Valo et al. (2004) investigated the influence of different pretreatments on anaerobic digestion of WAS. Results showed that thermo-chemical pretreatments were the most efficient on COD solubilization. Pretreatment of WAS under optimal conditions (170°C and pH 10) led to 71% COD degradation, 59% total solids (TS) degradation, and 54% increase in biogas production in the following anaerobic digestion. Muller et al. (2004) studied the effect of sludge pretreatment on anaerobic digestion. The disintegration techniques used included a stirred ball mill, an ultrasound disintegrator, a lysate centrifuge and ozone treatment. An enhancement of the degree of degradation of 7.4-20% was observed compared to a reference system without pretreatment. Kopplow et al. (2004) investigated the effect of sludge pretreatment with pulsed electric fields on the anaerobic digestion. Pretreatment increased the sludge disintegration by 20% and the degradation rate of organic matter increased about 9%. Takiguchi et al. (2004) investigated the effect of sludge processing on the anaerobic digestion of WAS. The results suggested that sludge processing for phosphorus recovery (heat treatment followed by calcium phosphate precipitation) could improve digestive efficiency and methane productivity at both mesophilic and thermophilic temperatures.

Dohanyos et al. (2004) studied improvement of anaerobic digestion of sludge. The Implementation of thermophilic anaerobic digestion (55°C) and excess sludge disintegration by means of lysate-thickening centrifuge can improve the raw sludge biodegradation and biogas production to an extent that the wastewater treatment plant can be energetically self-sufficient. Song et al. (2004) studied the anaerobic digestion of sewage sludge by mesophilic and thermophilic temperature co-phase anaerobic digester, single-stage mesophilic digester, and single-stage thermophilic digester. The temperature co-phased reactor achieved higher VS reduction and process stability than the single-stage reactors. The better performance was attributed to the well-functioned thermophilic digester and selection of high substrate affinity anaerobic microorganisms in the co-phase system. Mahmoud et al. (2004) studied the effect of SRT and process temperature on the hydrolysis, acidification and methanogenesis of primary sludge.

Hydrolysis was found to be the rate limiting-step of the overall digestion process, for the reactors operated at 35°C and 25°C, except for the reactor operated at 10 days and 25°C. At the latter conditions, methanogenesis was the rate-limiting step of the overall digestion process. Alam and Fakhru'l-Razi (2004) compared the liquid state bioconversion of sewage sludge in fermenter and in shake flask. The results revealed that the overall performance of fermenter was higher than the shake flask in terms of biosolids accumulation and biodegradation. Pereira et al. (2004) studied the mineralization of long chain fatty acids (LCFA) associated with anaerobic sludge. It was concluded that LCFA did not exert a bactericidal or permanent toxic effect toward the anaerobic consortia. Jung et al. (2004) investigated the solubilization of sewage sludge by alternating aerobic and anaerobic operations. Nitrogenous compounds among intracellular matters released by the lysis were completely removed biologically under an optimal condition due to appropriate reaction balance among hydrolysis, nitrification and denitrification rates. Reusser and Zelinka (2004) performed side-by-side evaluations of alternative sludge digestion systems. The VS reduction in laboratory thermophilic-mesophilic-phased digestion systems at total retention times of 10 and 12.5 days were found to be higher than in single-stage mesophilic digestion at 20 days, single stage thermophilic digestion at 15 days, or acid/methane-phased digestion system at 20 days. Ros and Zupancic (2004) studied the two-stage thermophilic anaerobic-aerobic digestion of WAS. The process showed a VSS removal of 61.8% and COD removal of 57.4% in 15 days hydraulic retention time (HRT). Comparison of the processes with recently published research indicated that this process was better than most published two-stage processes. Kim et al. (2004b) studied the anaerobic sludge digestion in mesophilic and thermophilic anaerobic digestion elutriated phased treatment system (M-ADEPT and T-ADEPT). Both M-ADEPT and T-ADEPT showed better effluent quality, reduced reactor volume requirements, and more stable methanogenesis than complete stirred tank reactors (CSTR).

## 2.2 Municipal Solid Waste (MSW) Treatment

Lissens et al. (2004a) investigated the effect of thermal wet oxidation on the anaerobic biodegradability and methane yields from different biowastes. Measured methane yields for raw yard waste, wet oxidized yard waste, raw food waste, and wet oxidized food waste were 345, 685, 536, and 571 ml $CH_4$/g VSS, respectively. The increase of the specific methane yield for the full-scale biogas plant by applying thermal wet oxidation was 35-40%. Lopes et al. (2004) tested the influence of bovine rumen fluid inoculum during anaerobic treatment of the organic fraction of MSW. The data obtained affirmed that the inoculum used substantially improved the performance of the process. Biostabilization time was decreased from 459 to 234 days and biogas methane content was increased from 3.6% to 42.6% when inoculum/MSW ratio was increased from 0 to 1/9. Forster-Carneiro et al. (2004) developed an optimized reactor start-up protocol based on the dry anaerobic digestion of organic fraction of MSW and other organic compounds (garden waste, rice hulls, animal waste and sludge). A system operating the optimized protocol showed a rapid start-up. The gas production was 6.5 l/d. Barnes and Keller (2004) investigated the possibility of degrading cellulosic organic materials in MSW using rumen-based microbial inoculum and anaerobic sequencing batch reactor (ASBR). The rumen ASBR system was found to achieve high acid production rate, 210-230 mg COD/ l•h at a cellulose loading rate of 10 g/l•d, which was comparable to previously described rumen simulation systems. Kim et al. (2004a) studied the co-digestion of sewage sludge and food waste using a temperature-phased anaerobic sequencing batch reactor (TPASBR). The TPASBR showed higher VS reduction, methane yield, and methane production rate than those of the mesophilic sequencing batch reactor (SBR). The enhanced performance of TPASBR was attributed to longer SRT, fast hydrolysis, higher methane conversion rate, and balanced nutrient condition of co-substrate. Rao and Singh (2004) studied the batch digestion of organic fraction of MSW. The net bioenergy yield from MSW and corresponding bioprocess conversion efficiency over the length of the digestion time were observed to be 12528 kJ/kg VS and 84.51%, respectively. The feasibility of nearly complete conversion of lignocellulosic waste (70% food crops, 20% faecal matter and 10% green algae) into biogas was investigated (Lissens et al. 2004b). The treatment system included a mesophilic CSTR, an upflow biofilm reactor, a fiber liquefaction reactor employing the rumen bacterium *Fibrobacter succinogenes* and a hydrothermolysis system in near-critical water. The total process yielded biogas corresponding with conversions up to 90% of the original organic matter. Rani and Nand (2004) investigated anaerobic digestion of pineapple peel waste that was rich in cellulose, hemicellulose and other carbohydrates. Ensilaging of pineapple peel resulted in the conversion of 55% carbohydrates into VFAs. Biogas digester fed with ensilaged pineapple peel resulted in the biogas yield of 0.67 $m^3$/kg VS added with methane content of 65%. Lee et al. (2004) investigated the in vitro stimulation of rumen microbial fermentation of cellulose by a rumen anaerobic fungal culture (AFC). The addition of AFC, filtered AFC, and autoclaved AFC caused a marked increase in gas production of 50, 29, and 32% after 24 hrs, respectively. It was suggested that the positive responses be caused by the high fibrolytic enzyme addition from the fungal cultures and increased microbial population despite of the antagonistic relationship of fiber break down by rumen fungi to rumen bacteria and unknown inhibitor factors in the rumen fluids. Yang et al. (2004c) investigated the anaerobic digestion of cellulose using a carbon felt fixed-bed reactor. In the batch operation, the VS reduction and cumulative methane production during mesophilic and thermophilic digestion were 52.2% and 15.9%, 96.7 and 49.2 ml/g TS fed, respectively. In the semi-continuous mesophilic digestion, cellulose degradation reached its highest level of 67.6% at HRT of 9 days. Hu et al. (2004) studied the anaerobic degradation of cellulose by rumen microorganisms at various pH values. The degradation efficiency increased with pH and the highest value of about 78% was achieved at pH 6.8 and 7.3. Gunaseelan (2004) reported the biochemical methane potential of fruits and vegetable solid wastes. The ultimate methane yields of fruit wastes and vegetable wastes ranged from 0.18 to 0.73 l/g VS and 0.19-0.4 l/g VS. These results provided a database on extent and rates of conversion of fruits and vegetable solid wastes that significantly contribute to organic fraction of MSW. Mshandete et al. (2004a) investigated the anaerobic batch co-digestion of sisal pulp and fish wastes. While the highest methane yields from sisal pulp and fish waste alone were 0.32 and 0.39 $m^3$ $CH_4$/kg VS, respectively, co-digestion with 33% of fish waste and 67% of sisal pulp gave a methane yield of 0.62 $m^3$ $CH_4$/kg VS. Han and Shin (2004) studied the two-stage process (BIOCELL) converting food waste to hydrogen and methane. The BIOCELL process demonstrated that, at the high VS loading rate of 11. 9 kg/$m^3$•day, it could remove 72.5% of VS and convert VS removed to $H_2$ (28.2%) and $CH_4$ (69.9%) on a COD basis in 8 days. Babel et al. (2004) studied the VFA production from solid pineapple waste. It was found that acid production was enhanced when the digester was operated at neutral pH. Bouallagui et al. (2004a) used a two coupled ASBR operated at mesophilic temperature to digest fruit and vegetable wastes. Phase separation with conventional ASBR reactors resulted in high process stability, significant biogas productivity and better effluent quality. The overall COD removal in the treatment system was 96%. Bacterial 16S rDNA showed at least 7 different major species with a very prominent one corresponding to a *Megasphaera elsdenii* in acidogenic reactor whereas bacterial 16S rDNA of a methanization bioreactor showed 10 different major species (Bouallagui et al. 2004b). Bouallagui et al. (2004c) studied the effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste. Biogas production from thermophilic digester was 144% and 41% higher than from psychrophilic and mesophilic digesters, respectively. VFAs could be obtained at 50 g/kg waste within 14 days when operating at pH 6.5-7.5. Demir et al. (2004) tested the effect of leachate recirculation on the methane generation rates in landfill site. Due to the appropriate conditions such as moisture content, solid waste decomposition rate in test cell with leachate recirculation was enhanced at a rate of 79% relative to that of test cell without leachate recirculation.

Cinar et al. (2004) investigated the co-disposal of solid waste with three types of sludges, including primary settling sludge, secondary settling sludge and a mixture of primary sludge and WAS. The stabilization of solid waste in the reactor receiving the mixture of primary settling sludge and WAS was faster, as indicated by the total gas production and COD removal data. Jansen et al. (2004) studied the anaerobic co-digestion of urban organic waste with sludge. Higher biogas yield was found during co-digestion than should be expected from digestion of the two materials separately. Heo et al. (2004) tested the effects of mixture ratio and HRT on single-stage anaerobic co-digestion of food waste and WAS. The optimum operating conditions of the single-stage anaerobic digester were found to be an HRT of 13 days and a mixture of 50:50. The VS removal efficiency and biogas production rate in this condition were 56.8% and 1.24 $m^3/m^3 \bullet d$, respectively with an organic loading rate (OLR) of 2.43 kg VS/ $m^3 \bullet d$.

### 2.3 Municipal Wastewater Treatment

Alvarez et al. (2004) studied the anaerobic digestion of raw domestic wastewater by a novel technology consisting of a UASB reactor and a completely mixed digester. The steady state efficiency of the UASB system was 79% TSS removal, 52% Total COD removal and 60% $BOD_5$ removal at 6-8 h HRT, 15-16°C, and 330-360 mg/L of influent Total COD. Kunte et al. (2004) developed a two-stage anaerobic digestion process, consisting of separate acidogenic and methanogenic digesters to treat human night soil. The process achieved complete inactivation of enteric pathogens while maintained efficient biogas generation. Zhao and Viraraghavan (2004) analyzed the performance of an anaerobic digestion system treating municipal wastewater. Thickening the primary sludge and increasing the VS loading rate were used to optimize the operation of the digestion system. It was also found that Chen-Hashimoto model and first-order model could be used to predict the volumetric methane production rate and efficiency of VS reduction, respectively. Singh and Viraraghavan (2004) studied the treatment of municipal wastewater by a UASB process. Changes in temperature and HRT impacted the reactor performance. Overall reactor performance (70-90% COD removal) was found to be stable up to an HRT of 6 hr and temperature of 11°C. This study demonstrated that UASB could be applied successfully with some minor adjustment for the treatment of municipal wastewater in temperate and cold regions. Xu et al. (2004) investigated the effect of zero valence Fe on the anaerobic digestion of domestic wastewater in UASB reactors. The Fe(0) application significantly increased the $CH_4$ yield by 8.7% and decreased the effluent COD concentration by 21% relative to the control reactor.

### 2.4 Industrial Waste Treatment

Ortega-Clemente et al. (2004) investigated the biological treatment of recalcitrant effluent (weak black liquor) from pulp mills by an integrated system consisting of a methanogenic fluidized bed reactor and an aerobic upflow reactor. Overall, the two-stage treatment achieved approximately 78% removal of the original organic matter and 75% removal of color and ligninoid contents. Yu et al. (2004) tested the biodegradability of thermomechanical pulping wastewater. A biochemical methane potential test showed approximately 13 ± 1% of the COD was anaerobically biodegradable. Addition of glucose enhanced the fragmentation of lignocellulosics by more than six times. Oz et al. (2004) studied the anaerobic digestion of a chemical synthesis-based pharmaceutical wastewater. The CSTR can treat wastewater consisting 100% pre-aerated wastewater. However, total failure of anaerobic reactor was observed at 60% wt/v raw wastewater fed. Fountoulakis et al. (2004) investigated the toxic effect of six chemicals present in pharmaceuticals on anaerobic biomass. Acetoclastic methanogens were found to be the most sensitive group of microorganisms. Pharmaceuticals tested caused a mild inhibition to the methanogens, related directly to the tendency of the compounds to adsorb on the anaerobic biomass. Duran and Tepe (2004) studied the anaerobic digestion of an industrial waste with 84% TS and 57% VS. It was concluded that the co-digestion of this industrial waste with the WAS was beneficial from the digestion kinetics point of view since the maximum specific substrate utilization rates increased approximately 20% from 0.138 to 0.165 g COD/g VSS•d. Wang (2004) studied the effect of di-n-butyl phthalate (DBP) on activated sludge. Although DBP showed inhibitory effect on activated sludge and unacclimated activated sludge could not degrade DBP, the acclimated activated sludge could degrade up to 100 mg/l DBP completely. Oliveira et al. (2004) investigated the anaerobic degradation of formaldehyde with a packed-bed reactor. Formaldehyde concentrations of 26.2-1,158.6 mg/l were applied in the reactor, resulting in formaldehyde and COD removal efficiencies of 99.7% and 92%, respectively. Mshandete et al. (2004b) studied the anaerobic degradation of potato-waste leachate using anaerobic, packed-bed bioreactors. The results demonstrated the suitability of a packed bed bioreactor operated at low recirculation flow rate for treating leachate from potato waste. Parawira et al. (2004) investigated the production of VFAs by anaerobic digestion of solid potato waste. After 300 h digestion, the fermentation products were chiefly acetic, butyric, propionic and caproic acid and gas production was negligible. Increase of potato solids load increased the butyric acid and lactic acid concentration. Rajbhandari and Annachhatre (2004) treated starch wastewater with a series of anaerobic ponds followed by facultative ponds. This system achieved an overall COD and TSS removal of over 90%. Murto et al. (2004) investigated the co-digestion of industrial waste from potato processing with sewage sludge and pig manure. Co-digestion of sewage sludge and industrial waste resulted in a low buffered system when the starch-rich waste was increased. Co-digestion of pig manure, slaughterhouse waste, vegetable waste, and industrial waste produced a high buffered system as the manure contributed to high amounts of ammonia. Borja et al. (2004a) studied the anaerobic digestion of wastewater derived from the production of protein isolates from chickpea flour. The digestion was carried out in a laboratory-scale, mesophilic fluidized-bed reactor with saponite as bacterial support. 85% of feed COD could be removed with OLR of up to 2.1 g COD/l•d. Because of the strong buffering capacity, the rate of methanogenesis was virtually independent of OLR applied. Farizoglu et al. (2004) investigated the treatment of raw cheese whey with a jet loop membrane bioreactor. A treatment efficiency of 97% was obtained for 1.6 days of sludge age and COD loads of 22.2 kg COD/ $m^3$•d. Sabbah et al. (2004) incorporated the pretreatment (sand filtration and powered activated carbon treatment) to the anaerobic treatment of olive mill wastewater. It was found that pretreatment enhanced the anaerobic activity of the sludge in the batch system significantly. Isidori et al. (2004) studied the biological treatment of olive-oil mill wastewater using commercial microbial formulations. The results obtained with the mixed formulations showed that maximum removal of the organic load was about 85%, whereas phenols were reduced by about 67%. D'Annibale et al. (2004) studied the treatment olive-mill wastewater by fungus *Panus tigrinus* (*P. tigrinus*). The initial soluble COD of 85,000 mg/l led to a delay in removal of color, organic load and phenol, which was attributed to the delayed onset of laccase and Mn-dependent peroxidase. On the other hand, *P. tigrinus*, when grown on olive mill wastewater with an initial soluble COD content of 43,000 mg/l, promptly and efficiently removed the aforementioned components. Raposo et al. (2004) compared the anaerobic digestion of olive mill effluents in reactors with suspended and immobilized biomass. It was observed that the reactor with support was always more efficient and stable showing higher total COD, soluble COD removal efficiencies and lower VFA/alkalinity ratio values than those found in the control reactor. Bertin et al. (2004a) studied the anaerobic digestion of olive mill wastewaters in biofilm reactors packed with granular activated carbon and silica beads. Under batch and continuous conditions, biofilm reactors exhibited COD and phenolic compound removal efficiencies markedly higher (from 60% to 250%) than those attained in a parallel anaerobic dispersed reactor. A comparison of 16S rRNA gene sequences of the inoculum and of biomass samples from different districts of the reactor revealed enrichment of specific microbial populations, probably minor members of the inoculum and/or of the olive mill wastewaters (Bertin et al. 2004b). They mainly consisted of the members of *Proteobacteria, Flexibacter-Cytophaga-Bacteroides*, and sulfate-reducing bacteria. The dominant sequence among Archaea (70% of clones) was closely related to *Methanobacterium formicicum*. Lalman and Komjarova (2004) studied the effect of LCFA on glucose fermentation under mesophilic conditions. It was found that linoleic acid was more inhibitory than oleic acid and stearic acid. Acetate accumulation indicated the acetoclastic methanogenic population was affected only by oleic acid and linoleic acid. Kim et al. (2004c) studied the two-phase anaerobic treatment system for fat-containing wastewater. The two-phase system was composed of a CSTR reactor for acidogenesis and a UASB for methanogenesis. More than 19.2% of LCFAs were degraded and 11.5% of unsaturated LCFAs were saturated in the acidogenesis of the two-phase system, which led to the enhanced specific methane production rate and the reduced scum layer of the subsequent UASB reactor. Mouneimne et al. (2004) studied effect of bentonite on the anaerobic digestion of solid fatty wastes. The experimental results showed that the best performance in the elimination of hexane extractable matter (73 ± 2.5%) and the production of VFAs (39 ± 1.5%) were achieved when bentonite/grease ratio was 0.9. Rodgers et al. (2004) treated the whey wastewater with a novel moving anaerobic biofilm reactor. In this process, biofilm was grown on a plastic biofilm media module, which was vertically moved up and down in the bulk fluid. It was reported that COD loading rate up to 11.6 kg COD/ $m^3$•d was achieved with the COD removal efficiency of 89% and HRT of 1 day. The percentage of methane in the biogas was 63% on average and the yield of methane was 333.4 L $CH_4$/kg COD removed. Boshoff et al. (2004) tested the possibility of using tannery effluent as a carbon source for biological sulfate reduction. Sulfate removals of 60-80% were obtained at total sulfate feed levels of up to 1,800 mg/l. This study demonstrated that acid mine drainage and tannery effluent could be treated simultaneously. Patidar and Tare (2004) tested the effect of micro-nutrients in anaerobic degradation of sulfate laden organics. Results indicated that precipitation of nutrients could seriously deteriorate process performance, leading to failure even before sulfide concentration attains toxic level. Gebauer (2004) studied the mesophilic anaerobic treatment of sludge from saline fish farm effluents using a CSTR reactor. COD stabilization between 36% and 55% and methane yields between 0.114 and 0.184 l/g

COD added were achieved. Strong inhibition by sodium was observed with propionic acid being the main compound of the VFAs. An anaerobic digestion technique was applied to azo-reactive dye aqueous solutions (Georgiou et al. 2004). Complete decolorization of all dye solutions was succeeded in 4-5 days when acetic acid served as external substrate. Zhang et al. (2004b) studied the methane production from anaerobic digestion of alcohol waste slurry. When fermentation was carried out at the optimum concentration of trace metal ions, the methane production rate was 2.35 l/l•d and 3.90 l/l•d for the CSTR and fixed-bed reactor, respectively. Tosun et al. (2004) studied the anaerobic digestion and methane generation potential of rose residue in batch reactors. Experimental results showed that hydrolyzed rose residue produced more methane than original residue. Chen-Hashimoto's model was found to be more suitable than first-order kinetic model. Jimenez et al. (2004) carried out a kinetic study on the anaerobic digestion of untreated beet molasses and molasses previously fermented with *Penicillium decumbens*. The anaerobic digestion process of both substrates was found to follow a first-order kinetics. The average methane yield coefficient for pretreated molasses was 305 ml $CH_4$/g COD removed, which was 35% higher than that provided by untreated molasses. Borja et al. (2004b) studied the anaerobic biodegradation of two-phase olive pomace. It was found that the increase of influent substrate concentration favored the process failure. The kinetic model of Andrews was used to describe the relation between anaerobic biodegradation of Total COD and VS and the formation of methane. The values of kinetic constants were determined.

## 2.5 Agricultural Waste Treatment

Yang et al. (2004b) investigated the optimization of physiological conditions (HRT, pH) to enhance the acidogenesis of swine wastewater. It was concluded that the enhanced acidification process to manage swine waste should be operated in the range of 2.1 to 2.4 days HRT at 34.5 ± 0.5°C with an ammonia nitrogen concentration of less than 1.2 g/l. Sanchez et al. (2004) studied the effect of organic volumetric loading rate on the performance of a down-flow anaerobic fixed bed reactor treating settled piggery waste. The reactor achieved good removal efficiencies and stability at OLR between 1.1-6.8 g COD/l•d. Ahn et al. (2004a) developed a novel high-rate anaerobic digestion elutriated phased treatment (ADEPT) process for treating a slurry-type piggery waste. The ADEPT process contained an acid elutriation reactor for hydrolysis and acidification, followed by a UASB reactor for methanification. Methane production and content in the system were 0.3 l $CH_4$/g VS fed and 80%, respectively. A full-scale biogas plant was applied to the processing of swine manure (Chae et al. 2004). The plant consisted of an anaerobic digester and an engine generator. The digester operation resulted in an 81% of COD removal and methane-rich biogas production that was used to generate electrical and thermal energy. The electricity could supply 50% of the energy required to further reduce ammonia and residual COD by an electro-chemical treatment. Zhang et al. (2004a) developed a bench-scale integrated swine wastewater treatment system consisted of one ASBR, one or two aerobic SBR (SBR1 and SBR2), one sludge settling tank, one sandfilter, and one reverse osmosis unit. The COD and solids in the wastewater were reduced by 89% and 97% after treatment with ASBR and SBRs. Masse et al. (2004) evaluated the effect of scale-up on the performance and stability of psychrophilic ASBR treating high-strength swine manure. Performance of three semi-industrial scale reactors showed that scale-up of the reactors by a factor of 20 to 40 to commercially operated farm digesters should not affect process efficiency and stability. It was indicated that conical-bottom ASBR did not perform differently from the flat-bottom ASBR at the scale tested. El-Mashad et al. (2004) studied the effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. The results showed that the methane production rate at 60°C was lower than that at 50°C at all experimental conditions except when downward temperature fluctuations were applied at an HRT of 10 days. It was also found that the free ammonia concentration not only affected the acetate-utilizing bacteria but also the hydrolysis and acidification process. Demirer and Chen (2004) studied the effect of retention time and OLR on two-stage anaerobic acidification and biogasification of dairy manure. The results indicated that pre-acidification of dairy manure led to significantly high VS reduction efficiencies and biogas production in the subsequent methanogenic reactor. Lower performance was observed for the high OLR due to the possible wash-out of the acidifiers. Demirel and Yenigun (2004) tested the anaerobic acidogenesis of dairy wastewater in a laboratory-scale mesophilic reactor. The reactor was operated at HRT between 12-24 hr and OLR up to 9.3 kg COD/$m^3$•d. The highest degree of acidification and the rate of acid production were 56% and 3.1 g/l•d at 12 h HRT. Acetic, propionic, butyric, valeric acids were the common acidogenesis products. Gungor-Demirci and Demirer (2004) investigated the anaerobic treatability and biogas generation potential of broiler and cattle manure. Results revealed that the efficiency of total COD removal was 32.0-43.3% and 37.9-50% for initial COD concentrations of 12,000 and 53,500 mg/l, respectively. A decrease in biogas yield was observed as the fraction of broiler manure increased in the mixture at initial COD values of 53,500 mg/l. McGrath and Mason (2004) developed a biogas production assessment method based on the visual monitoring of biogas evolution events in an anaerobic waste stabilization pond treating farm dairy wastewater. Major biogas-induced perturbations at the pond surface were classified as with type 1, type 2, or small bubble events. Mean counts of type 1 and 2 events varied from 7.3 to 30 per hour, respectively. Future method development included an increased number of event categories and automatic recording of events. Nielsen et al. (2004) compared the anaerobic digestion of cattle manure with a two-stage thermophilic (68°C/55°C) digester and a one-stage thermophilic (55°C) digester. When an OLR of 3 g VS/l•d was applied, the two-stage setup had a 6% to 8% higher specific methane yield and a 9% more effective VS removal than the conventional single-stage reactor. Moller et al. (2004) determined the methane productivity of manure in terms of VS, volume and livestock production. The methane productivity was higher in pig and sow manure than in dairy cattle manure.

## 3 Microbiology

Yang et al. (2004a) investigated the methanogenic community and performance of fixed- and fluidized-bed reactors with reticular polyurethane foam. The best performance was obtained from the fixed-bed reactor with the 20 cells/25 mm polyurethane foam. 16S rRNA and polymerase chain reaction (PCR) analysis indicated that the major immobilized methanogens belonged to the genus *Methanosarcina*. Savant and Ranade (2004) studied the application of hydrogen utilizing methanogens



 

*Methanobrevibacter acididurans* on the methane production in anaerobic digesters. Experimental results showed that addition of this acid tolerant hydrogen trophic methanogen to digesting slurry increased the methane production and decreased the accumulation of VFAs. McMahon et al. (2004) studied the microbial population dynamics during start-up and overload conditions of anaerobic digesters treating MSW and sewage sludge. Changes in community structure were monitored using ribosomal RNA-based oligonucleotide probe hybridization. It was found that digesters with high levels of Archaea started up successfully. Digesters with a history of poor performance tolerated a severe organic overload better than digesters that had previously performed well. It was concluded that higher levels of syntrophic propionate-oxidizing bacteria, saturated fatty acid-beta-oxidizing syntrophs, and their methanogenic partners were responsible for this behavior. Chackhiani et al. (2004) used polymerase chain reaction-single strand conformation polymorphism (PCR-SSCP) to study dynamics of microbial populations during start-up of thermophilic anaerobic digestion of cattle manure. 16S rDNA characterization showed that the dominant bacterial SSCP peak were phylogenetically close to *Bacillus thermoterrestris*, where dominant archaeal SSCP peaks were close to *Methanoculleus thermophilicus* and *Methanosarcina thermophila.* Yang et al. (2004d) evaluated four bed materials for their effect on microbes immobilization. The best methane yield was obtained from the reactor with loofah sponge as supporting materials. The results of the 16S rRNA phylogenetic analysis indicated that the major immobilized methanogens were *Methanobacterium formicicum*, *Methanosarcina barkeri* and *Methanosarcina mazei* in all the bed materials. Continuous methane fermentation in a fixed-bed reactor packed with loofah showed that the carrier immobilized almost 95% of the methanogens, which led to a more effective bio-reaction (Yang et al. 2004e). Burrell et al. (2004) identified and detected the *Clostridium* population in an anaerobic bioreactor treating crystalline cellulose. The majority of the microorganisms fell into one of five lineages of the *Clostridia* (Clone group 1-5). It was demonstrated in fluorescence in situ hybridization (FISH) experiments that bacteria targeted by the probes for clone groups 1, 2, 3, and 5 were very abundant on the surfaces of the cellulose particles and likely the key cellulolytic microorganisms in the landfill bioreactor. Sawayama et al. (2004) studied the effect of ammonium addition on the methanogenic community in a fluidized bed anaerobic reactor. The results of the clone analysis suggested that the major methanogens were changed from *Methanosaeta* sp. and *Methanomicrobiales* to *Methanobacterium* and *Methanosarcina* sp. after immobilization. It was also indicated that methanogens were relatively more sensitive to ammonium than bacteria.

## 4 Mathematical Modeling

Batstone et al. (2004) used data from sequencing operation to estimate the ADM1 (Anaerobic digestion model) parameters describing winery wastewater degradation. The parameters were found effectively representing the pulses of acetate and ethanol within 4 days of the winery-fed cycles. The main discrepancy was poor prediction of pH dynamics, Seco et al. (2004) developed a biological nutrient removal model – BNRM1. The model included most of the biological and physico-chemical processes taking place in all treatment operations. Growth of bacterial groups can be determined by environmental conditions. BNRM1 can be used to design, simulate and optimize the whole wastewater treatment plant. Redzwan and Banks (2004) developed a mathematical function to determine the maximum methane production in batch anaerobic reactor. The equation could estimate experimental gas production curve with a high degree of similarity. Mora-Naranjo et al. (2004) developed a mathematical model to simulate the biodegradation of anaerobic degradation of organic matter in municipal landfills. Anaerobic reactions including hydrolysis, acetogenesis, and methanogenesis were incorporated. It was found that environmental factors such as temperature and water content significantly impacted the overall degradation of solid waste. Eldem et al. (2004b) developed a new model to account for the influences of pH and ammonia on methane production in the anaerobic treatment of wastewaters. The model was evaluated by using two different sets of experimental data (Eldem et al. 2004a). The proposed model can be used to calculate optimal pH as a function of total ammonia nitrogen concentration. High levels of correlation were achieved by the application of the model to the experimental data. Muroyama et al. (2004) investigated the reaction kinetics for anaerobic biodegradation of volatile acids components that were commonly contained in the wastewater from breweries. The batch degradation sequences for the single and multiple volatile acids in the batch sludge bed reactor were explained well by the numerical solutions of multiple differential mass balance equations. Haarstrick et al. (2004) developed a model to simulate the biodegradation of easily hydrolysable solid organic matter, the generation of biogas, and heat release. The overall decomposition of the organic matter was assumed to follow hydrolysis, acidogenesis, and methanogenesis. Temperature, pH, and oxygen changes were integrated into the degradation model as reaction influencing terms. The model could be used to predict the time-dependent change of organic substances, gases, and biomass. A mathematical model simulating the hydrological and biochemical processes occurring in landfilled waste was presented (Zacharof and Butler 2004). Waste decomposition was modeled using traditional biochemical waste decomposition pathways. Water flow through the waste was represented using a statistical velocity model. It was concluded that the model provided a good basis for making predictions of landfill processes. Vavilin et al. (2004) developed a distributed mathematical model to describe the balance between the rates of hydrolysis/acidogenesis and methanogenesis during anaerobic digestion of rich (food) and lean (non-food) solid wastes. The results showed that initial spatial separation of food waste and inoculum enhanced methane production and waste degradation in a one-stage solid-bed digester at high waste loading. Yildiz et al. (2004) developed a mathematical model to simulate the leachate quality and quantity in MSW landfills. The model incorporated governing equations that described leachate flow, dissolution, acidogenesis, and methanogenesis. The use of the proposed conceptual model enabled the prediction of the spatial and temporal distributions of moisture and leachate constituents. Ahn et al. (2004b) studied the anaerobic acidogenesis of starch-processing wastewater. A fourth order Runge-Kutta approximation was used to determine the Monod kinetics of the acidogens. The model outputs and experimental data fit together satisfactorily.

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