Anaerobic Co-digestion of Biomass for Methane Production: Recent Research Achievements

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ABSTRACT
Anaerobic digestion (AD) is a process by which microorganisms break down biodegradable material in the absence of oxygen. Anaerobic digestion can be used to treat various organic wastes and recover bio-energy in the form of biogas, which consists mainly of CH_4 and CO_2. A great option for improving yields of anaerobic digestion of solid wastes is the co-digestion of multiple substrates. Numerous studies demonstrate that using co-substrates in anaerobic digestion system improves the biogas yields due to positives synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates. In addition, co-digestion offers several possible ecological economical advantages. Recent research (published during the past three years) on this topic is reviewed in the current paper. Special attention is paid to anaerobic co-digestion of animal waste, crop and crop residues, municipal solid waste (MSW), as well as municipal sewage sludge.

KEYWORDS: Anaerobic; Co-digestion; Biomass; Methane; Animal Manure

INTRODUCTION

Biomass

Biomass has been defined as organic matter formed by photosynthetic capture of solar energy and stored as chemical energy (Gunaseelan, 1997), which includes agricultural crops and wastes, animal wastes, forest and mill residues, wood and wood wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes. Recently, oil crisis have brought great interest in the exploration of renewable energy, specially, bioenergy contained in biomass. The solar energy stored in biomass could be released as biogas, a mixture of methane (CH_4), carbon dioxide (CO_2), and some trace gases, through anaerobic digestion.

Anaerobic digestion

Anaerobic digestion (AD) is a process in which microorganisms break down biodegradable material in the absence of oxygen. Anaerobic digestion can be used to treat various organic wastes and recover bio-energy in the form of biogas, which contains mainly CH_4 and CO_2. Methane could be a source of renewable energy producing electricity in combined heat and power plants (Clemens et al., 2006). The organic loading rate (OLR) and hydraulic retention time are two major parameters used for sizing the digesters and their optimum values are specific to the substrate as well as the operating temperature of digesters (Romano and Zhang, 2007) Significant effort has been dedicated in recent years to find ways of improving the performance of digesters treating different biomass. One of options for improving yields of anaerobic digestion of organic matter is co-digestion.

Co-digestion

What is co-digestion?

Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. Traditionally, anaerobic digestion was a single substrate, single purpose treatment. Recently, it has been realized that AD as such became more stable when the variety of substrates applied at the same time is increased.

The most common situation is when a major amount of a main basic substrate (e.g. manure or sewage sludge) is mixed and digested together with minor amounts of a single, or a variety of additional substrate (Braun, 2002). The use of co-substrates usually improves the biogas yields from anaerobic digester due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates (Mata-Alvarez et al., 2000)

Advantages and Limitations of co-digestion

Several possible ecological, technological and economical advantages and limitations was shown in Table 1

Table 1 Merits and Limits of co-digestion technology (Braun, 2002)

Merits	Limits
• Improved nutrient balance and digestion	• Increased digester effluent COD
• Equalization of particulate, floating, settling, acidifying, etc. wastes, through dilution by manure or sewage sludge	• Additional pre-treatment requirements
• Additional biogas collection	• Increased mixing requirements
• Possible gate fees for waste treatment	• Wastewater treatment requirement
• Additional fertilizer (soil conditioner) reclamation	• High utilization degree required
• Renewable biomass (“Energy crops”) disposable for digestion in agriculture	• Decreasing availability and rates
	• Hygienisation requirements
	• Restrictions of land use for digestate
	• Economically critical dependent on crop costs and yield

Improved nutrient balance

Co-digestion can provide a better nutrient balance and therefore better digester performance and higher biogas yields. Desai et al. (1994) reported the combination of whey and poultry manure had been found to be capable of maintaining the proper C/N ratio in the reactor. According to Murto et al. (2004), highly buffered system was obtained by co-digestion of solid slaughterhouse waste, manure, and fruit and vegetable waste and the process worked well with gas yields of 0.8-$1 m^3 kg^{-1}$VS.

Optimization of rheological qualities

Waste with poor fluid dynamics, aggregating wastes, particulate materials, floating wastes or materials with high disturbing or inhibiting components can be utilized more effectively as co-substrates when co-digest with well performing sewage sludge or liquid manure (Braun, 2002).

Effective utilization of digester volumes in sewage plans

Adding co-substrate in existing digesters help to utilize the availability of free capacities. Additionally, the wide distribution of sewage treatment plants minimizes transportation costs. Economic advantages also derived from the fact of sharing equipment. Therefore, application of co-substrates can considerably improve the overall economics of the plant (Braun, 2002).

Energy crops as co-substrate

The addition of energy crops or silage as co-substrates allows for further increase in the biogas productivity of agricultural digesters (Braun, 2002). Animal manure usually contains high ammonia concentration that had an inhibitory effect on the glycolytic pathway. Co-digestion of plant material and manures, manures provide buffering capacity and a wide range of nutrients, while the addition of plant material with high carbon content balances the carbon to nitrogen (C/N) ratio of the feedstock, thereby decreasing the risk of ammonia inhibition (Lehtom¨aki et al., 2007).

Ghaly (1996) studied a two-stage, two-phase, unmixed anaerobic reactor of 155L to treat whey with dairy manure and concluded that pH should be controlled at the methanogenic phase; otherwise production of biogas was not possible. Somayaji and Khanna (1994) conducted a study with digesters fed with cow manure and varying proportions of wheat straw and conclude the highest specific methane yields were observed with 40% of wheat straw of total solids (TS) in the feedstock.

This term paper focuses on reviewing literature that evaluates anaerobic co-digestion technology published after 2005.

ANAEROBIC CO-DIGESTION TECHNOLOGY----REVIEW AND CASE STUDY

Anaerobic co-digestion animal manure, energy crops and crop residues

Anaerobic co-digestion of grass silage, sugar beet tops and oat straw with cow manure was evaluated by Lehtomaki et al. (2007) in semi-continuously fed laboratory continuously stirred tank reactors (CSTRs). It showed that it is feasible with up to 40% VS of crops in the feedstock. The highest specific methane yields of 268, 229 and 213 $lCH_4\,kg^{-1}$ VS added in co-digestion of cow manure with grass, sugar beet tops and straw, respectively, were obtained when feed with 30% of crop in the feedstock. Compared with that in reactors fed with manure alone at a similar loading rate, volumetric methane production increased by 65, 58 and 16% in reactors fed with 30% VS of sugar beet tops, grass and straw, respectively, along with manure. After doubling the OLR from 2 to 4 kg VSm−3 day−1 less methane was extracted per added VS, leading to a 16–26% decrease in specific methane yields, thus leaving more untapped methane potential is being left in the residues.

Gelegenis et al. (2007) examined a series of laboratory experiments in continuously stirred tank reactors at mesophilic conditions, fed semi-continuously with various mixtures of diluted poultry manure and whey. Co-digestion of whey with manure was proved to be possible up to 50% participation of whey (by volume) to the daily feed mixture without any need of chemical addition. However, specific biogas production (L/kg V) remained roughly unchanged at the various whey fractions added in the feed mixture. The authors suggested that it is only due to the lower chemical oxygen demand (COD) of whey compared to that of manure. As whey fractions above 50%, the reactor turned to be unstable, as shown by the considerable decrease in pH and biogas production. Then, they scaled the experiments up to a continuously stirred pilot tank reactor and found biogas production increased from 1.5 to 2.2L/LRd (almost 40%) for a hydraulic retention time of 18 days at 35 1C and organic loading rate. Higher biogas production is due to the higher biodegradability of carbohydrates (main constituent of whey) compared to lipids (main constituent of manure) and to the correction (increase) of C: N ratio.

The possible use of potato tuber and its industrial by-products (potato stillage and potato peels) on farm-scale co-digestion with pig manure was examined in a laboratory (Kaparaju and Rintala**,** 2004**).** The results showed that the potato tuber and its industrial by-products can be co-digested with pig manure at a loading rate of 2 kg VS m^{-3} day^{-1} in CSTR at 35 °C. The proportion of waste in the mixture appears to be important and feed VS may contain at least 15–20% of potato waste. The authors also point out that post-digestion of the digested materials indicated that the digested materials still contained some degradable material and would produce an appreciable amount of methane during post-storage. The study also revealed that under similar process conditions such as total feed VS, loading rate and feed VS ratio, the methane yields and process performance for potato tuber would be similar to those of its industrial by-products.

Anaerobic co-digestion animal manure and other organic waste

The potential of semi-continuous mesophilic anaerobic digestion (AD) for the treatment of solid slaughterhouse waste, fruit-vegetable wastes, and manure in a co-digestion process has been experimentally evaluated and presented by Alvarez et al. (2007). They found that a combined treatment of different Bolivian waste types like manure (cattle and swine), solid slaughterhouse wastes (rumen, paunch content, and blood from cattle and swine), and FVW in a mesophilic co-digestion process gives the possibility of treating waste, which cannot be successfully treated separately. They used a semi-continuous co-digestion process with these substrates can be expected to result in a reduction of the volatile solid contents of between 50% and 65% and give a methane yield of about 0.3 m^3 kg^{-1}VS added at OLRs up to 1.3 kg VS m^{-3} d^{-1}.

Anaerobic co-digestion organic waste (OW) and municipal sludge

Zupancic et al. (2007) conducted a full-scale experiment on co-digestion of OW of domestic refuse (swill) with municipal sludge is presented. Results have shown that anaerobic digestion is the solution to handling OW (swill) and above all it is very beneficial with little adverse impacts on the environment. They demonstrated that OW was virtually complete degraded and no increase in effluent VSS during the experiment as well as degradation efficiency increased from 71% to 81%. 80% increased biogas quantity was also observed. BPR increased from 0.32 to 0.67 m^3 m^{-3} d^{-1}. SBP increased from 0.39 to a peak of 0.89m3 kg VSS inserted.

Anaerobic co-digestion of sludge from grease traps and sewage sludge was successfully performed both in laboratory batch tests and in continuous pilot-scale digestion tests (Davidsson et al., 2007). Single-substrate digestion of grease trap sludge showed high methane potentials in batch tests (845–928 N ml/g VS_{in}), but could not reach stable methane production in the continuous digestion tests. Addition of grease trap sludge when digesting sewage sludge increases the methane potential and methane yield (amount of produced methane per added amount of VS). In the pilot-scale tests, the increase in methane yield was 9–27% for GS-amounts corresponding to 10–30% of the total VS added.

The feasibility of the anaerobic co-digestion of a mixed industrial sludge with municipal solid wastes (MSW) was investigated in three simulated anaerobic landfilling bioreactors during a 150-day period (Agdag et. al., 2007). They concluded that anaerobic co-digestion of industrial sludge with MSW is a feasible process in the stabilization of the waste and in the treatment of leachate releases from the simulated anaerobic reactors. The supplementation of industrial sludge to MSW in simulated anaerobic bioreactors is a viable alternative for recovering high energy in the form of biogas with 72% methane content while at the same time improving the leachate quality.

Gomez et al. (2006) presented the results obtained for the digestion of primary sludge (PS) and co-digestion of this sludge with the fruit and vegetable fraction of municipal solid wastes under mesophilic conditions. The co-digestion of the fruit and vegetable fraction of municipal solid wastes with primary sludge produced more biogas than did the digestion of primary sludge, due to the higher concentration of volatile solids contained in this feed. The parameters measuring the performance of the digestion process (specific gas production—SGP, and biogas yield) are more or less the same for the two kinds of feed evaluated. The application of a sudden increase in the organic load of the co-digestion systems led to higher gas production, accompanied by a downgrading of the performance of the digesters, even though the pH of the system was not affected.

The feasibility of the anaerobic co-digestion of five coffee wastes from the production of instant coffee substitutes and sewage sludge was assessed by Neves et al. (2006). Methane yields in the range of 0.24–0.28 m^3/kg VS were obtained with the exception of a barley-rich waste that achieved only 0.02 m^3 CH_4/kg VS. Four of the five wastes also presented a high reduction of TS (50–73%) and VS (75–80%), as well as 75–89% of the theoretical methane potential (350 l/kg COD removed). Hydrolysis constant rates in the range of 0.035–0.063 d^{-1} were obtained.

Fernandez et al. (2005) evaluated the potential of mesophilic anaerobic digestion for the treatment of fats of different origin through co-digestion with the organic fraction of municipal solid wastes. No important differences in the performance of the anaerobic co-digestion were observed when a fat from animal origin was suddenly changed by a fat of vegetable origin with a completely different long chain fatty acid (LCFA) profile. This may indicate that no important metabolic changes are implied in the degradation of different LCFAs with an acclimatized sludge. The authors concluded that the co-substrates may be variable in composition and, thus, in expected inhibition.

Fezzani et al. (2007) investigated for the first time the thermophilic (55 °C) anaerobic co-digestion of olive mill wastewater with olive mill solid wastes in laboratory scale semi-continuous tubular digesters. They concluded that olive mill wastewater could be degraded successfully in co-digestion with olive mill solid wastes under thermophilic conditions without previous dilution and without addition of chemical nitrogen substances. The best performance in methane productivity and SCOD removal efficiency were 46 l CH_4/ ((L olive mill wastewater fed) day) and 68.97%, respectively. Besides, the best net energy production from digesters operated at thermophilic temperature was 427 kJ/day higher than from those operated at mesophilic temperature for the same conditions of feed concentration and HRT. However, thermophilic anaerobic co-digestion of olive mill wastewater with olive mill solid wastes is not entirely successful in reaching the treatment efficiencies required by the national regulations of all the Mediterranean area countries and the COD removal efficiency was lower than that obtained using mesophilic conditions.

Case study

The co-digestion of onion juice and aerobic wastewater sludge produced from an onion processor using an anaerobic mixed biofilm reactor (AMBR) was investigated by Romano et al. (2007) for biogas energy production potential and waste treatment.

The onion juice was prepared by first treating the onion solids with lime and then extracting the juice from the solids using a screw press. The aerobic sludge was obtained from a clarifier, which was used to settle the effluent from an aerobic treatment process.

The AMBR used in this study consisted of a sludge blanket at the bottom, and floating bio-media pellets at the top (Fig 1.)

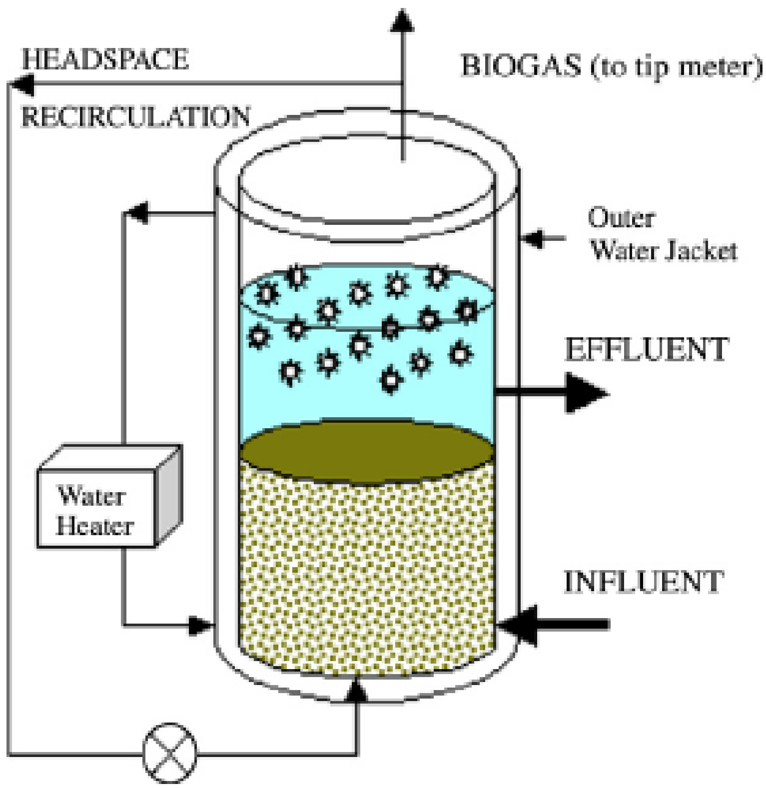

Fig. 1. Laboratory anaerobic digester. Biomedia pellets are indicated by ☼ objects in the upper portion of the digester.

Two experiments were conducted to study the performance of an AMBR at different organic loading rates (OLRs) using different mixtures of onion juice and aerobic sludge. In experiment 1, the amount (VS) of aerobic sludge in the feed mixture was kept constant. In experiment 2, C/N was kept constant.

In the first experiment, the OLR was increased from 1.24 to 4.37 g VS/L/d by increasing the amount of onion juice in the feed mixture while maintaining a constant amount of aerobic sludge. When the OLR reached 4.37 g VS/L/d, the AMBR failed as indicated by decreased biogas production and pH. The characteristics of the digester feed mixture, biogas and methane yields, and solids reduction is shown in Table 2 and Fig. 2. The authors suggested increasing of carbon to nitrogen ratio (C/N) from 13.7 to 20.3 and lacking of proper alkalinity were suspected to be the causes for the failure.

In the second experiment, the C/N of the feed mixture was maintained at about 15 while the OLR was increased from 1.40 to 3.60 g VS/L/d. The digester showed stable performance. The average biogas and methane yields of the two experiments were 0.62 ± 0.05 L/g VS and 0.37 ± 0.08 L/g VS, respectively. The fractions of onion juice and aerobic sludge used for each OLR tested are summarized in Table 3 and The biogas and methane yields, and solids reduction for each loading rate are shown in Fig.3.

Table 2
VS loading and C/N of onion juice and aerobic sludge, and their mixture (digester feed) used in experiment #1

OLR (gVS/L/d)	Aerobic sludge VS loading (%)	Onion juice VS loading (%)	Aerobic sludge C/N	Onion juice C/N	Digester feed C/N
1.24	27	73	5.8	26.7	13.7
2.23	16	84	5.8	26.7	16.9
3.08	14	86	5.8	26.7	17.7
4.37	9	91	5.8	26.7	20.3

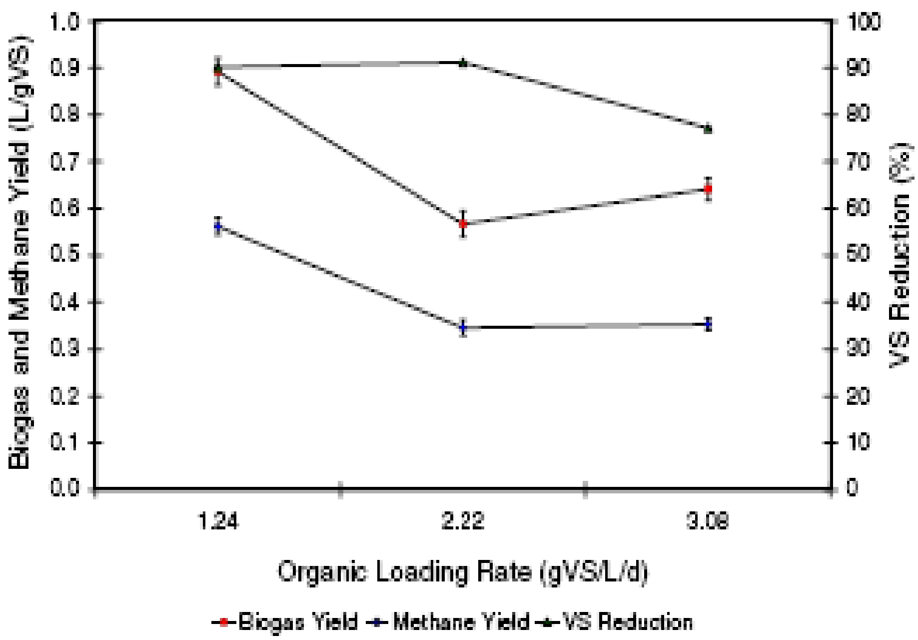

Fig. 2. Average biogas yield, methane yield, and VS reduction for experiment #1.

Based on the result of this study, the authors recommended maintaining the C/N of the feed mixture at about 15.

Table 3

VS loading and C/N of onion juice, aerobic sludge, and their mixture (digester feed) used in experiment #2

OLR (gVS/L/d)	Aerobic sludge VS loading (%)	Onion juice VS loading (%)	Aerobic sludge C/N	Onion juice C/N	Digester feed C/N
1.39	26	74	4.7	17.4	12.4
2.73	11	89	4.8	16.7	14.8
3.60	19	81	7.2	19.8	14.9

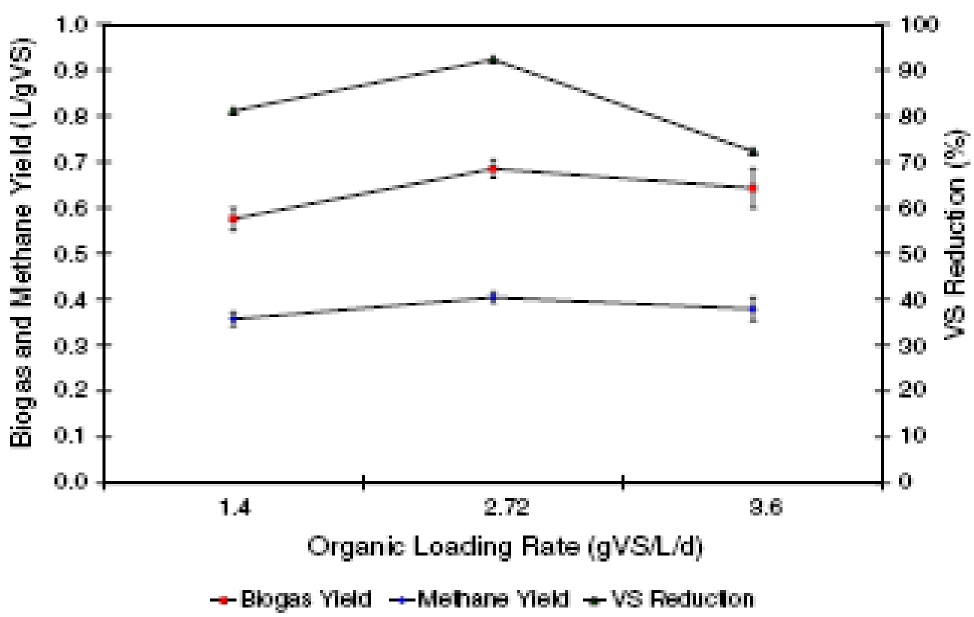

Fig. 3. Average biogas yield, methane yield, and VS reduction for experiment #2.

CONCLUSION

Co-digestion is the simultaneous digestion of a homogenous mixture of multiple substrates. The most common situation is when a major amount of main basic substrates is mixed and digested together with minor amounts of a single, or a variety of additional substrates. Recent research demonstrates that using co-substrates in anaerobic digestion systems improves biogas yields through positives synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates.

REFERENCE

Agdag, O. N. and Delia Teresa Sponza. 2007. Co-digestion of mixed industrial sludge with municipal solid wastes in anaerobic simulated landfilling bioreactors, *Journal of Hazardous Materials Volume* **140**: 75-85.

Alvarez,R. and G. Liden. 2007. Semi-continuous co-digestion of solid slaughterhouse waste, manure, and fruit and vegetable waste. *Renewable Energy (In Press)*. Available online 15 June 2007.

Braun. R. 2002. Potential of Co-digestion. http://www.novaenergie.ch/iea-bioenergy-task37/Dokumente/final.PDF. Access on Nov. 7th, 2007.

Clemens, J.; M. Trimborn; P. Weiland; and B. Amon. (2006). Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agriculture, Ecosystems and Environment* **112**: 171-177.

Davidsson. A. , C. Lovstedt, J. la Cour Jansen, C. Gruvberger and H. Aspegren, Co-digestion of grease trap sludge and sewage sludge, *Waste Management (In Press)*. Available online 22 May 2007.

Desai M, Patel V, Madamwar D. 1994.Effect of temperature and retention time on biomethanation of cheese whey–poultry waste–cattle dung. *Environ Pollut.* **83**:311-315

Fernandez, A.; Antoni Sanchez and Xavier Font, 2005. Anaerobic co-digestion of a simulated organic fraction of municipal solid wastes and fats of animal and vegetable origin, *Biochemical Engineering.* **26**: 22-28.

Fezzani, B. and R. B. Cheikh. 2007. Thermophilic anaerobic co-digestion of olive mill wastewater with olive mill solid wastes in a tubular digester, *Chemical Engineering Journal* **132** (1-3):195-203.

Mata-Alvarez, J.; S. Mace; P. Llabres. 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology* **74**: 3-16.

Gelegenis, J.; D. Georgakakis; I. Angelidaki; and V. Mavris. 2007. Optimization of biogas production by co-digesting whey with diluted poultry manure. *Renewable Energy* **32**:2147-2160

Ghaly A. 1996. A comparative study of anaerobic digestion of acid cheese whey and dairy manure in a two-stage reactor. *Bioresource Technol*. **58**: 61–72.

Gomez,G. M.J. Cuetos, J. Cara, A. Moran and A.I. Garcia, 2006. Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes: Conditions for mixing and evaluation of the organic loading rate, *Renewable Energy*. **31**:2017-2024.

Gunaseelan V. N. 1997. Anaerobic digestion of biomass for methane production: a review. *Biomass and Bioenergy* **13**:83-114.

Kaparaju,P. and Jukka Rintala, 2005. Anaerobic co-digestion of potato tuber and its industrial by-products with pig manure, *Resources, Conservation and Recycling.* **43**: 175-188.

Lehtom¨aki, A.; S. Huttunen, J.A. Rintala. 2007. Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources, Conservation and Recycling.* **51**: 591–609

Murto M, Bjo¨ rnsson L, Mattiasson B. 2004. Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure. *J Environ Manage* **70**:101–7.

Neves,L.; R. Oliveira and M.M. Alves, 2006. Anaerobic co-digestion of coffee waste and sewage sludge, *Waste Management*. **26**: 176-181.

Rowena T. Romano and Ruihong Zhang, 2007. Co-digestion of onion juice and wastewater sludge using an anaerobic mixed biofilm reactor, *Bioresource Technology (In Press)*. Available online 1 June 2007.

Zupancic, G. D.; N. Uranjek-Zevart and M. Ros, 2007. Full-scale anaerobic co-digestion of organic waste and municipal sludge, *Biomass and Bioenergy (Article in Press)*. Available online 20 August 2007.