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Recent Trends in Anaerobic Codigestion: A Review

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Abstract:
Anaerobic digestion is the most promising alternative to disposal this kind of waste, due to high energy recovery. The main objective of anaerobic digestion is the degradation and destruction of organic substances, with consequent reduction of the odorous emissions and pathogens. This conversion is catalyzed by a large of bacteria that operate in synergy, catalyzing different chemical reactions, hence the metabolic pathways involved in the anaerobic degradation are quite complex. Anaerobic digestion process follows four major steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis is the rate-limiting step of the overall process degradation. In anaerobic digestion, co-digestion is the term used to describe the combined treatment of several wastes with complementary characteristics, being one of the main advantages of the anaerobic technology. Anaerobic digestion (AD) is a process by which microorganisms break down biodegradable material in the absence of oxygen. A great option for improving yields of anaerobic digestion of solid wastes is the co-digestion of multiple substrates. If co-substrates are used in anaerobic digestion system it improves the biogas yields due to positives synergisms established in the digestion medium and the supply of missing nutrients. Recent research on this topic is reviewed in the current paper. Special attention is paid to anaerobic co-digestion of animal waste, crop and crop residues, industrial sludge, municipal solid waste (MSW), as well as municipal sewage sludge.

Keywords: Anaerobic digestion; Co-digestion; Biodegradable; Synergisms; Co-substrate

1.0 Introduction:
Anaerobic digestion involves a very complex set of biochemical and physicochemical reactions. A solid understanding of the underlying science is an important prerequisite for the successful operation of anaerobic digestion. The latter is two-fold: it consists of avoiding digestion failure and also improving performance in terms of greater stability, higher yields and/or destruction of organic matter.

1. 1 Anaerobic Digestion Process:
Anaerobic digestion is the multi-step biological process during which organic material is converted to biogas and digestate in the absence of oxygen. Anaerobic biodegradation of organic material proceeds in the absence of oxygen and the presence of anaerobic microorganisms. Anaerobic digestion is the consequence of a series of metabolic interactions among various groups of microorganisms. It occurs in four stages, hydrolysis/liquefaction, acidogenesis, acetogenesis and methanogenesis. These stages are described in detail below. Figure 1.1 shows the anaerobic pathways in anaerobic degradation.

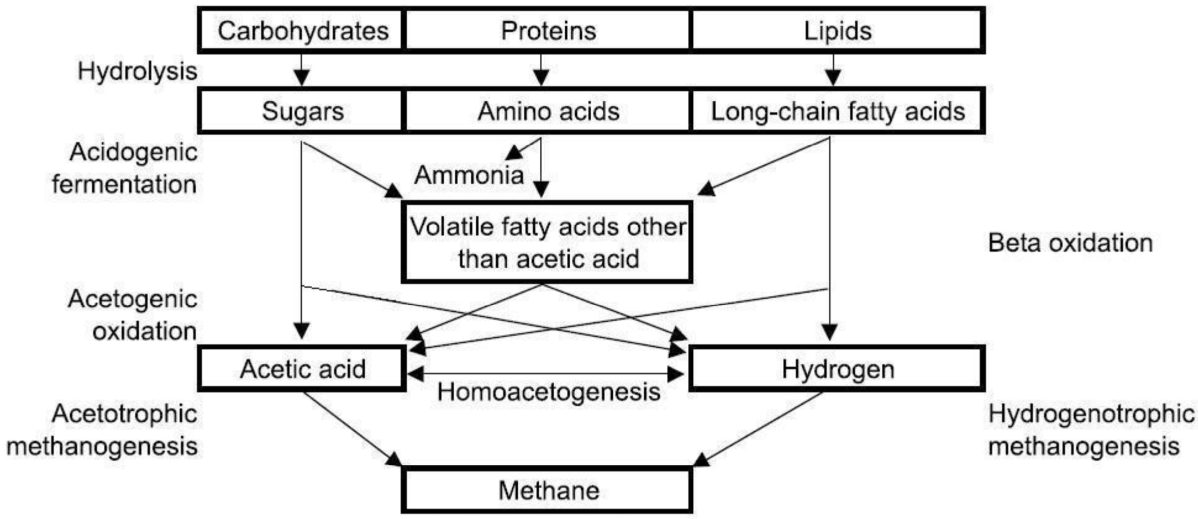

Figure 1.1: Anaerobic pathways in anaerobic degradation (Salminen et al., 2002)

1.1.1 Hydrolysis/liquefaction:

This step is very important for the anaerobic digestion process since polymers cannot be directly utilized by the fermentative microorganisms. Hydrolysis therefore renders the substrate accessible for the subsequent conversion steps. In this step insoluble complex organic matter is broken down into their backbone constituents in order to allow their transport through microbial cell membrane (Madigan et al., 2008). Hydrolysis is achieved through the action of hydrolytic enzymes. In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. Proteases, secreted by proteolytic microbes, convert proteins into amino acids; celluloses and/or xylanases, produced by cellulytic and xylanolytic microbes, hydrolyze cellulose and xylose (both complex carbohydrates) into glucose and xylem (both sugars), respectively; finally lipases, created by lipolytic microbes, convert lipids (fats and oils) into long-chain fatty acids and glycerol (Salminen et al., 2002). The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. The application of chemicals to enhance the first step has been found to result in a shorter digestion time and provide a higher methane yield.

Hydrolysis/Liquefaction reactions (1)

Lipids	→	Fatty Acids
Polysaccharides	→	Monosaccharides
Protein	→	Amino Acids
Nucleic Acids	→	Purines & Pyrimidines

1.1.2 Acidogenesis (fermentation):

Fermentation involves the conversion of the sugars, amino acids and fatty acids to hydrogen, acetate, carbon dioxide, VFAs such as propionic, butyric and acetic acid, ketones, alcohols and lactic acid by facultative and anaerobic bacteria. Even though a simple substrate such as glucose can be fermented, different products are produced by the diverse bacterial community. Equations: 2, 3 and 4 show the conversion of glucose to acetate, ethanol and propionate, respectively.

$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$ (2)

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ (3)

$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$ (4)

In an equilibrated system, most of the organic matter is converted into readily available substrates for methanogenic microbes (acetate, hydrogen and carbon dioxide), but a significant part (approximately 30%) is transformed to short chain fatty acids or alcohols (Angelidaki et al., 2007). Degradable organic matter is removed in this stage (Angelidaki et al., 2007). By-product of amino acids fermentation, ammonia and hydrogen sulphide are released (Salminen et al., 2002) that can be inhibitory for anaerobic digestion.

1.1.3 Acetogenesis:

Acetogenesis is the conversion of certain fermentation products such as VFAs with more than two carbon atoms , alcohols and aromatic fatty acids into acetate and hydrogen by obligate hydrogen producing bacteria (Boe, 2006). In this stage, acetogenic bacteria, also known as acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acid (CH3COOH), propionic acid (CH3CH2COOH), butyric acid (CH3CH2CH2COOH), and ethanol (C2H5OH). The products formed during acetogenesis are due to a number of different microbes, e.g., syntrophobacter wolinii, a propionate decomposer and sytrophomonos wolfei, a butyrate decomposer. Other acid formers are clostridium spp., peptococcus anerobus, lactobacillus, and actinomyces (www.biogasworks.com- Microbes in AD). While hydrogen-producing acetogenic bacteria produce acetate, H_2 and CO_2 from volatile fatty acids and alcohol, homoacetogenic bacteria create acetate from CO_2 and H_2 (Sterling et al., 2001). But most of the acetate is created by hydrogen-producing acetogenic bacteria (Angelidaki et al., 2007).
An acetogenesis reaction is shown below:
$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

1.1.4 Methanogenesis:

A variety of methane-forming bacteria is required in the anaerobic digestion system, since no single species can degrade all the available substrates. The methanogenic bacteria include methanobacterium, methanobacillus, methanococcus and methanosarcina. Methanogenesis can also be divided into two groups: acetate and H2/CO2 consumers. Methanosarcina spp. and methanothrix spp. (also, methanosaeta) are considered to be important in AD both as acetate and H2/CO2 consumers. Approximately 70% of the methane is produced from acetate (Smith et al., 1966), while the remaining 30% is produced from the reduction of carbon dioxide by hydrogen and other electron donors (Hashimoto et al., 1981). According to the type of substrate utilized by the methanogens, methanogenesis is divided into two main types (Bitton, 2005):

1. Hydrogenotrophic methanogenesis. Hydrogen and carbon dioxide are converted into methane according to the following reaction:
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

2. Acetotrophic or aceticlastic methanogenesis. Methane is formed from the conversion of acetate through the following reaction:
$CH_3COOH \rightarrow CH_4 + CO_2$

1.2 Important Operating Parameters in AD Process:

The rate at which the microorganisms grow is of paramount importance in the AD process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Some of these parameters are discussed in the following section.

1.2.1 Waste composition/Volatile Solids (VS):

The wastes treated by AD may comprise a biodegradable organic fraction, a combustible and an inert fraction. The biodegradable organic fraction includes kitchen waste, food waste, and garden waste. The combustible fraction includes slowly degrading lignocellulosic organic matter containing coarser wood, paper, and cardboard. As these lignocellulosic organic materials do not readily degrade under anaerobic conditions, they are better suited for waste-to-energy plants. Finally, the inert fraction contains stones, glass, sand, metal, etc. This fraction ideally should be removed, recycled or used as land fill. The removal of inert fraction prior to digestion is important as otherwise it increases digester volume and wear of equipment. The Volatile Solids (VS) in organic wastes are measured as total solids minus the ash content, as obtained by complete combustion of the feed wastes. The volatile solids comprise the Biodegradable Volatile Solids (BVS) fraction and the Refractory Volatile Solids (RVS).It is seen that knowledge of the BVS fraction of substrate helps in better estimation of the biodegradability of waste, of biogas generation, organic loading rate and C/N ratio. Lignin is a complex organic material that is not easily degraded by anaerobic bacteria and constitutes the refractory volatile solids (RVS) in organic matter. Waste characterized by high VS and low non-biodegradable matter, or RVS, is best suited to AD treatment.

1.2.2 Alkalinity:

Acid-neutralizing or buffering capacity of a digester is termed as Alkalinity. It is attained with the help of number of substances and it mostly described by the carbonate, bicarbonate and hydroxide content of the digester (Chynoweth, 1987). At the neutral pH at which anaerobic digesters operate, the carbon dioxide-bicarbonate system is primarily responsible for controlling alkalinity, and therefore bicarbonate alkalinity is of the greatest importance (Altamira, 2008). Bicarbonate is also the main source of carbon for methane-forming bacteria.

Alkalinity is crucial in pH control and enhances digester stability. Alkalinity is mainly present in the form of bicarbonates in equilibrium with carbon dioxide gas at a given pH (Gerardi, 2003). Alkalinity in anaerobic digestion is also derived from the degradation of organic nitrogen containing compounds. Such compounds are amino acids and proteins. During their degradation, amino groups are released which will further lead to the production of ammonia. Ammonia will further react with CO_2, yielding alkalinity in the form of ammonium bicarbonate. According to Speece et al. (1996) and Altamira et al. (2008) additional alkalinity can be generated from the metabolism of the microorganisms in the anaerobic digester. This type of alkalinity consists of the release of cations during the degradation of organic compounds.

1.2.3 pH Level:

The pH requirements of the groups of microorganisms participating in anaerobic digesters differ. While acidogenic bacteria can perform well when the pH is above 5, methanogenic bacteria require a minimum pH value of 6.2. Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions. It has been determined that an optimum pH value for AD lies between 5.5 and 8.5. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and in a batch reactor acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. After gas production, pH is the best indicator of future digester instability (Poliafico, 2007). Initially, pH will decrease as organic matter undergoes acetogenesis, but methanogens rapidly consume those acids increasing pH and stabilizing digester performance. Due to their sensitivity to acid conditions, excessive generation of acid can inhibit methanogens. Reduction in pH can be controlled by the addition of lime or recycled filtrate obtained during residue treatment.

1.2.5 Sulphate:

In anaerobic digestion system, sulphate is reduced biologically under anaerobic conditions to sulfide, which may upset the biological process if the sulphide concentration exceeds 200 mg/l (Metcalf and Eddy, 2003). Some inhibitory compounds may equally affect all major microbial groups in the digester (e.g. LCFA and phthalate esters) while others may specifically impair some microbial species (Ahring, 2003).

1.2.6 Ammonia:

In anaerobic digestion ammonia originates from soluble ammonia in the influent, from protein degradation and other compounds such as urea. There are two forms of ammonia which depends upon the pH of the system: ammonium ion (NH_4^+ and dissolved non-ionized form of ammonia (NH_3). It is generally accepted that it is the non-ionized form of ammonia that is responsible for inhibition. pH has a significant effect on the level of ammonia inhibition, as the pH value determine the degree of ionization.

2.2.7 Temperature:

Temperature is a principal environmental factor affecting performance. It affects the physical and physico-chemical properties of compounds present in the digester and the kinetics and thermodynamics of biological processes (Boe, 2006). There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges.

1) Mesophilic digestion takes place optimally around 30 to 38°C, or at ambient temperatures between 20 and 45°C, where mesophilic are the primary microorganism present.
2) Thermophilic digestion takes place optimally around 49 to 57°C, or at elevated temperatures up to 70°C, where thermophilic are the primary microorganisms present.

1.2.8 Carbon to Nitrogen Ratio (C/N):

The relationship between the amount of carbon and nitrogen present in feedstock is represented by the C/N ratio. It is a very important process parameter of the process as a low ratio can cause ammonia inhibition whereas a high ratio will lead deficiency (Mata-Alvarez, 2000). The adjustment of the ratio to be within the optimum range (25-30) can be achieved through the co-digestion of different waste streams (Monnet, 2003). Optimum C/N ratios in anaerobic digesters are between 20 & 30. A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with animal manure or sewage.

1.2.9 Nutrients:

Methane forming bacteria have particular growth requirements. It has been demonstrated that specific metals such as nickel, cobalt, molybdenum and iron are necessary for optimal growth and methane production (Speece et al., 1987). Trace metals play an important role to stimulate methanogenic activity. Selenium, molybdenum, manganese, aluminum, and boron have been recommended as additional components in media (Azbar et al. 2000). The recommended requirements for iron, cobalt, nickel, and zinc are 0.002, 0.004, 0.003 and 0.02mg/g acetate produced respectively. It is noted that a requirement for nickel is quite unusual for biological systems, and this requirement uniquely characterizes methanogenic bacteria. Supplementation of anaerobic digesters with solutions of metal ions can improve the performance of the system.

1.2.10 Total solids content (TS)/Organic Loading Rate (OLR):

Low solids (LS) AD systems contain less than 10 % TS, medium solids (MS) about 15-20% and high solids (HS) processes range from 22% to 40%. An increase in TS in the reactor results in a corresponding decrease in reactor volume. The organic loading rate (OLR) is the organic matter flowing into the digester per time, expressed as mass of organic matter over digester volume over time. Typical values of OLR ranges between 0.5 and 3 kg $VS/m^3/d$ (Poliafico, 2007).Organic loading rate (OLR) is also defined as measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry. In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading.

1.2.11 Feedstock:

Feedstock is defined to include any substrate that can be converted to methane by anaerobic bacteria. Carbon, oxygen, nitrogen, hydrogen and phosphorus are the main components in organic wastes (feedstock**)**, and microbial cell material is approximately 50, 20, 12, 8 and 2 % of those elements, respectively (Gerardi, 2003). Also sulphur is required to synthesize vital proteins in metabolic and anabolic pathways (Madigan et al., 2008). Feedstocks can range from readily degradable wastewater to complex high-solid waste. A feedstock C/N ratio of 25:1 produces optimal gas production (Gerardi, 2003). If the C/N ratio is low too much nitrogen is present leading to ammonia (NH3) accumulation that causes either high pH values or methanogenic inhibition (Salminen et al., 2002). If the C/N ratio is high nitrogen is rapidly depleted and results lower gas production (Poliafico, 2007).

1.2.12 Retention (or residence) Time:

HRT stands for hydraulic retention time while SRT stands for solid retention time. HRT is the time that the fluid element of the feed remains in the digester. SRT is the time that refers to the residence time of the bacteria (solids) in the reactor. The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilic range. A high solids reactor operating in the thermophilic range has a retention time of 14 days.Anaerobic digestion retention times range from 14 and 30 days. Given the relatively long generation time of methanogens, SRT should be over 12 days in order to avoid microbial washout (Gerardi, 2003). A short retention time will produce higher biogas per volume, but less organic matter will be degraded. Although a short retention time is desired for reducing the digester volume, a balance must be made to achieve the desired operational conditions.

1.2.13 Mixing:

The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. Also mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester.

The benefits of mixing include:
1) Eliminates or reduces scum buildup.
2) Eliminates thermal stratification or localized pockets of depressed temperature.
3) Maintains digester sludge's chemical and physical uniformity throughout the tank.
4) Stimulates the rapid dispersion of metabolic wastes produced during substrate digestion that could otherwise inhibit methane production.
5) Stimulates the rapid dispersion of any toxic material entering the tank (minimizing toxicity).
6) Mixing also prevents deposition of grit.

1.2.14 Compost:
When the digestion is complete, the residue slurry, also known as digestate, is removed, the water content is filtered out and re-circulated to the digester, and the filter cake is cured aerobically, usually in compost piles, to form compost. The compost product is screened for any undesirable materials, (such as glass shards, plastic pieces etc) and sold as soil amendment.
The quality of compost is dependent on the waste composition. Some countries have prescribed standards for compost quality. The U.S. Department of Agriculture has set standards for heavy metals in the compost. These standards are for compost treated by the aerobic process but may also be applied to AD compost product.

1.3 Bye-Products:
The three principal products of anaerobic digestion are biogas, digestate, and wastewater.

1.3.1 Biogas:
Biogas is the ultimate product of the anaerobic digestion and is mostly methane and carbon dioxide also with a small amount of hydrogen and trace hydrogen sulfide. Most of the biogas is produced during the middle of the digestion, after the bacterial population has grown, and tapers off as the putrescible material is exhausted. The gas is normally stored on top of the digester in an inflatable gas bubble or extracted and stored next to the facility in a gas holder.

1.3.2 Wastewater:
The final output from anaerobic digestion systems is water and this water may be released from the dewatering of the digestate or may be implicitly separated from the digestate. The wastewater exiting the anaerobic digestion facility will typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). These measures of the reactivity of the effluent indicate it's an ability to pollute.

1.3.3 Digestate:
Digestate is the solid remnants of the original input material to the digesters that the microbes cannot use. It also consists of the mineralized remains of the dead bacteria from within the digesters. Digestate can come in three forms: fibrous, liquor, or a sludge-based combination of the two fractions. In two-stage systems, different forms of digestate come from different digestion tanks. In single-stage digestion systems, the two fractions will be combined and, if desired, separated by further processing

1.4 Advantages and Disadvantages of Anaerobic Digesters:
1.4.1 Advantages
1) Generation of biogas and
2) Reduction of greenhouse gas emissions through methane recovery
3) Combined treatment of different organic waste and wastewaters
4) Reduction of solids to be handled
5) Good pathogen removal depending on temperature
6) Process stability

1.4.2 Disadvantages
1) Small- and middle-scale anaerobic technology for the treatment of solid waste in middle- and low-income countries is still relatively new
2) Experts are required for the design and construction, depending on scale may also for operation and maintenance
3) Reuse of produced energy (e.g. transformation into, fire/light, heat and power) needs to be established
4) High sensitivity of methanogenic bacteria to a large number of chemical compounds
5) Sulphurous compounds can lead to odour.

1.5 Anaerobic Co-digestion:
Co-digestion is the simultaneous digestion of two or more organic waste feedstock. The anaerobic co-digestion processcan be defined as the simultaneous treatment of two – or more – organic biodegradable

waste streams by anaerobic digestion offers great potential for the proper disposal of the organic fraction of solid waste coming from source or separate collection systems. This type of treatment offers the possibility of using existing anaerobic reactors in wastewater treatment plants, with minor modifications and some additional requirements. By bringing together the treatments of two problematic wastes i.e. organic part of municipal solid waste and paper pulp sludge higher yield in the production of biogas can be achieved. 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. 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 (Alvarez et al., 2008)

1.5.1 Advantages and disadvantages of anaerobic Co-digestion:

1.5.1.1 *Advantages:*

1) Improved nutrient balance and digestion.
2) Additional biogas collection.
3) Possible gate fees for waste treatment.
4) Additional fertilizer i.e soil conditioner
5) Renewable biomass disposable for digestion in agriculture.

1.5.1.2 Disadvantages:

1) Increased digester effluent COD.
2) Additional pre-treatment requirements.
3) Increased mixing requirements.
4) Wastewater treatment requirement
5) Hygienization requirements.
6) Restrictions of land use for digestate.
7) Economically critical dependent on crop.

1.6 Anaerobic Co-Digestion Technology

1.6.1 Food waste as an effective feedstock for anaerobic digestion

Zhang *et al.*(2009), evaluated anaerobic digestibility and biogas and methane yields of the food waste. This test was performed at 50^0c using batch anaerobic digestion mode. The daily average moisture content (MC) and the ratio of volatile solids to total solids (VS/TS) after week sampling determined were 70% and 83%, respectively. While the weekly average MC and VS/TS were 74% and 87%, respectively. The food waste contained well balanced nutrients for anaerobic microorganisms as per nutrient content analysis. The methane yield after 10days of digestion was 348 mL/g VS and 435 mL/g VS after 28 days of digestion. The average methane content of biogas was 73%. The average VS destruction at the end of the 28-day digestion test was 81%.

The results of this study indicate that the food waste is a highly desirable substrate for anaerobic digesters with regards to its high biodegradability and methane yield.

1.6.2 Dry-thermophilic anaerobic digestion of organic fraction of the municipal solid waste: focusing on the inoculum sources

Forster *et al.*(2007) have evaluated the effect of inoculum source on anaerobic thermophilic digestion. For this he has carried out experiment using six different inoculums sources: corn silage ; restaurant waste digested mixed with rice hulls ; cattle excrement ; swine excrement ; digested sludge and swine excrement mixed with digested sludge (1:1). The esperiment were dcarried out at 55 °C and the other conitions were 25% of inoculum, 30% of total solid. The initial startup phase for the six inoculum sources was in the range between 2 and 4 days and the initial methane generation began after 10 days of operation. Results indicated that digested sludge is the best inoculum source for anaerobic thermophilic digestion of the treatment of organic fraction of municipal solid waste at dry conditions (30% TS). after 60 days of operation period, it was observed that digested sludge reactor can achieve COD removal efficiencyof 44.0% and VS removalefficiency of 43.0%. In stabilization phase, digested sludge reactor showed higher volumetric biogas generated of 78.9 mL/day reaching a methane yield of 0.53 L CH_4/g VS. At these experimental conditions even swine excrement and swine excrement mixed with digested sludge (1:1) were good inoculums.

1.6.3 Anaerobic Co-digestion of kitchen waste and sewage sludge

Sharom *et al.*(2004) to make comparative study of the biogas generation capacity of the mixture of organic fractions of municipal solid waste from kitchen waste and sewage sludge in different composition conducted experiments on anaerobic digesters. The batch digestion of samples was carried out under controlled temperature 35°C and pH 7. Samples were of various percentages of kitchen waste and sewage sludge .

Table 1: Loading Details of the Digesters

Details	R_1	R_2	R_3	R_4	R_5
% of kitchen waste added	100%	75%	50%	25%	----
% of activated sludge added	----	25%	50%	75%	100%

The cumulative biogas production increased when the mixture kitchen waste and activated sludge was used. The highest value of methane production was for sample 2 (75% kitchen waste and 25% activated sludge), which produced 59.7 ml. The best result for the rate of biogas production was for sample 2, after that samples 1, 4, and 3 were settled respectively. The the least biogas was produced in the 5^{th} sample.
Anaerobic Co-digestion of industrial sludge and organic fraction of municipal solid wastes (OFMSW)
Delia *et al*.(2007), conducted experiment on anaerobic co-digestion of industrial sludge and organic fraction of municipal solid wastes. Reactors were operated with leachate recirculation. After 98 days of anaerobic incubation, it was observed that the pH, COD, VFA concentrations in the leachate samples of the industrial sludge-added reactors (especially run 2) was better than in the control reactor. Thus this proves that co-digestion is better than mono digestion.

Table 2: Reactor Details

Details	control reactor	run1 dry solid basis	run 2 dry solid basis
OFMSW	Only OFMSW	1	1
industrial sludge	----	1	2
leachate recirculation rate	300 ml/day	300 ml/day	300 ml/day

1.6.4 Anaerobic Co-digestion of activated sludge and organic fraction of municipal solid wastes:
Battistoni *et al.*(2010), summarizes the performances obtained in full scale anaerobic digesters co-digesting waste activated sludge and organic fraction of municipal solid wastes. Results of experiments showed that anaerobic digestion of activateed sludgeor muncipal solid alone were bettre than codigestion of the two waste. The experiment showed that when waste activated sludge was co-digested with the organic fraction of municipal solid wastes with a ratio of 60:40 (sludge:OFMSW) on a TVS basis allowed for an increase of the organic loading rate up to1 kgVS perm^3 per day. Also biogas production when only waste activated sludge was digested was 0.13m^3 kg VS^{-1} which increased up to 0.43m^3 kg VS^{-1} in the case of co-digestion.

1.6.5 Effect of Waste Paper on Biogas Production from co-digestion of cow dung and water hyacinth
Yusuf *et al.*(2008), carried out the co-digestion of Cow Dung and Water Hyacinth. This experiment was carried oput in five batch reactor for a period over 60 days with varied proportion of paper waste. Waste paper addition was varied keeeping the amount of cow dung and water hyacinth fixed until maximum biogas production was achieved. The biogas produced during the process was measured by water displacement method.. Maximum biogas volume of 1.11liters was observed at a waste paper amount of 17.5g which corresponded to 10.0% total solids of the biomass in 250ml solution. Thus for maximum biogas production maximum 17.5g of waste paper can be combined with 5g of cow dung and 5g of water hyacinth in 250ml of water.

1.6.6 Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure.
Samani *et al.(*2008), carried out the experiment of anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) and dairy cow manure (CM) alone and compared the results with the co-digestion of the same. The results were when OFMSW was digested alone produced 62m^3 methane/ton and CM produced 37m^3 methane/ton of dry waste . Co-digestion of OFMSW and CM produced 172m^3 methane/ton of dry waste. Comparing the single waste digestions with co-digestion of combined wastes, it was shown that co-digestion resulted in higher methane gas yields.

1.6.7 Anaerobic co-digestion of dairy manure and food waste.
El-Mashad *et al.*(2004), evaluated the biogas production potential of different mixtures of unscreened dairy manure and food waste. These

results were compared with the yield from manure or food waste alone. Also the effect of manure-screening on the biogas yield of dairy manure was evaluated. The methane yields after 30days of fine fractions of screened manure , coarse fractions of screened manure and unscreened manure were 302 L/kgVS, 228 L/kgVS and 241 L/kgVS, respectively. Approximately 93%, 87%, and 90% of the biogas yields was obtained, respectively after 20days of digestion. Average methane content of the biogas of fine fractions of screened manure, coarse fractions of screened manure and unscreened manure was 69%, 57%, and 66% respectively. The methane yield of the food waste was 353 L/kgVS after 30days of digestion. Two mixtures: 1) unscreened manure (68%) and food waste (32%) and 2) unscreened manure(52%) and food waste(48%) produced methane yields of 282 and 311L/kgVS, respectively after 30days of digestion. After 20days, approximately 90% and 95% of the final biogas was obtained. The average methane content was 62% and 59% for the first and second mixtures, respectively. The predicted results from the model showed that adding the food waste into a manure digester at levels up to 60% of the initial volatile solids significantly increased the methane yield for 20days of digestion.

1.6.8 Anaerobic digestion of municipal solid waste and co-digestion with manure.

Hartmann *et al* (2005), investigated anaerobic digestion of the organic fraction of municipal solid waste (OFMSW). This was carried out in two thermophilic (55 ^{0} C) wet digestion treatment systems R_1 and R_2. Initially OFMSW was co-digested with manure with a successively higher concentration of OFMSW, at a hydraulic retention time (HRT) of 14-18 d and an organic loading rate (OLR) of 3.3-4.0 g-VS/l/d. Over a period of 6 weeks adaptation of the co-digestion process was established to a OFMSW:manure ratio of 50% (VS/VS). This co-digestion ratio was maintained in reactor R_2 while the ratio of OFMSW to manure was slowly increased to 100% in reactor R_1 over a period of 8 weeks. Use of recirculated process liquid to adjust the organic loading to R_1 was found to have a beneficial stabilization effect. The pH raised to a value of 8 and the reactor showed stable performance with high biogas yield and low VFA levels. The biogas yield from source-sorted OFMSW was 0.63-0.71 l/g-VS both in the co-digestion configuration and in the treatment of 100% OFMSW with process liquid recirculation. This yield is corresponding to 180-220 m^3 biogas per ton OFMSW. VS reduction of 69-74% was achieved when treating 100% OFMSW. None of the processes showed signs of inhibition at the free ammonia concentration of 0.45-0.62 g-N/l.

1.7 Conclusions:

1) Co-digesting improves nutrient balance and enhances pH buffer capacity.
2) Comparing the single waste digestions with co-digestion of combined wastes, it was seen that co-digestion resulted in higher methane gas yields and also had a positive impact on the quality and quantity (CH_4 content) of biogas produced.
3) The use of co-substrates usually improves the biogas yields from anaerobic digester due to positive synergisms established in the digestion medium.
4) Economic advantages of co digestion can result from shared equipment, easier handling of feedstock, and a more stable process in general.
5) The main disadvantage of co-digestion is that it still remains largely unstudied.

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