# Anaerobic Digestion for Use in the Pulp and Paper Industry and Other Sectors: An Introductory Mini-Review

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Anaerobic digestion is a well-established biological process for converting biomass in waste streams into a renewable energy source, and it also contributes to the treatment of these waste streams. In this introductory mini-review, some fundamental aspects of anaerobic digestion for use in the pulp and paper industry and other sectors are briefly summarized. The contents include the basics of anaerobic digestion, feedstocks, key process parameters, and typical anaerobic digesters/reactors and their representative manufactures. Fostering the more efficient and widespread commercial use of anaerobic digestion technologies would be a critical strategy to address the issues of energy, the environment, and sustainability.

*Keywords: Anaerobic digestion; Biogas; Pulp and paper industry*

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## INTRODUCTION

In the context of the global economy's dependency on non-renewable fossil-based energy, the use of bioenergy derived from various biodegradable organic sources such as agricultural residues and various industrial/municipal waste streams is of strategic significance. As a low-carbon renewable energy source, bioenergy can contribute to the elimination of global warming and it is indeed a significant component in the world's strategic energy portfolio for stepping forward to a sustainable future.

Anaerobic digestion is a well-known process for the conversion of carbon-rich feedstocks into biogas, which can be used as replacement of fossil fuels in heat and power generation and as a transportation fuel, facilitating the development of a sustainable energy supply (Weiland 2010; Ziganshin *et al.* 2013; Bialek *et al.* 2014; Li *et al.* 2014a). In addition to biogas production, anaerobic digestion offers a platform for waste treatment (*e.g.* water treatment) in terms of environmental management. The integrated biorefinery market economy involving the conversion of biomass into bio-based chemicals, bio-materials, and biofuels can also be developed and implemented based on anaerobic digestion (Uellendahl and Ahring 2010; Uggetti *et al.* 2014). Typically, in the context of the integration of forest biorefinery with traditional pulp and paper manufacturing processes (Van Heiningen 2006; Amidon and Liu 2009; Jahan *et al.* 2013; Wen *et al.* 2013; Ahsan *et al.* 2014; Dansereau *et al.* 2014; Dashtban *et al.* 2014; Hou *et al.* 2014; Oveissi

and Fatehi 2014; Rafione *et al.* 2014; Wang *et al.* 2014; Liu *et al.* 2015; Matin *et al.* 2015), anaerobic digestion of organic wastes from these processes for biogas production would fit well into the biorefinery concept. At a minimum, the waste liquors from traditional pulp and paper manufacturing processes can be converted to valuable products by using anaerobic digestion. In this sense, the adoption of anaerobic digestion in the pulp and paper industry is rather promising. In addition to the pulp and paper industry, the application of anaerobic digestion to other sectors would create new possibilities as well.

In the present report, some fundamentals related to the anaerobic digestion of organic feedstocks derived from various sources or process streams for biogas production and the commercial practices are briefly reviewed, which may possibly provide a useful basis for those working in the industry, *e.g.*, pulp and paper process engineers.

## BASICS OF ANAEROBIC DIGESTION

The practical application of anaerobic biodegradation probably dates back more than 2000 years with the biodegradation of animal manure in China and India (Veenstra 2000). This is a phenomenal concept for both biodegradable waste management and biogas production. The production of biogas from various feedstocks by anaerobic digestion is a biological gasification process (Jingura and Matengaifa 2009). Thus, various anaerobic systems are often referred to as "biogas systems" (DeBruyn and Hilborn 2007). Because of several benefits like small ecological footprints and energy efficiency compared to conventional aerobic waste management, application of anaerobic biodegradation has been drawing much interest for industrial and municipal waste management.

The anaerobic digestion process is related to the breakdown of organic matter by a consortium of microorganisms in the absence of oxygen, ultimately leading to the formation of digestate and biogas primarily consisting of methane and carbon dioxide (Kelleher *et al.* 2000; Chen *et al.* 2008). This digestate is the decomposed substrate resulting from biogas production, and it can be utilized as a bio-fertilizer (Al Seadi 2001; Seadi 2008).

The biochemistry and microbiology involved in the anaerobic digestion of various organic feedstocks is rather complex (Parawira 2004; Mudhoo 2012). To date, the fundamentals have not been fully understood. However, for simplicity, this process may reasonably be divided into several steps: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis (Zupančič and Grilc 2012; Biarnes 2013).

### Hydrolysis

In the hydrolysis/liquefaction/solubilization step, organic materials consisting of carbohydrates, proteins, lipids, and other organics are broken down or depolymerized into smaller molecules by hydrolytic exo-enzymes (*e.g.*, cellulase, amylase, protease, and lipase) excreted by fermentative microorganisms (EPA 2006; van Haandel and van der Lubbe 2007). For example, carbohydrates, lipids, and proteins may be converted into simple sugars, fatty acids, and amino acids, respectively (Gerardi 2003). An example of the hydrolysis reaction (Ostrem 2004) is:

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2 \quad (1)$$

These microorganisms consist of both facultative and strict anaerobes (Broughton 2009). In the enzymatic hydrolysis step, the water-insoluble organics can be solubilized by utilizing water to split the chemical bonds (Parawira 2004), and the resulted simple soluble compounds can be taken up by the bacterial cells (Gerardi 2003). While some products from hydrolysis (*e.g.*, hydrogen and acetate) may be used by the methanogens in the anaerobic digestion process, the majority of the molecules, which were still relatively large, must be further converted to small molecules, *e.g.*, acetic acid, so that they may be used to create methane (Biarnes 2013). It is noted that hydrolysis is a relatively slow step and it can limit the rate of the overall anaerobic digestion process, particularly when using solid waste as the substrate (van Haandel and van der Lubbe 2007).

## Acidogenesis

Hydrolysis is immediately followed by the acid-forming step of acidogenesis (Ostrem 2004). During acidogenesis or acidification, the acidogenic microorganisms convert the soluble compounds resulting from hydrolysis into simple molecules with a low molecular weight, including short-chain volatile fatty acids (*e.g.*, acetic-, propionic-, and butyric acid), alcohols, aldehydes, and several types of gases (*e.g.*, carbon dioxide, hydrogen, and ammonium) (van Haandel and van der Lubbe 2007; Biarnes 2013). Typical reactions (Bilitewski *et al.* 1997; Ostrem 2004) during acidogenesis are:

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \quad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (4)$$

Although acidogenic bacteria further break down the organic matter, it is still unusable for the ultimate goal of biogas production so the subsequent step of acetogenesis is required (Biarnes 2013).

## Acetogenesis

During acetogenesis, the products from acidogenesis are converted into methanogenic substrates (Seadi 2008). Specifically, the acetogenic acid-forming bacteria catabolize products such as volatile fatty acids and alcohols into acetate (or acetic acid), carbon dioxide, and hydrogen gas, which can subsequently be used by methane forming bacteria (Gerardi 2003; Seadi 2008). Typical reactions (Ostrem 2004) in this step are:

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (5)$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (6)$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 3H_2 + H^+ \quad (7)$$

The hydrogen gas formed in this step can be regarded as a "waste product" of acetogenesis because it inhibits the metabolism of acetogenic bacteria; however, it can be consumed by methane-producing bacteria functioning as hydrogen-scavenging bacteria and converted into methane (Seadi 2008).

### Methanogenesis

As the final step of anaerobic digestion, methanogenesis or biomethanation results in the conversion of the products of acetogenesis as well as the intermediate products from hydrolysis and acidogenesis into methane and other byproducts (Biarnes 2013). Methanogenesis is a critical step in the entire anaerobic digestion process, and its biochemical reactions are the slowest in comparison to those in other steps (Seadi 2008). As one group of strict anaerobes, vulnerable to even small amounts of oxygen, the methane-producing bacteria responsible for bioconversion can be subdivided into two groups: acetoclastic methane bacteria (acetophilic) and methane bacteria (hydrogenophilic) (Paul and Liu 2012). Another group of methane-producing bacteria, the methyltrophic bacteria, may also be able to create methane from methanol (Gerardi 2003). The typical reactions (Verma 2002) involved in this step are:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (8)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (9)$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (10)$$

As one of the most important components of volatile acids from prior steps, acetic acid or acetate is the main source of methane in anaerobic digestion, and most of the remaining methane is formed from the reduction of carbon dioxide in the presence of hydrogen as the energy source (Paul and Liu 2012).

## FEEDSTOCKS FOR ANAEROBIC DIGESTION

In contrast to the feedstocks/substrates used for bioethanol or biodiesel production, biogas can be made from more diversified organics in the form of solids, slurries, and concentrated/diluted liquids (Feng *et al.* 2013; Kabir *et al.* 2013; Teghammar *et al.* 2013; Wilkie 2013; Xiao *et al.* 2013; Cheng and Zhong 2014; Li *et al.* 2014b; Yuan *et al.* 2014; Zhao *et al.* 2014). The waste streams from pulp and paper manufacturing processes are typical feedstocks for biogas production. In general, the eligible feedstocks for anaerobic digestion for biogas production include agricultural wastes, municipal bio-wastes, industrial wastes and wastewater, and energy crops (*e.g.*, maize) (Steffen *et al.* 1998). Particularly, the utilization of bio-wastes for biogas production is rather promising in terms of both environmental protection and bioenergy production. These feedstocks may consist of but are not limited to the following (Seadi 2008):

- Waste from agriculture (*e.g.*, crop residues and animal manures), horticulture, aquaculture, forestry, hunting and fishing, and food preparation and processing
- Waste from wood processing and the production of panels and furniture, pulp, paper, and cardboard
- Waste from the leather and fur and textile wastes from the leather and fur industries
- Waste packing, absorbents, wiping cloths, filter materials, and protective clothing not otherwise specified

- Waste from waste management facilities, off-site waste water treatment plants, the preparation of water intended for human consumption, and water for industrial use
- Municipal waste (household waste and similar commercial, industrial, and institutional wastes) including separately collected fractions

Depending on the solids content of the feedstocks, anaerobic digestion can usually be divided into two processes: 1) dry (solids content of 15% to 40%) and 2) wet (solids content of less than 15%) (Renewables East 2007). The pretreatment of feedstocks (*e.g.*, the recalcitrant lignocellulosic materials) prior to anaerobic digestion can facilitate biogas production. The pretreatment can be based on physical, chemical, or biological actions (Ariunbaatar *et al.* 2014; Zheng *et al.* 2014). For example, thermal pretreatment of sewage sludge can result in increased biogas production (Pilli *et al.* 2015). Biological pretreatment of corn stover, a typical lignocellulosic feedstock, with laccase, can increase the digestibility of the substrate, improving hydrolysis, the rate limiting step in biogas production (Schroyen *et al.* 2014). Co-digestion of different feedstocks can also be a practical approach for enhancing the efficiency of anaerobic digestion due to such factors as a higher buffer capacity and an optimum nutrient balance as a result of co-digestion (Meyer and Edwards 2014; Zhang *et al.* 2014).

## KEY PROCESS PARAMETERS FOR ANAEROBIC DIGESTION

The growth of digestive microorganisms is of paramount importance in the anaerobic digestion process and it strongly determines the process efficiency (Verma 2002). It is critical that appropriate conditions for anaerobic microorganisms are provided (Seadi 2008). Once reasonable activity of these microorganisms is well controlled, the degradation of feedstocks and methane production would be facilitated. The main process parameters in anaerobic digestion include temperature, system pH, volatile fatty acid content and conversion, availability of micro and trace nutrients, mixing, and toxicity. These parameters may overlap each other; for example, volatile acid content can be related to the toxicity of the feedstocks and pH of the system.

### Temperature

The control of temperature is rather critical for the anaerobic digestion process. Common recurring problems associated with anaerobic digesters are loss of heating capability and maintenance of optimum digester temperature (Gerardi 2003).

In general, there are two temperature ranges that provide optimum conditions for anaerobic biodegradation: the mesophilic and thermophilic ranges (Verma 2002). Typically, the mesophilic temperature is in the range of 30 to 35 °C, usually around 35 °C, while the thermophilic temperature ranges from 50 to 60 °C, usually around 55 °C (Gerardi 2003). Thus, at temperatures between 40 and 50 °C, methane-producing bacteria can be inhibited, leading to a decrease in biogas production.

Many modern large anaerobic reactors operate at thermophilic temperature, which is due to its inherent advantages over the mesophilic process (Seadi 2008; Nayono 2009):

- Higher rate of biomass hydrolysis in the hydrolysis step
- Effective destruction of pathogens
- Higher growth rate of methane-producing bacteria at higher temperature and hence higher methane production rate
- Reduced retention time, making the process faster and more efficient
- Improved digestibility and availability of substrates
- Better degradation of solid substrates and better substrate utilization
- Better possibility for separating liquid and solid fractions

However, the thermophilic process also has its pronounced disadvantages, including large degree of imbalance, higher energy demand as a result of high temperatures, and more sensitivity to toxic inhibitors and changes in process parameters (Mata-Alvarez 2002; Seadi 2008).

During the digestion process, it is important to keep a constant temperature, as temperature changes or fluctuations will negatively affect the biogas production (Seadi 2008).

## System pH

It is known that the anaerobic digestion of substrates is a joint work of several types of microorganisms, from which the methanogens are the most sensitive to low pH because of the significant inhibiting effect of acidic conditions on their growth (Verma 2002; Labatut and Gooch 2012).

Acetogenesis can lead to the formation of organic acids, essentially volatile fatty acids, which accounts for the decrease in system pH. However, maintenance of the system pH in the neutral range (*e.g.*, 6.5 to 7.6) is required for efficient anaerobic digestion (Labatut and Gooch 2012). The methanogenic activity decreases significantly at a pH below 6.3 and above 7.8 and this will inhibit methane production (Leitao *et al.* 2006). The most preferable pH for highest methanogenic activity is in the narrow range of 7.0 to 7.2 (Ostrem 2004).

It is crucial to measure the pH throughout the entire process to ensure the health of the methanogens and, thus, continued methane production (Biarnes 2003). Reduction in system pH may be controlled by the addition of lime (Verma 2002).

## Volatile Fatty Acids

Under unbalanced digestion conditions, volatile fatty acids can build up, which is the main cause of toxicity and reactor failure (Ahring *et al.* 1995; Björnsson *et al.* 1997; Parawira 2004). As a process performance indicator, the concentration of volatile fatty acids, including acetic acid/acetate, propionic acid/propionate, butyric acid/butyrate, valeric acid/valerate, caproic acid/caproate, and enanthic acid/enanthate (acetate is predominant), is probably the most sensitive parameter to monitor (Labatut and Gooch 2012). The presence of an excess concentration of volatile acids can be corrected with the addition of an alkaline compound (Gerardi 2003).

## Nutrients

All organisms need essential nutrients, micro-nutrients, and trace elements for their healthy growth (Lettinga 1995; Parawira 2004). For example, in the methanogenesis step of the anaerobic digestion process, the nutrients for the methanogens can be divided into two groups: 1) macro-nutrients (*e.g.*, nitrogen and phosphorous) and 2) micro-nutrients (*e.g.*, cobalt, iron, nickel, and sulfur) (Gerardi 2003). Sufficient nutrients are required for stable biogas production. However, some trace metal elements such as copper and zinc can be toxic to anaerobic processes (Lin 1993).

## Mixing

In an anaerobic reactor, the mixing of the contents can significantly influence the process efficiency; in particular, hydraulic dead zones are extremely detrimental to the reaction kinetics involved in anaerobic digestion (Verhoff *et al.* 1974). Effective mixing is critical for process stability, maximum contact of feedstocks with microorganisms, maximizing biogas production, minimizing scum and foam formation, and preventing solids deposition in the digester (Massart *et al.* 2008). Mixing can also enhance the digestion process by equalizing temperature and rapid dispersion of any toxic materials entering the digester, minimizing toxicity (Gerardi 2003). However, the mixing needs to be delicately controlled because methanogens are very sensitive to rapid mixing; if rapid mixing continuously washes out methanogens, then a retention period of less than seven days is not realistic (Gerardi 2003). As stated by Williams and Shea (2012), too little mixing can allow pockets of gas to accumulate, creating density gradients, while too much mixing can entrain gas on a wider scale, creating density gradients.

## Toxicity

The presence of inhibitory substances may be the cause of anaerobic reactor upset or failure (Chen *et al.* 2008). These commonly include ammonium, sulfide, light metal ions, heavy metal ions, and some organics. Specifically, the toxic substances may include the following (Gerardi 2003):

- Alcohols (isopropanol)
- Alkaline cations ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$)
- Alternate electron acceptors, nitrate, and sulfate
- Ammonia
- Benzene ring compounds
- Cell bursting agent (lauryl sulfate)
- Chemical inhibitors used as food preservatives
- Chlorinated hydrocarbons
- Cyanide
- Detergents and disinfectants
- Feedback inhibition
- Food preservatives

- Formaldehyde
- Heavy metals
- Hydrogen sulfide
- Organic-nitrogen compounds (acrylonitrile)
- Oxygen
- Pharmaceuticals (monensin)
- Solvents
- Volatile acids and long-chain fatty acids

Typically, for wastewater from the pulp and paper industry (Table 1), the most common inhibitors to anaerobic digestion processes include sulfide, tannins, resin acids, long chain fatty acids, and halogenated compounds (Ali and Sreekrishnan 2001; Chen *et al.* 2008). For example, sulfide toxicity is most likely to occur under low organic loadings, which is due to poor stripping of sulfide as a result of the deficiency in biogas production. In this regard, a common practice to prevent sulfide toxicity is to add iron, which precipitates the sulfide as iron sulfide (Gerardi 2003). The understanding of the working mechanisms of the inhibitors is essential for efficient biogas production.

**Table 1.** Characteristics of Wastewater Generated from Pulp and Paper Industry (Saleh and Mahmood 2004*)

| Wastewater | COD (mg/L) | Degradation (%) | Inhibitors of anaerobic digestion |
|---|---|---|---|
| Wet debarking | 1300-4100 | 44-78 | Tannins, resin acids |
| Pulping | 1000-5600 | 60-87 | Resin acids |
| Thermomechanical/ chemithermomechanical pulping | 2500-13,000 | 40-60 | Resin acids, fatty acids, sulfur |
| Chemical pulping | 7000 | - | Sulfur, ammonia |
| Chlorine bleaching | 900-2000 | 30-50 | Chlorinated phenols, resin acids |
| Sulfite spent liquor | 120,000-220,000 | - | Sulfur, resin acids, fatty acids, terpenes |
| Kraft condensate | 1000-33,600 | 83-92 | |
| Sulfite condensate | 7500-50,000 | 50-90 | Sulfur, organic sulfur |
| * Data cited by authors, original data source not found. | | | |

## TYPICAL ANAEROBIC REACTORS AND REPRESENTATIVE MANUFACTURERS OF COMMERCIAL REACTORS FOR WASTEWATER TREATMENT

The anaerobic digestion process takes place in a warmed, sealed, airless container, which creates the ideal conditions for the microorganisms to convert feedstocks into methane, carbon dioxide, and small amounts of other gases (Singh and Prerna 2009). In practice, the main ways in which anaerobic digestion systems can be configured include: (1) wet or dry (feedstocks); (2) plug flow or fully mixed; (3) mesophilic or thermophilic;

(4) single stage or multi-stage; and (5) batch or continuous (Renewables East 2007). According to how the biomass is retained in the system, anaerobic digestion systems can be divided into three categories: (1) anaerobic suspended growth systems; (2) anaerobic attached growth systems; and (3) hybrid anaerobic filters (Hassan *et al.* 2013).

## Typical Anaerobic Reactors

*Anaerobic lagoon or covered lagoon reactor*

As the oldest and simplest anaerobic technology, an anaerobic lagoon is a deep impoundment, essentially free of dissolved oxygen, which promotes anaerobic conditions (EPA 2002). This type of anaerobic reactor can be used for the treatment of animal manures or the pre-treatment of industrial wastewaters, while producing methane as a bio-product.

The covered lagoon digestion system is a modified form of the anaerobic lagoon (Hamilton 2012). For the anaerobic digestion process, the biogas yield is dependent upon environmental temperature, *i.e.*, high in warm months and low in winter months (Saele 2004).

*Completely stirred reactor or contact reactor*

The completely stirred (mixed) reactor (CSTR) (Hamilton 2012), which contains a mixer to maintain good contact between microorganisms and the feedstock, was applied during the 1970s. To increase organic load and reduce retention time, the microorganisms can be recycled from a separator or clarifier to the reactor, and this version of the CSTR is referred as a "contact" reactor.

*Plug-flow anaerobic reactor*

The idea behind the plug-flow reactor (Hamilton 2012) is the same as the completely stirred reactor. Because there is very little mixing, the input feedstocks move through the digester as a "plug," hence the name "plug-through".

*Anaerobic filter reactor*

The anaerobic filter (Hamilton 2012), also known as the fixed film digester or packed bed digester, was initially commercialized in the late 1980s. This reactor relies upon a media substrate to retain the microorganisms within the reactor vessel, and the filter material is usually made from ceramics, glass, plastic, or wood (EPA 2002). As the growth of microorganisms requires relatively long periods of time to develop, their holding in the reactor by the media can facilitate the anaerobic digestion process (Gerardi 2003).

*Upflow anaerobic sludge blanket reactor*

The upflow anaerobic sludge blanket (UASB) reactor was developed during the 1970s. It is basically a tank with a sludge bed (Gómez 2011; Lettinga *et al.* 1979). In this reactor, the mixing between sludge and the feedstock is achieved by an even flow-distribution combined with a sufficiently high flow velocity and the agitation resulting from gas formation (Lettinga 1995; Duncan Mara 2003). The development of sludge into high-density granules results in the formation a blanket or granular matrix, which is kept in suspension by controlled upflow velocity (Duncan Mara 2003).

**Table 2.** Representative Producers of Anaerobic Digesters for Biogas Production

| Country | Company | Website | Key features of the reactor/reactors or technologies |
|---|---|---|---|
| Canada | ADI systems Inc. | http://www.adisystemsinc.com/en/technologies/anaerobic-treatment | ADI-BVF®: A combination of the features of the upflow anaerobic sludge blanket and anaerobic contact systems.<br>ADI-CGR®: A robust low-rate anaerobic system used primarily for bioenergy production (in the form of biogas). ADI-ECSB: An ultrahigh-rate anaerobic treatment process which is highly compact.<br>ADI-AnMBR: A high-rate anaerobic process with membrane separation.<br>ADI-CSTR: A moderate-rate, continuously stirred, anaerobic process.<br>ADI-Hybrid: A proprietary high-rate system that combines two anaerobic processes, upflow anaerobic sludge blanket and upflow fixed-film. |
| The Netherlands | Biothane Systems International | http://www.biothane.com/en/Biothane-technologies/Anaerobic-wastewater-treatment/ | Biobed® Advanced: A combination of the excellent performance of the UASB reactor with the cost effectiveness of an EGSB system<br>Memthane®: Biothane's Memthane® Anaerobic MBR (AnMBR) technology.<br>Biobulk CSTR: The Biobulk CSTR (Completely Stirred Tank Reactor) technology<br>Sulfothane™: A biogas desulphurization technology.<br>Biogas Scrubbers: complementary solutions to clean the produced biogas.<br>Upthane™: An Upflow Anaerobic Sludge Blanket (UASB) treatment system. |

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|---|---|---|---|
| France | Degrémont | http://www.degremont-industry.com/en/our-expertise-technologies/wastewater/anaerobic-biological-treatment/ | ANAPULSE (granular sludge (UASB)): A process applicable to effluent from sugar refineries, wine producers and breweries.<br>ANALIFT (contact reactor): Suited to chemical, pulp and paper residue, and the treatment of complex food juices.<br>ANAFLUX (fluidised bed): Used to treat evaporation condensate and alcohols. |
| The Netherlands | Paques BV | http://en.paques.nl/pageid=68/BIOPAQ%C2%AE.html | BIOPAQ®AFR: Anaerobic COD removal including fats and proteins.<br>BIOPAQ®IC: Anaerobic COD removal and biogas production.<br>BIOPAQ®UASB: Anaerobic COD removal and biogas production.<br>BIOPAQ®UASB+: Anaerobic COD removal and biogas production.<br>BIOPAQ®UBOX: Anaerobic and aerobic COD removal. |
| Sweden | Purac AB | http://purac.se/?page_id=672 | ANAMET™: The completely stirred tank reactor (CSTR) commonly used throughout the world for organic wastewaters containing high loads of suspended solids, e.g., from sugar and yeast production. |
| India | M/s. Acsion Engineering Pvt. ltd | http://www.acsionindia.net/upflow-anaerobic-sludge-blanket.htm | UASB reactor |
| United States | Clearfleau Ltd. | http://www.clearfleau.com/page/anaerobic-digestion | High rate digestion system |
| The Netherlands | Colsen Group | http://www.colsen.nl/csn-prod&serv/en/uasb-ind-en-flyer.pdf | UASB reactor |

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|---|---|---|---|
| China | Shandong Jinhaosanyang Environmental Protection Equipment Co., Ltd | http://www.cnjinhaosanyang.com/cn/product_115_2.html | UASB reactor, EGSB reactor |
| China | Guangxi Bossco Environmental Protection Technology Co., Ltd. | http://www.bossco.cc/newsview-718.aspx | So-called UMAR reactor |
| Note: numerous companies involved in anaerobic reactors can be found at http://www.environmental-expert.com/companies/keyword-anaerobic-digestion-1833 and http://www.alibaba.com/showroom/anaerobic-reactor.html | | | |

**Table 3.** Typical Early Examples of the Use of Anaerobic Technologies for Biogas Production in the Pulp and Paper Industry (Wang *et al.* 2004)

| Mill | Influent type and characteristics | Supplier | Reactor details | Start-up year | Plant performance |
|---|---|---|---|---|---|
| MacMillan Bloedel Ltd., Canada | Corrugated cardboard/NSSC<br>Flow: 6300 $m^3$/d<br>COD load: 107 t/d | Biothane Systems International | UASB V=7000 $m^3$<br>(2×3500 $m^3$ R)<br>VLR=15.4 kg | 1989 | Gas production: 1140 $m^3$/h<br>COD reduction: 55%<br>BOD reduction: 85% |
| Stone Container, Canada | CTMP/NSSC recycle<br>Flow: 656 $m^3$/d<br>COD load: 7.7 t/d | Biothane Systems International | UASB V=15,600 $m^3$<br>(2×7800 $m^3$ R)<br>VLR=12 kg | 1988 | BOD reduction: 85% |
| Industriewater, The Netherlands | Total flow from 3 mills: 12,400 $m^3$/d<br>COD load: 22 t/d | Paques BV | UASB V=2184 $m^3$<br>VLR=6-7 kg | 1990 | Gas production: 2000-3600 $m^3$/h<br>COD reduction: 70%<br>BOD reduction: 80% |

| | | | | | |
|---|---|---|---|---|---|
| Satia Paper Mills Ltd., India | Chemical pulping using agricultural residues<br>Flow: 4500 $m^3$/d<br>COD load: 53 t/d | Paques BV | UASB V=5200 $m^3$<br>(2×2600 $m^3$ R)<br>VLR=10 kg | 1997 | Gas production: 10,000-12,000 $m^3$/h<br>COD reduction: 50-60%<br>BOD reduction: 60-70% |
| Papetries Lecoursonnois Paper Mill, France | Corrugated medium and coated paper<br>Flow: 600 $m^3$/d<br>COD load: 3.6 t/d | Degrémont | Fluidized bed capacity of the reactor = 20-30 $m^3$/h | 1994 | COD reduction: 75%<br>BOD reduction: 85% |
| Modo Paper AB, Sweden | Sulfite condensate<br>Flow: 6000 $m^3$/d<br>COD load: 72 t/d | Purac AB | V=30,000 $m^3$<br>(2×15,000 $m^3$ R)<br>Reactor loading rate: 125 t COD/d | 1984 | Gas production: 23,000 $m^3$/h<br>COD reduction: 81%<br>BOD reduction: 98% |
| Pudumjee Pulp and Paper mills, India | 40 tpd bagasse bleached pulp<br>Flow: 2200 $m^3$/d<br>COD load: 20-22 t/d | Sulzer Brothers Ltd., Switzerland | Continuous stirred tank (An-OPUR)<br>V=13,000 $m^3$<br>(2×6500 $m^3$ R)<br>VLR=3-5 kg | 1989 | Gas production: 5000-6000 $m^3$/h<br>COD reduction: 60-70%<br>BOD reduction: 85-98% |

*Expanded granular sludge bed reactor*

The expanded granular sludge bed (EGSB) (Gómez 2011) is basically the vertically stretched version of the UASB reactor, and it separates the biomass, biogas, and wastewater in a 1-step three-phase-separator on top of the reactor (Driessen and Vereijken 2003). It can be defined as a modification of the UASB reactor in which the granules are partially fluidized by effluent recycle at a liquid upflow velocity of 5 to 6 m/h (Frankin and Zoutberg 1996). This reactor has improved mass transfer characteristics over the UASB reactor (Mutombo 2004).

*Internal circulation reactor*

The internal circulation (IC) reactor can be considered as two anaerobic treatment compartments (like UASB) on top of each other, one highly loaded and the other with low loading (Mutombo 2004). A unique feature associated with the IC reactor is related to its highly efficient multi-level circulation system. As an upflow granular sludge bed system, the IC technology is based on the proven UASB process (Habets 2005). Typically, the loading rate of the IC reactor can be higher than that of the UASB reactor (Driessen and Vereijken 2003).

### Current Representative Manufactures of Commercial Reactors for Wastewater Treatment

Currently, most commercial anaerobic reactors for wastewater treatment are based on the upflow anaerobic sludge blanket (UASB) or internal circulation (IC) reactor principles. The reactors may also be based on combinations of the unique features of different reactors so that their efficiency can be optimized. The representative commercial anaerobic manufacturing companies and some examples of using these technologies in the pulp and paper industry are shown in Tables 2 and 3. For the waste streams generated from pulp and paper manufacturing processes, the identification of new possibilities associated with the use of suitable anaerobic reactors in certain occasions is quite essential.

Despite the fact that anaerobic treatment of pulp and paper mill waste streams is widely accepted, its commercial practices are now still limited (Meyer and Edwards 2014). The widespread use of anaerobic digestion for converting these wastes to a valuable bioproduct, *i.e*., biogas, has much potential.

## CONCLUDING REMARKS

Anaerobic digestion is a well-established process for the biological treatment of organic waste streams from various industrial processes, including the pulp and paper manufacturing processes. Its wide industrial adoption is also motivated to produce biogas from these organic feedstocks.

Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the key steps in the overall process. For efficient anaerobic digestion, the key process parameters include temperature, system pH, volatile fatty acids, nutrients, mixing, and toxicity. Various anaerobic reactors/digesters are commercially available, which include anaerobic lagoon/covered lagoon reactor, stirred reactor/contact reactor, plug-flow anaerobic reactor, anaerobic filter reactor, upflow anaerobic sludge blanket reactor, expanded granular sludge bed reactor, and internal circulation reactor, among others. These reactors can be

specifically tailored for practical applications dealing with various feedstocks. A number of producers of these anaerobic reactors are available on the global market. Much potential do exist in terms of the more efficient and widespread use of anaerobic digestion technologies, which calls for technological advancements and breakthroughs related to biochemical, biological, and processing machinery aspects of the process. Future anaerobic digestion technologies such as those related to the concept of integrated biorefinery would play a significant role in meeting the high demand of environmental protection and bioenergy production. The enhancement of the efficiency of anaerobic reactors through scientific and technological innovations would also serve as the key to more widespread commercial use of anaerobic digestion.

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