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Performance of anaerobic digestion systems: A review

D.A. Thompson, S. Nanukuttan and D. McPolin
Queen's University Belfast, Northern Ireland, United Kingdom

ABSTRACT

Anaerobic digesters contain extreme environments that change drastically during the production cycle. Organic material is broken down first into amino and fatty acids, then into volatile fatty acids, ammonia, CO_2, H_2S and other by-products. These acids and alcohols are converted to acetic acid as well as CO_2 and H_2, which is then used to create methane. All these biological processes mean that the pH, temperature and type of bacteria vary, creating conditions outside the scope of current standards, such as a concentration of ammonium ions 8 times greater than the upper limit of the XA3 class of highly aggressive chemical attack for concrete in BS EN 206-1:2000. Depending on the source, the concrete may be exposed to heavy metals, antibiotics or surfactants, which are not even considered by current standards. Anaerobic digestion (AD) is a growing industry, and this paper gives estimates for investment in anaerobic digestion around the world: nearly £2.5 billion in India, over £3 billion in the UK and USA, and nearly £14.5 billion invested in Germany, with China becoming the largest AD market in the world. This means that anaerobic digestion has sizable economic value as well as positive environmental effects. However, as part of maximising these benefits, it is necessary to better understand the chemical and biological attack the concrete that is used to build these digesters undergoes, so that steps can be taken towards limiting premature deterioration. This article will show the current gaps in both knowledge and legislation, with the aim of promoting further research into the aforementioned areas.

Keywords: Anaerobic digestion, premature concrete deterioration, exposure classes, chemical attack

1.0 INTRODUCTION

Methane is a major contributor to global warming. The main source of methane from human activities comes from agriculture and waste. Methane is released as bacteria break down the organic components of waste from agriculture and landfill. Anaerobic digestion is the idea of using these bacteria to break down organic waste in a controlled environment and to capture the methane for use in energy production. This is the appeal of the system, however, each anaerobic digester requires a relatively large amount of infrastructure and control systems. With this comes a significant capital cost and a sizable maintenance cost, however they are profitable despite this if run correctly. How the different environments within these systems affect concrete is still largely unknown. Current manufacturers rely on empirical knowledge as opposed to regulations laid out in the codes of practice. This paper aims to set out what is known, and what areas require further research.

2.0 METHANE AS A GREEENHOUSE GAS

2.1 Impact of Methane on the Environment

Table 1 gives a summary of Global Warming Potential (GWP) Values from different reports from the Intergovernmental Panel on Climate Change.
These values compare the GWP of different compounds to a base line, which is carbon dioxide (CO_2). The latest report, AR5 (Stocker, et al., 2013), indicates that methane is 28 times more potent than carbon dioxide. In other words, 1 tonne of methane is equivalent to 28 tonnes of CO_2. CO_2 is used as the

Table 1. Abstract from summary of Global Warming Potential Values (Myhre, et al., 2014)

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon dioxide	CO2	1	1	1
Methane	CH4	21	25	28
Nitrous oxide	N2O	310	298	265

base line because it is the most well-known greenhouse gas, but it is clearly not the worst.

2.2 Anthropological Sources of Methane

Table 2 from AR5 (Stocker, *et al.*, 2013) gives a breakdown of global methane sources. As can be seen, agriculture and waste are by far the largest contributors to global methane year on year. Ruminants, such as cattle and sheep, are almost equal with fossil fuels for each decade, with methane from ruminants and landfills increasing each decade. This follows the increase in scale that industrialised farming has allowed.

3.0 ANAEROBIC DIGESTERS

Anaerobic Digestion (AD) systems have a dual advantage, they trap methane, preventing it's release into the atmosphere, and they then burn this in a generator to produce electricity. The gas can also be cleaned and injected into the natural gas network for use in homes.

3.1 Overview of AD Systems

As an overview of the different components normally found within an anaerobic digestion system, feedstock is first brought to site and stored in silage clamps. This feedstock can be acidic, for example, grass silage can be between 3.5 and 4 pH. These are usually open air storage areas. The feedstock is taken by mobile plant and placed in the pre-treatment machinery. Pre-treatment can vary significantly, from injecting additives, such as sodium hydroxide that raise the pH, adding chemicals to remove heavy metals, pasteurising the feedstock to kill off pathogens, adding water to create either wet or dry feedstock, or shredding the material to increase the surface area. Which processes are included depends on what type of feedstock it is and what exactly the process is in their digester. This treated feedstock is then pumped into the digester tank, typically through stainless steel pipes. The optimum running pH is between 6.8 and 7.2 for mesophilic digesters (Gerardi, 2003), (Hagos, *et al.*, 2017).

There is an equilibrium between ammonia and ammonium throughout the process. The concentration of ammonium ions has been reported as 8 times greater than the upper limit of the XA3 class of highly aggressive chemical attack for concrete in BS EN 206-1:2000 (Voegel, *et al.*, 2016).

Hydrolysis, acidogenesis, acetogenesis and methanogenesis are the processes that occur inside the digester. Each of these stages are carried out by different sets of bacteria within the three main species of bacteria, which will be described later. Hydrolysis is where complex carbohydrates, lipids and proteins are broken down into simple sugars, fatty acids and amino acids. These are then converted, during acidogenesis, into organic acids and alcohols. Acetogenic bacteria then produce acetate from these acids and alcohols. Acetoclastic methanogenesis is where the acetate is used to produce methane and CO_2, hydogenotrophic methanogenesis uses hydrogen and CO_2 to produce methane, and methyltrophic methanogenesis produces methane and water from methanol (Gerardi, 2003), (Hagos, *et al.*, 2017).

Some systems have partial coatings on the inside of their concrete digesters, typically at the top of the walls and on the interior of the roof, if it is concrete and not a flexible membrane. This is to protect the concrete from the corrosive constituents of the gas layer, such as hydrogen sulphide (H_2S) gas. Concrete that is only in contact with the liquid portion can be left unprotected in concrete digesters, although some manufacturers choose to protect the entire surface of the walls. These are typically a type of polymer coating, and can be formwork that is designed to be

Table 2. Abstract from Table 6.8 (Stocker, *et al.*, 2013)

Tg(CH4) yr–1	1980–1989		1990–1999		2000–2009	
	Top-Down	Bottom-Up	Top-Down	Bottom-Up	Top-Down	Bottom-Up
Anthropogenic Sources	348 [305–383]	308 [292–323]	372 [290–453]	313 [281–347]	335 [273–409]	331 [304–368]
Agriculture and waste	208 [187–220]	185 [172–197]	239 [180–301]	187 [177–196]	209 [180–241]	200 [187–224]
Rice		45 [41–47]		35 [32–37]		36 [33–40]
Ruminants		85 [81–90]		87 [82–91]		89 [87–94]
Landfills and waste		55 [50–60]		65 [63–68]		75 [67–90]
Biomass burning (incl. biofuels)	46 [43–55]	34 [31–37]	38 [26–45]	42 [38–45]	30 [24–45]	35 [32–39]
Fossil fuels	94 [75–108]	89 [89–89]	95 [84–107]	84 [66–96]	96 [77–123]	96 [85–105]

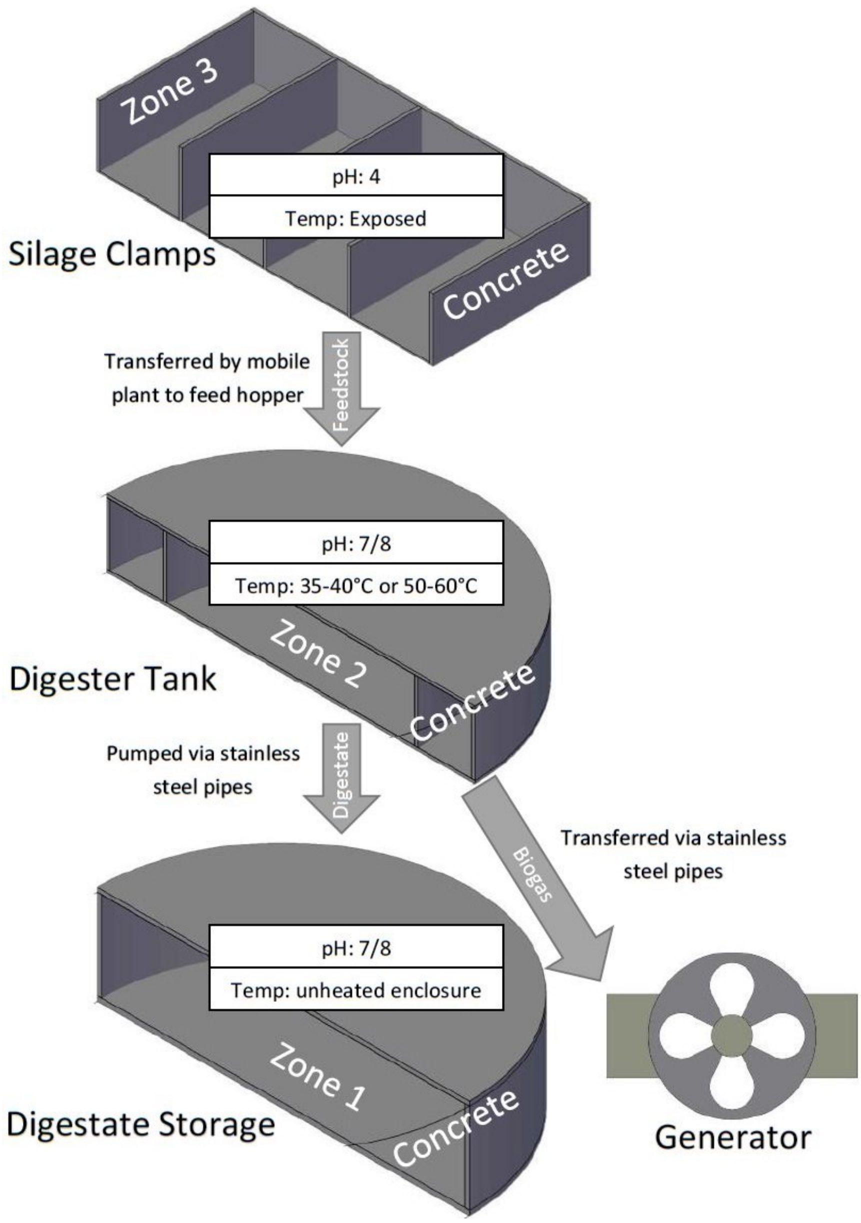

Fig. 1. Pictorial representation of common AD system components

left in place after the concrete has been poured in situ, or can be applied later. In order to keep the digesters at the required temperature, insulation is installed on the outside of the tank. The tanks are also buried where possible to minimise heat loss from the digesters.

The roof of the digesters are normally flexible membranes, in order to allow for the changes in gas pressure inside the tank. As mentioned previously, some concrete digesters will instead have concrete lids, however there are reports of the seals between wall and lid failing and allowing gas to escape, but these are unconfirmed.

The methane produced can be used in a Combined Heat and Power (CHP) system on the site to produce electricity and heat water, which is pumped into the heating tanks of the digesters to maintain the correct temperature, but can also provide hot water to local buildings, such as houses. The electricity produced is used to run the facility and any excess can be sold to the grid. This kind of set up is common, as it makes the AD system self-sustaining. Boilers can be used instead if there are large requirements for heat on or near the site. It is also possible to "clean" the biogas produced, turning it into biomethane, and add a smell so that it can be injected into the gas grid. The biogas which is produced during digestion is typically 60% methane and 40% CO_2. In order to be used in the gas grid, the gas must contain at least 95% methane. Once cleaned, biomethane can also be used to power vehicles (DOE, 2013), (Hagos, *et al.*, 2017).

A gas flare is also a requirement in order to prevent explosions from the build-up of gas in the storage areas.

The liquid digestate that is left over from the process is normally around 95% of the starting volume of the feedstock. This digestate has a pH around 7-8 and can be used as fertiliser, with the benefit that it has a largely reduced smell. This is an advantage in acidic farmland, as the process has converted acidic feedstock to more neutral/basic digestate. Monitoring of the nutrient content is necessary to prevent eutrophication in the local water courses.

3.2 Overview of Digester Variations

In terms of the bacteria, there are 3 species of bacteria that can be used, each with their own preferred temperature range. Psychrophilic bacteria operate best between 5-25 degrees Celsius, although these bacteria produce less gas and require a longer hydraulic retention time compared to the other two, and so are never used. Mesophilic and thermophilic bacteria are the two types that are used in anaerobic digesters, with mesophilic being the more commonly used. Thermophilic bacteria prefer a temperature around 50-60 degrees Celsius, digest the feedstock quicker and produce more gas per unit of feedstock, however they are more difficult to manage and are more affected by changes in temperature, pH and other environmental factors. Mesophilic bacteria are then the preferred choice. They operate around 30-35 degrees Celsius, and are more tolerant to changes in their environment (Gerardi, 2003), (DOE, 2013).

As mentioned before, the feedstock can be either wet or dry. The classification for this is the amount of solid present in the feedstock. 5-15% solids mean it is considered wet, whereas >15% solids mean it is considered dry. Wet feedstock allows for simplifications in the processing equipment, which translates into lower capital costs. Wet feedstock typically gives more gas per unit than dry feedstock, and due to a simpler system it usually has lower running costs. For this reason, wet feedstock systems are normally used. The bacteria described previously can work with either type of feedstock (DOE, 2013).

Continuous flow systems are digesters where feedstock is continually being injected in at a constant rate, and the equivalent amount of digestate is being extracted from the system, so that once the digester is running it never stops. Batch flow systems are different in that they will start using a batch of feedstock, run for one cycle, and then stop, with all the digestate being removed. Wet feedstock systems lend themselves to continuous flow digesters, while dry feedstock is more suitable for batch flow, meaning that continuous systems are the more common type. With continuous systems there is also no loss in gas production from downtime, however continuous systems require a reliable supply of feedstock and do not allow for inspection or maintenance of the tanks. (DOE, 2013).

The first digesters were single stage systems. This was where the 4 stages of methane production, hydrolysis, acidogenesis, acetogenesis and methanogenesis, occurred together in one tank. However, this was an inefficient set up, as the acidogenic bacteria prefer a lower pH of about 4-5, whereas the methanogenic bacteria prefer a pH of 7-8. As these digesters were operated around a neutral pH to encourage the methanogenic bacteria, this meant that acidogenesis was the limiting factor is biogas production. Two stage digesters were then developed, where the process of acidogenesis was separated from methanogenesis. This was done by adding a second tank, where the feedstock would enter the first, undergo hydrolysis and acidogenesis, then move to the second tank to go through acetogenesis and methanogenesis. This improved the efficiency, as the primary tank was then able to be kept at a lower pH, with the second around a neutral pH. There also exist three stage digesters, which aim to further improve efficiency by continuing with this idea (Nasir, et al., 2012), (Hagos, et al., 2017).

4.0 COST OF AD SYSTEMS

4.1 Initial and Operational Costs

UK

The Academy of Champions for Energy (ACE) state in one of their action packs:

"Energy farms will cost between £1-4million for 200kW-1000kW plants. Set out below are the indicative costs of building a 500kW plant with one concrete ring in ring plant (i.e. with an inner and outer tank) of 42m diameter… A 500kW plant costing £2m can create a gross income of £700,000 p.a. (principally from the sale of energy and financial incentives). Costs will be around £425,000 p.a. (principally for feedstock and maintenance costs). This leaves around £250,000 p.a. to cover finance and management costs. These figures do not assume that all heat can be sold." (Weddle, 2014)

The Department of Energy and Climate Change (DECC) give the following analysis when predicting the cost of AD systems for the period of 2013 - 2017 in their 2012 report:

"The technology is currently under-developed due to relatively expensive capital costs, estimated to be between £1.7 million and £7.3 million per MW for power-only plants (including use of heat for efficient running of the generator) and £1.8-7.7 million per MW for CHP plants (where heat offtake is for a separate activity), coupled with non-financial constraints related to planning, permitting, grid connection, skills and lack of awareness." (DECC, 2012)

Up until 2017, the Waste and Resources Action Programme (WRAP) were offering the following funding to parties interested in developing AD systems:

"The first part is a business plan grant up to £10,000 to investigate the environmental and economic potential of building an AD plant on the farm.

The second part is a capital loan up to £400,000 (or a maximum of 50% of the project cost). This is available for AD plants producing up to 250kW of power."
(WRAP, 2017)

As of the writing of this report, the funding is currently under review, but still serves as an indication of the scale of the capital costs for small systems of 250kW.

Germany
Odega is a company in germany that has recently finished a 1.7 MW digester costing EUR 7.5 million, which is the same as nearly £3.9 million, per MegaWatt (Onlinezeitung, 2016).

USA
In a publication from Washington State University, the capital cost of different AD systems was contrasted with the operating costs of those systems. This analysis is summarised in Table 3. Using this data, the average Combined Heat and Power (CHP) AD system has a capital cost of $4.4 million, or roughly £3.3 million (Galinato, et al., 2015).

India
There are a large number of small scale dairy farms in India, and investigations have been done into the feasibility of small scale digesters of approximately 1 m^3. These digesters have been costed to Rs 17000, which around £200 (York, et al., 2016). Larger digesters of 1 MW have also been built to run on cow dung, such as the digester at the Haibowal Dairy Complex, Ludhiana, Punjab. This digester cost Rs 136 million, approximately 14 Crore, which is equivalent to nearly £1.6 million (Dhussa, 2008), (Gill, 2013).

China
In 2009, a 3 MW anaerobic digester was built in Shandong Minhe, funded by The World Bank. The total investment was RMB 69.55 million, which is the same as £7,866,105. This works out as £2,622,035 per MW (World Bank, 2014).

The above shows that AD systems have a high capital cost no matter where in the world they are built.

4.2 Service Life

As can be seen in Table 3, the average annual capital cost is calculated from the total capital cost divided by 26 years, meaning that the sevice life has been taken as 26 years.

This is consistent with other sources, which state a design life of 20-25 years (DOE, 2013), (Weddle, 2014).

4.3 Worldwide Investment in AD Systems

UK
At the end of 2016 there were 576 AD systems in the UK, producing 708 MW of electricity. Using the figures shown above, that gives a total investment of between £1,036 million - £4,435 million, with an average of £3,363 million at £4.75M per MW (Davies, 2016).

Germany
There were approximately 8000 plants by the end of 2014 in Germany, with an electrical capacity over 3700 MW (Blumenstein, et al., 2015). This equates to £14,430 million at an average of £3.9 million per MW.

USA
In 2014 the USA had 239 anaerobic digesters on farms, which gave a capacity of 116 MW. There were 1,241 wastewater treatment plants using an anaerobic digester and 636 landfill gas projects, totalling over 2000 plants (American Biogas Council, 2014), (US EPA, OAR,OAP, 2017). This gives approximately 970 MW. Assuming £3.3 million per MW, this is an investment of £3,201 million.

India
For India, estimating the total power production is more difficult, as AD systems are primarily designed to provide a cleaner alternative fuel for cooking applications in households. However, in 2010, Dr. A.R. Shukla, an adviser on bio-energy for the Ministry of New and Renewable Energy, reports that there was 91.55 MW of electrical capacity from anaerobic digestion (Shukla, 2010). Only 6% of the total biogas production was used to create electricity, therefore the total electricity production possible in 2010 was

Table 3. Average annual capital and operating costs of an AD project under different system configurations (Galinato, et al., 2015)

AD Project	Capital cost	Operating cost	Operating cost—Capital cost ratio
AD-Combined heat and power (baseline project)	$169,231	$283,270	1.67
AD-Boiler	$169,231	$33,000	0.2
AD-Renewable natural gas	$377,901	$293,706	0.78

1,525 MW, which equals £2,440 million at £1.6 million per MW.

China

Like India, AD systems are normally installed as small family sized digesters. In 2008, there were 30.5 million household digesters, accounting for roughly 1.2% of the rural household energy use (Gregory, 2010). The 15th IWA World Conference on Anaerobic Digestion (AD-15) was held in Beijing this year, where it was stated that china has become the world's largest AD market (REN, *et al.*, 2017).

Taking all this into consideration, it is evident that AD systems have accumulated a significant investment worldwide.

5.0 IMPROVING FEASABILITY OF AD SYSTEMS

The cost of electricity from major renewables, such as solar and wind, has been falling year on year and has recently become cheaper than fossil fuels (Cunningham, 2017). The biggest advantage of anaerobic digestion over wind and solar is consistency. As long as the digester is supplied with feedstock, it will run itself, independent of daylight or wind speed. However, the cost of electricity from anaerobic digestion has remained relatively stable, as Figure 2 shows. The cost of electricity from AD is affected by a combination of factors, such as the price of the feedstock, lack of improvement in the efficiency of the systems and the larger amount of infrastructure required to run the system compared to other renewables, which leads to high capital and maintenance costs. Maintenance of the feed hoppers, structure, generators, control systems and mobile plant all contribute to the running cost of AD systems. In order to keep AD competitive in the energy market, costs associated with the systems must be reduced. One area of improvement will rely on a better understanding of the process from start to finish, leading to better designs with less maintenance and/or longer life spans, which will help towards making AD systems more efficient.

The environment created at each step in the process of AD, as shown by Fig. 1 previously, is still not fully understood. Many of the chemical and biological factors are not considered by current building standards (Voegel, *et al.*, 2016).

Characterisation of the feedstock is the next area of development that is needed (Hagos, *et al.*, 2017), (Jha & Schmidt, 2017), (Li, *et al.*, 2017). Once feedstock can be reliably characterised, the biological processes can be accurately predicted, and the environment the biological processes will produce can be better defined. This means that the environment, including chemical composition, temperature and applied stresses, can be classified and used to design more durable concrete infrastructure that can give anaerobic digesters a longer service life and reduced maintenance costs.

6.0 CONCLUSIONS

AD is a complex process, that has great potential for both environmental and economic benefits. The major conclusions of this review are:

- AD can play a vital role in closing the loop of the circular economy by recovering energy from a major waste stream and reducing landfill intake.
- Significant investment has been made into AD worldwide, for both its environmental and economic benefits.
- In order to keep AD systems competitive, improvements must be made. Part of this will take the form of better characterisation of the whole process, leading to more durable designs of these systems.

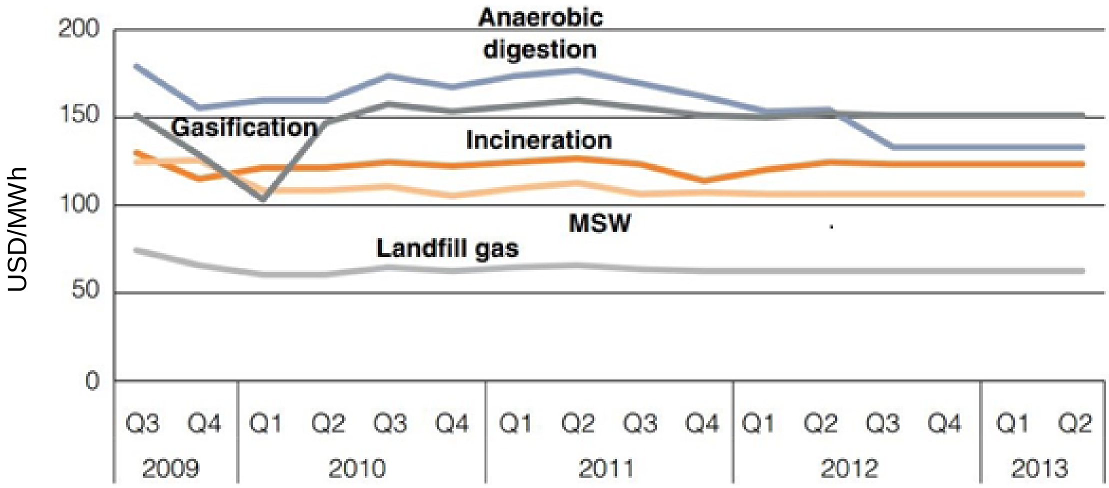

Fig. 2. Levelised cost of biomass electricity over time, developed market average **-** Abstract from World Energy Perspective Cost of Energy Technologies (World Energy Council, 2013)

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