Chapter 12

Anaerobic Digestion Enhancement With Microbial Electrolysis Cells:

Is Biomethane Production the Direction to Go for Commercialization?

Ellie Vipond
Teesside University, UK

Pattanathu K.S.M. Rahman
Teesside University, UK

ABSTRACT

The engineering of replacements for crude oil is a priority within industrial biotechnology. Biogas, produced by anaerobic digestion (AD) during organic waste degradation, has been used for electricity generation and heating. Microbial electrolysis cells (MECs) are an emerging technology which when combined with AD can produce higher yields of such energy whilst simultaneously treating waste water and sludge. MECs are bioelectrochemical systems which utilize the metabolism of microbes to oxidize organics. The majority of the research has been focused on biohydrogen production, despite associated issues, which has resulted in poor commercialization prospects. Consequently, scientists are now suggesting that methane production should be the focus of MEC technology. This chapter presents lab research on the bioprocessing of biomethane using AD and MECs and addresses important issues, namely the lack of pilot-scale studies. Downstream processing techniques are discussed, as well as a novel suggestion of further utilising MECs in the purification process.

DOI: 10.4018/978-1-5225-3540-9.ch012

INTRODUCTION

The heavy use of fossil fuels has resulted in a global energy crisis which has provided an incentive for researchers to find sustainable alternatives to meet modern-day society's demands. It has been estimated that current treatment of municipal waste water accounts for approximately 3% of global electricity consumption (Li et al., 2014). Waste water contains significant amounts of energy e.g. domestic waste water contains 7.6 kJ L^{-1} (Heidrich & Dolfing, 2011). Harnessing the energy contained in these dissolved organics would mitigate the burdens associated with treatment, whilst simultaneously producing renewable fuels. The use of novel bio-technologies is allowing for this energy capture, which has caused a shift in what was traditionally classified as waste. Anaerobic digestion (AD) is a popular technology used to extract bio-energy in the form of biogas during the microbial conversion of organic substrates (Bharathiraja et al., 2016) e.g. high strength waste water and sludges. Unfortunately, there are several bottlenecks to AD technology application such as slow metabolism of methanogens and accumulation of inhibitory volatile fatty acids (VFAs) (Zhang et al., 2009). This combined with the fact that AD can be energy expensive, makes it apparent that more efficient bio-catalytic routes need to be developed which convert organic waste into green fuels.

Over the past decade, bioelectrochemical systems (BSEs) have been gaining speed as a new generation of technologies which show great potential for waste treatment whilst generating hydrogen or methane. A form of these advancements called Microbial Electrolysis Cells (MECs) has been studied as a hopeful candidate to improve gas energy production. The objective of this chapter is to discuss MEC assisted methane production as well as what needs further investigation if MECs are to achieve commercialization.

Background

MECs utilize exoelectrogenic microbes to oxidize organic waste substrates which transfer the electrons to the anode. The electrons are then transferred to the cathode where they can reduce protons for hydrogen production, or produce methane via several pathways (Lu & Ren, 2016). A small external voltage is required between the electrodes to overcome the thermodynamic barrier, which can be supplied by microbial fuel cells. It is apparent that research into hydrogen production using MECs has been prioritised. Hydrogen makes an ideal fuel due to being carbon free and having high energy content (Zhang & Angelidaki, 2014). However, the production of hydrogen presents numerous challenges that prohibit upscaling and commercialization. This was demonstrated in the largest MEC reactor reported to date. After 43 days, methanogenisis led to H_2 consumption, and consequently methane became the dominant product (Cusick et al., 2011). Methane is relatively safer than hydrogen for storage, and most importantly, its production has been demonstrated to be more robust and consistent (Clauwaert & Verstraete, 2008). Moreover, the incorporation of MECs into traditional AD systems is proving to be an extremely hopeful technology. All of this suggests that methane production should be at the forefront of MEC research.

BIOMETHANE BIOPROCESSING

Microorganisms

Commonly in bioprocessing, analysis and optimization of microbes occurs prior to production. However in this case, molecular techniques are employed afterwards to determine the bacterial dynamics involved. The main species responsible for methane formation belong to *Geobacter* and methanogenic archaea. Figure 1 demonstrates the current consensus on the various catalytic pathways. *Geobacter* sp. adapt to grow with electrodes and have a key role in stimulating electron transfer from organic matters to the anode, giving a higher current density (Yin et al., 2016; Zhao et al., 2015). Generally, CO_2 reduction to methane is processed via hydrogenotrophic methanogens in sequential pathways which first requires the formation of hydrogen (Figure 1) (Bo et al., 2014). It was then discovered that exoelectrogenic methanogens have the ability to produce methane from CO_2 reduction by using the cathode as a direct electron donor (electromethanogenesis) (Cheng et al., 2009). Albeit, current density readings of a MEC reactor indicated that the methane production via this cathodic reduction only accounted for 6.3% of the increment (Zhao et al., 2016). The enhancement of sludge decomposition and methane production in this work was shown to be a result of direct interspecies electron transfer (DIET). This is a syntrophic interaction (Figure 1) recently observed between *Geobacter* sp. (*G. metallireducens*) and methanogens (*Methanosaeta* and *Methanosarcina* sp.), which are highly abundant in AD systems. These interactions provide efficiency in methane production as *Methanosarcina* can utilize two pathways in AD-MEC reactors: hydrogen interspecies transfer (HIT) and DIET (Yin et al., 2016). In addition, DIET in the presence of conductive material did not require electrically conductive pili or outer surface C-type cytochromes (Zhao et al., 2016). This offers an ecological advantage for users as investments in DIET can be reduced.

Figure 1. The steps involved in the sequential break-down of organic waste by bacteria in anaerobic digestion. Acetate (acetic acid) is central to the process as it directly feeds into methanogenisis. Abbreviations in Figure 1: VFA (Volatile fatty acids) DIET (Direct interspecies electron transfer)

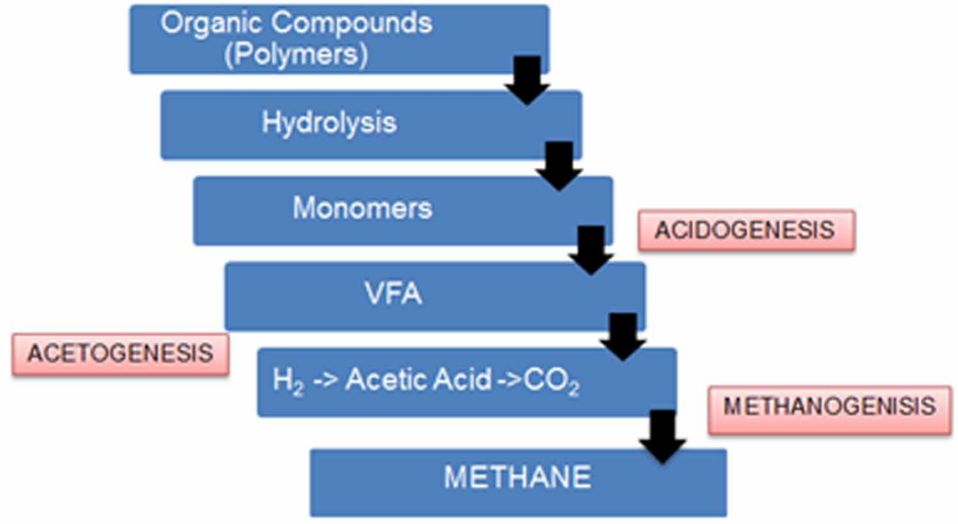
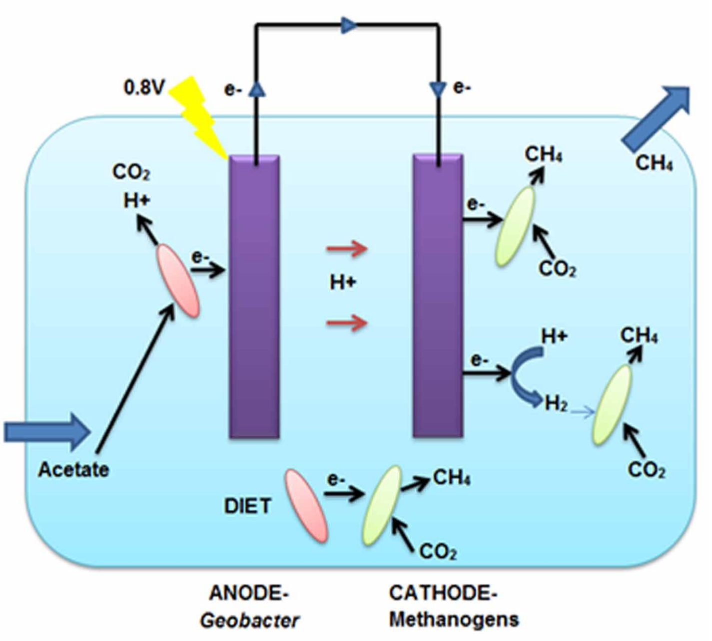


Figure 2. A typical MEC cell with the various pathways of bacterial methane production presented.



Substrates

Due to its application niche, MEC studies are predominantly based on the use of WASTE WATER or sludge as the substrate. Table 1 presents some typical substrates that have been tested in different reactors under varying parameters. The biodegradability of sludge and waste water can be characterised using the following measurements- total and volatile suspended solids, chemical oxygen demand (COD) and total: carbohydrate, protein and short-chain fatty acids (mg COD/L) (Zhao et al., 2016). Additionally, Figure 1 demonstrates how these are eventually deduced to methane by bacteria. A lot of studies use specified amounts of simple substrate e.g. acetate which allows the researchers to control substrate composition (Xafenias & Mapelli, 2014). Yin et al. (2016) achieved one of the highest methane yields (360.2 mL/g-COD), which was able to compete with the maximum yield in an anaerobic digester (370.0 mL/g-COD), by feeding with acetate for 3 months. Gajaraj, Huang et al. (2017) compared glucose (1000 mg/L) and waste activated sludge (WAS) as substrates in batch-digestion experiments. They found that when sludge was used as the substrate, the digesters showed longer time intervals for volatile fatty acid (VFA) production and degradation, due to the sludge complexity. These studies highlight the fact that studies utilising unconventional substrates are needed to assess the real-world potential of this technology and improve MEC performance.

Operating Parameters

One of the advantages of utilising MECs for methane production is the process which occurs at ambient temperatures (Table 1), thereby saving energy. Heidrich et al. (2014) found their large-scale MEC functioned to produce hydrogen in North East England at water temperature 1-5 °C. However, metha-

Table 1. Production rates of methane achieved with various microbial electrolysis cell (MEC) reactor designs and operating parameters

MEC Configuration	Substrate	Voltage (V)	Temperature (˚C)	Production Rate	Source
Single chamber	Synthetic Media Waste water	1.0 1.0	21 ± 2 21 ± 2	8.0 ± 0.2 mL-CH_4 Lr^{-1} d^{-1} 1.4 ± 0.3 mL-CH_4 Lr^{-1} d^{-1}	(Moreno et al., 2016)
Two chambers	Acetate	0.2	24 ± 2	0.28 L/L d	(Villano et al., 2013)
Single Chamber	Waste activated sludge	0.6	35 ± 1	0.020 ± 0.002 L CH4 L^{-1} day^{-1}	(Gajaraj et al., 2017)
Two chambers	Acetate	0.5	24	0.018 L L^{-1} d^{-1}	(Villano et al., 2011)
Single chamber	Acetate	1.0	25 ± 2	360.2 mL/g-COD	(Yin et al., 2016)
Single chamber	Raw sludge	0.3	35	170.2 L/kg-VSS	(Feng et al., 2015)
Single Chamber	Acetate	0.8	22	0.17-0.75 L L^{-1} d^{-1}	See (Villano et al., 2011)
Single Chamber	Acetate	0.9	30	0.12 L L^{-1} d^{-1}	(Rader, & Logan, 2010)

nogenic wastewater treatment systems are limited by low temperatures (Bowen et al., 2014). One theory to overcome this is to use a seed from low temperature environments or use the autochthonous bacteria present (Heidrich et al., 2014; Jadhav, & Ghangrekar, 2009).

Changes in pH can occur throughout the AD procedure, typically associated with the accumulation of VFAs in acetogenesis. There are no major reports of pH controls being set in place for MEC reactors as small fluctuations are usually short-lived if the reactor design is functional. Gajaraj et al. (2017) found there was a decrease in pH (8.0 to 7.1) in all digesters during the first 24 h of AD, which recovered due to the rapid consumption of VFAs.

Applied voltage affects the activities of microorganisms in MEC and hence impacts methane generation. The right voltage application improves MEC performance compared to the presence of conductive material alone. Zhao et al. (2016) showed that carbon felt could improve methanogenisis as compared to control however, adding a small voltage (0.6 V) improved this further (32%). Ding et al. (2016) suggested the optimum voltage to operate a MEC to treat waste water is 0.8 V. They reported excessive voltages (1.0 and 2.0 V) decreased COD removal efficiency and methane yield due to higher plasmatorrhexis and lower growth and metabolism.

Electrodes, Membranes and Reactor Configurations

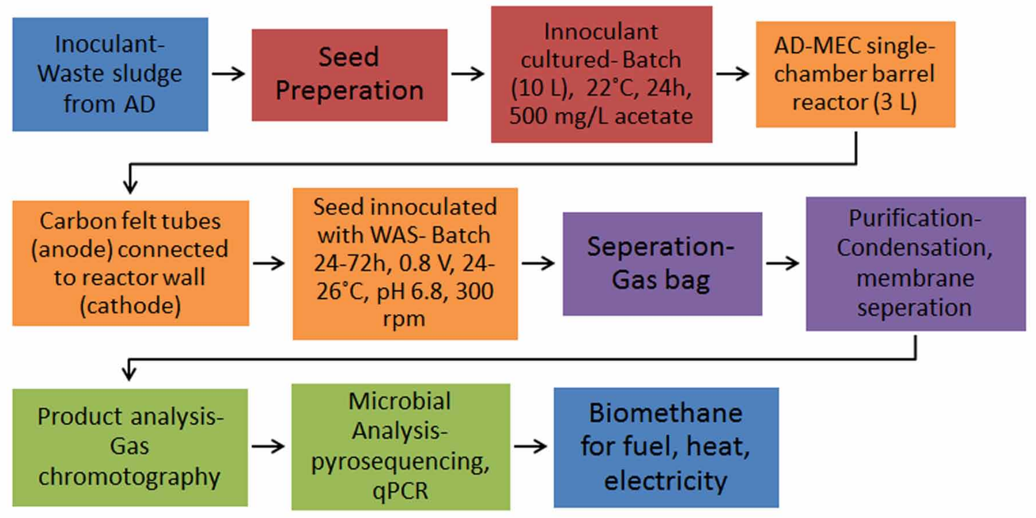
For upscaling the above should allow high conductivity leading to efficiency and controlled internal resistance. They should possess biological and physio/chemical stability e.g. with stand corrosion. In addition they must be economically viable which involves using less expensive materials (Escapa et al., 2016). Carbon-based materials e.g. carbon felt and graphite granules meet many of these requirements and this has made them a popular electrode material (Zhao et al., 2016; Villano et al., 2011). Microbial biocathodes have received attention as cheaper, self-regenerating and sustainable alternative to abiotic cathodes. The bacteria here act as catalytic agents, functioning via aforementioned pathways. Using a hydrogenotrophic methanogenic culture as the biocathode has proven to reduce CO_2 to methane, at coulombic efficiencies exceeding 80% (Villano et al., 2010).

Downstream Processing

Most lab scale studies report collection of methane through gas bags. This can then be analysed by using gas chromatography techniques e.g. two-channel gas chromatographer (Xafenias, & Mapelli, 2014). Although not always needed, the techniques for biomethane purification produced in this way will be homologous to those used for biogas purification. Removal of water can be achieved through physical (condensation) or chemical (adsorption, absorption) drying. For CO_2 removal absorption with water or polyethylene glycol, PSA (e.g. carbon molecular sieves) and membrane technology are in operation on a large-scale (Ryckebosch et al., 2011). Recently, swollen polyamide thin-film composite membranes were proposed for effective CO_2/CH_4 separation, based on the higher solubility of CO_2 in water as compared to that of methane (Simcik et al., 2016). The type of technique that is implemented must be an economically relevant choice that maintains methane yield. In Sweden, water scrubbers are used mostly where as in the Netherlands they also use PSA-units and membrane technology (Ryckebosch et al., 2011). Figure 3 depicts a process flow diagram of the upstream and downstream processes involved in the production of biomethane.

Other researchers have used continuous modes of operation. A higher HRT with continuous mode resulted in a better chemical oxygen demand removal. Despite this, a significant amount of the acetate consumed was not converted to electricity. This was most likely due to the presence of acetoclastic microorganisms that consume acetate for non-electrogenic methane production (Moreno et al., 2016). Other researchers have used semi-batch mode in a two chamber MEC where retention times can be up to 72 days (Villano et al., 2013).

Figure 3. A process flow diagram for the production of biomethane in batch mode using microbial electrolysis cell (MEC) and anaerobic digestion (AD) technology. Abbreviations:HRT (Hydraulic retention time), WAS (Waste activated sludge, AD (Anaerobic Digestion), MEC (Microbial Electrolysis Cell).



SOLUTIONS AND RECOMMENDATIONS

Several reactor designs have been put forward each bearing strengths and limitations, as previously discussed. Another design, the MEC coupled baffled reactor, represents an innovative configuration which can produce both hydrogen and methane. Ran et al., (2014) showed the level of efficiency this system can achieve. In the first compartment 20.7% proportion of hydrogen was generated. The anaerobic intermediate metabolites formed the substrates for the last three continuous MECs, which achieved up to 98.8% proportion of methane and a 98.8% COD removal rate.

Furthermore, originally in MEC design the anode and cathode were separated usually using an ion exchange membrane (IEM). This offered advantages such as protecting the methanogenic consortia against inhibitory compounds (Villano et al., 2010). However, IEMs can also increase internal resistance by reducing charge circulation (Escapa et al, 2016) and DIET. More recent studies are moving towards designs that couple AD and MEC in single-chamber (Yin et al, 2016). These membraneless reactors are more economically feasible and have shown successful results e.g. CH_4 content >98% was achieved when this design was used (Bo et al, 2014).

The biggest limitation of this technology is the lack of pilot-scale studies or research into "real-world" scenarios. At present, most lab studies are conducted using acetate in a 10–100 mL reactor with many papers not stating the duration of experiments. Clearly research has a long way to go before the MEC can meet its potential as a full-scale waste treatment/methane producing technology. This will involve treating complex waste with indigenous populations, operating throughout yearly temperatures and working at industrial scales (Heidrich et al, 2014). To also bridge the gap between lab-scale and commercial development, improved data reporting and standardised methods of characterising MECs are required (Escapa et al., 2016).

FUTURE RESEARCH DIRECTIONS

One of the main challenges involves gaining a better understanding of the syntrophic and competitive interactions amongst specified microbial groups. This will allow methods for promoting beneficial interactions or minimizing energy losses to be developed for system scale up. Research is expanding in the area of synthetic microbial consortia (SMC) for bioprocessing, which is particularly interested in biofilms (Shong et al., 2012). The authors therefore suggest that MEC and SMC technologies should be brought together. The reasons being, MECs operate on the basis of biofilms and synthetic biology research involves developing metabolic models that can predict community behaviour and synergy between organisms.

In terms of downstream processing, a method of biogas purification known as biological methane enrichment (BME) is not yet operated on a large scale. Strevett et al. (1995) investigated the mechanism and kinetics of this 'chemo-autotrophic biogas upgrading'. Different methanogens, using only CO_2 as a carbon source and H_2 as an energy source, were examined. When a synthetic biogas of ~50% CH_4, ~40% CO_2 and 1-2% H_2S was mixed with H_2 and fed to the organisms, it was found the biological system could effectively remove CO_2, while approximately doubling the original CH_4 mass (Strevett et al., 1995).

This was due to methanogens exhibiting methanogenisis and conversion of CO_2 by pathways already detailed. There are noticeable similarities between this, as a purification technique, and the production of methane in MECs. It is therefore justifiable to suggest that MEC technology could also be used as a purification strategy to purify methane produced in AD-MEC reactors. As usual, the voltage would be used to promote oxidation of the electrode by exoelectrogens. This would then promote the formation of methane by hydrogenotrophic methanogens, which would utilise the H_2 energy source, as well as the direct reduction of the CO_2 carbon source. Hence in theory with a real biogas mixture this would remove the CO_2 contaminants whilst increasing the CH_4 yield further, as observed in BME.

CONCLUSION

BESs have shown promise as being a robust, economically viable and environmentally friendly way to produce renewable energy. Methane-producing MECs should be recognised as suitable alternatives to hydrogen-producing MECs. Designs which combine both methane and hydrogen production are also an option as seen in the baffled reactor and BME. Notwithstanding, there is much more research to be done if this technology is to be taken seriously as a suitable way of producing replacements for fossil fuel derivatives. Before commercialization can occur, large scale pilot studies must be carried out to confirm real-world applications as well as further molecular analysis of the complex microbial interactions involved. MECs are not likely to replace conventional AD, due to being more favorable for low-strength waste streams. Despite this AD and MECs, which were once considered competing technologies, are showing great promise when combined. In addition, this is a relatively new technology and in future years it is likely MECs will be an additional tool for scientists faced with tackling the energy crisis.

REFERENCES

Bharathiraja, B., Sudharsanaa, T., Bharghavi, A., Jayamuthunagai, J., & Praveenkumar, R. (2016). Biohydrogen and Biogas – An overview on feedstocks and enhancement process. *Fuel*, *185*, 810–828. doi:10.1016/j.fuel.2016.08.030

Bo, T., Zhu, X., Zhang, L., Tao, Y., He, X., Li, D., & Yan, Z. (2014). A new upgraded biogas production process: Coupling microbial electrolysis cell and anaerobic digestion in single-chamber, barrel-shape stainless steel reactor. *Electrochemistry Communications*, *45*, 67–70. doi:10.1016/j.elecom.2014.05.026

Bowen, E., Dolfing, J., Davenport, R., Read, F., & Curtis, T. (2014). Low-temperature limitation of bioreactor sludge in anaerobic treatment of domestic wastewater. *Water Science and Technology*, *69*(5), 1004. doi:10.2166/wst.2013.821 PMID:24622549

Cheng, S., Xing, D., Call, D., & Logan, B. (2009). Direct Biological Conversion of Electrical Current into Methane by Electromethanogenesis. *Environmental Science & Technology*, *43*(10), 3953–3958. doi:10.1021/es803531g PMID:19544913

Clauwaert, P., & Verstraete, W. (2008). Methanogenesis in membraneless microbial electrolysis cells. *Applied Microbiology and Biotechnology*, *82*(5), 829–836. doi:10.100700253-008-1796-4 PMID:19050859

Cusick, R., Bryan, B., Parker, D., Merrill, M., Mehanna, M., Kiely, P., ... Logan, B. E. (2011). Performance of a pilot-scale continuous flow microbial electrolysis cell fed winery wastewater. *Applied Microbiology and Biotechnology*, *89*(6), 2053–2063. doi:10.100700253-011-3130-9 PMID:21305277

Ding, A., Yang, Y., Sun, G., & Wu, D. (2016). Impact of applied voltage on methane generation and microbial activities in an anaerobic microbial electrolysis cell (MEC). *Chemical Engineering Journal*, *283*, 260–265. doi:10.1016/j.cej.2015.07.054

Du, Z., Li, H., & Gu, T. (2007). A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy. *Biotechnology Advances*, *25*(5), 464–482. doi:10.1016/j.biotechadv.2007.05.004 PMID:17582720

Escapa, A., Mateos, R., Martínez, E., & Blanes, J. (2016). Microbial electrolysis cells: An emerging technology for wastewater treatment and energy recovery. From laboratory to pilot plant and beyond. *Renewable & Sustainable Energy Reviews*, *55*, 942–956. doi:10.1016/j.rser.2015.11.029

Feng, Y., Zhang, Y., Chen, S., & Quan, X. (2015). Enhanced production of methane from waste activated sludge by the combination of high-solid anaerobic digestion and microbial electrolysis cell with iron–graphite electrode. *Chemical Engineering Journal*, *259*, 787–794. doi:10.1016/j.cej.2014.08.048

Gajaraj, S., Huang, Y., Zheng, P., & Hu, Z. (2017). Methane production improvement and associated methanogenic assemblages in bioelectrochemically assisted anaerobic digestion. *Biochemical Engineering Journal*, *117*, 105–112. doi:10.1016/j.bej.2016.11.003

Heidrich, E., Curtis, T., & Dolfing, J. (2011). Determination of the Internal Chemical Energy of Wastewater. *Environmental Science & Technology*, *45*(2), 827–832. doi:10.1021/es103058w PMID:21142001

Heidrich, E., Edwards, S., Dolfing, J., Cotterill, S., & Curtis, T. (2014). Performance of a pilot scale microbial electrolysis cell fed on domestic wastewater at ambient temperatures for a 12month period. *Bioresource Technology*, *173*, 87–95. doi:10.1016/j.biortech.2014.09.083 PMID:25285764

Jadhav, G., & Ghangrekar, M. (2009). Performance of microbial fuel cell subjected to variation in pH, temperature, external load and substrate concentration. *Bioresource Technology*, *100*(2), 717–723. doi:10.1016/j.biortech.2008.07.041 PMID:18768312

Li, X., Liang, D., Bai, Y., Fan, Y., & Hou, H. (2014). Enhanced H2 production from corn stalk by integrating dark fermentation and single chamber microbial electrolysis cells with double anode arrangement. *International Journal of Hydrogen Energy*, *39*(17), 8977–8982. doi:10.1016/j.ijhydene.2014.03.065

Lu, L., & Ren, Z. (2016). Microbial electrolysis cells for waste biorefinery: A state of the art review. *Bioresource Technology*, *215*, 254–264. doi:10.1016/j.biortech.2016.03.034 PMID:27020129

Moreno, R., San-Martín, M., Escapa, A., & Morán, A. (2016). Domestic wastewater treatment in parallel with methane production in a microbial electrolysis cell. *Renewable Energy*, *93*, 442–448. doi:10.1016/j.renene.2016.02.083

Rader, G., & Logan, B. (2010). Multi-electrode continuous flow microbial electrolysis cell for biogas production from acetate. *International Journal of Hydrogen Energy*, *35*(17), 8848–8854. doi:10.1016/j.ijhydene.2010.06.033

Ran, Z., Gefu, Z., Kumar, J., Chaoxiang, L., Xu, H., & Lin, L. (2014). Hydrogen and methane production in a bio-electrochemical system assisted anaerobic baffled reactor. *International Journal of Hydrogen Energy*, *39*(25), 13498–13504. doi:10.1016/j.ijhydene.2014.02.086

Ryckebosch, E., Drouillon, M., & Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. *Biomass and Bioenergy*, *35*(5), 1633–1645. doi:10.1016/j.biombioe.2011.02.033

Shong, J., Jimenez Diaz, M., & Collins, C. (2012). Towards synthetic microbial consortia for bioprocessing. *Current Opinion in Biotechnology*, *23*(5), 798–802. doi:10.1016/j.copbio.2012.02.001 PMID:22387100

Simcik, M., Ruzicka, M., Karaszova, M., Sedlakova, Z., Vejrazka, J., Vesely, M., ... Izak, P. (2016). Polyamide thin-film composite membranes for potential raw biogas purification: Experiments and modeling. *Separation and Purification Technology*, *167*, 163–173. doi:10.1016/j.seppur.2016.05.008

Strevett, K., Vieth, R., & Grasso, D. (1995). Chemo-autotrophic biogas purification for methane enrichment: Mechanism and kinetics. *The Chemical Engineering Journal and the Biochemical Engineering Journal*, *58*(1), 71–79. doi:10.1016/0923-0467(95)06095-2

Villano, M., Aulenta, F., Beccari, M., & Majone, M. (2010). Microbial generation of H_2 or CH_4 coupled to wastewater treatment in bioelectrochemical systems. *Chemical Engineering Transactions*, *20*, 163–168. doi:10.3303/CET1020028

Villano, M., Monaco, G., Aulenta, F., & Majone, M. (2011). Electrochemically assisted methane production in a biofilm reactor. *Journal of Power Sources*, *196*(22), 9467–9472. doi:10.1016/j.jpowsour.2011.07.016

Villano, M., Scardala, S., Aulenta, F., & Majone, M. (2013). Carbon and nitrogen removal and enhanced methane production in a microbial electrolysis cell. *Bioresource Technology*, *130*, 366–371. doi:10.1016/j.biortech.2012.11.080 PMID:23313682

Xafenias, N., & Mapelli, V. (2014). Performance and bacterial enrichment of bioelectrochemical systems during methane and acetate production. *International Journal of Hydrogen Energy*, *39*(36), 21864–21875. doi:10.1016/j.ijhydene.2014.05.038

Yin, Q., Zhu, X., Zhan, G., Bo, T., Yang, Y., Tao, Y., ... Yan, Z. (2016). Enhanced methane production in an anaerobic digestion and microbial electrolysis cell coupled system with co-cultivation of *Geobacte*r and *Methanosarcina. Journal of Environmental Sciences (China)*, *42*, 210–214. doi:10.1016/j.jes.2015.07.006 PMID:27090713

Zhang, P., Chen, Y., & Zhou, Q. (2009). Waste activated sludge hydrolysis and short-chain fatty acids accumulation under mesophilic and thermophilic conditions: Effect of pH. *Water Research*, *43*(15), 3735–3742. doi:10.1016/j.watres.2009.05.036 PMID:19555988

Zhang, Y., & Angelidaki, I. (2014). Microbial electrolysis cells turning to be versatile technology: Recent advances and future challenges. *Water Research*, *56*, 11–25. doi:10.1016/j.watres.2014.02.031 PMID:24631941

Zhao, Z., Zhang, Y., Quan, X., & Zhao, H. (2016). Evaluation on direct interspecies electron transfer in anaerobic sludge digestion of microbial electrolysis cell. *Bioresource Technology*, *200*, 235–244. doi:10.1016/j.biortech.2015.10.021 PMID:26492177

Zhao, Z., Zhang, Y., Wang, L., & Quan, X. (2015). Potential for direct interspecies electron transfer in an electric-anaerobic system to increase methane production from sludge digestion. *Scientific Reports*, *5*(1), 11094. doi:10.1038rep11094 PMID:26057581

KEY TERMS AND DEFINITIONS

Anaerobic Digestion: A sequence of biological processes in which microorganisms break down organic material under hypoxic conditions. One of the metabolic end products is biogas.

Biocathode: In microbial electrolysis cells the cathode is the 'electron sink', meaning it accepts electrons and protons produced from the anodic oxidation of the substrate. A bio-cathode utilises microorganisms for this catalytic purpose.

Bioelectrochemical Systems (BESs): Systems which harness the metabolisms of microbes to convert chemical energy into electrical energy e.g. Microbial Electrolysis Cell and Microbial Fuel Cell.

Direct Interspecies Electron Transfer (DIET): DIET is a syntrophic interaction that occurs in methanogenic communities. Free electrons are transferred directly from one microbial cell to another rather than being shuttled by reduced molecules such as hydrogen.

Downstream Processing: The later stages of bioprocessing namely recovery and purification of biosynthetic products.

Energy Crisis: This is an ongoing global issue that is concerned with the fact that natural resources (fossil fuels), used to power industrial society, are diminishing and the demand for them continues to rise. Suitable renewable replacements must be sought which is the aim of industrial biotechnology.

Exoelectrogen: Bacteria which can transfer electrons extracellularly e.g. *Geobacter* species.

Methanogen: Microorganisms that produce methane as a metabolic by product under anaerobic conditions.

Sludge: Sludge is semi-solid slurry and can be produced as part of numerous industrial processes. For example, sewage sludge refers to the residual material that is produced as a by-product during sewage treatment of wastewater. The term activated sludge refers to suspended sludge containing many active bacteria, which remove biodegradable substances from wastewater or waste activated sludge (WAS). WAS refers to excess sludge produced in an activated sludge system which must be processed in a further treatment chain.