

Anaerobic Digestion and the Circular Economy

A Systemic Approach to the Circulation of Resources

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INTRODUCTION

A 'systemic approach' to the concept of a circular economy is essential, as it aims to consider the interactions and dependencies of every contributing factor in the production process rather than treating each one as a separate entity.

Global initiatives are being developed which emulate this continual circulation of resources and, as a result, there has been growing interest towards the benefits of anaerobic digestion (AD) over the last few years.

AD technologies make use of natural biochemical conversion processes contained in an engineered environment. As such, AD accelerates natural cycles from small to large scale using a wide variety of substrates such as organically polluted industrial wastewaters (van Lier et al, 2015), municipal/domestic sewage (Chernicharo et al, 2019), excess sludges, manure and agro-wastes. Application of AD in the industrial setting contributes to the recovery of (biochemical) energy and other resources, including carbon and nutrients.

The goal of this review paper is to outline challenges and opportunities for researchers and practitioners in supporting a circular economy, including resource recovery, waste treatment, as well as promoting and encouraging a wider role for anaerobic digestion technologies in a more diverse range of applications.

Keywords: Anaerobic Digestion, Resource Recovery, Circular Economy, Nutrient Recovery, Renewable Energy, Biogas, Biochemicals And Bioenergy, Biopolymers, Biohydrogen.

MAJOR EMERGING THEMES IN ANAEROBIC DIGESTION

The main *paradigm shift* in the past few years concerning anaerobic digestion is that the technology is no longer seen as a "waste treatment" technology. Instead it is seen as a fundamental enabler of the envisaged "circular economy" through resource recovery, including energy, safe water and nutrients, from valuable by-products of industries, municipalities and agro-industrial settings.

In this context, some of the highlights in the AD field in recent years included the development of microbial ecology for resource recovery with anaerobic digestion (van Loosdrecht, 2019) and solid-state anaerobic digestion of mixed organic waste (Nigel *et al.*, 2019). Another innovative and promising development area is the production of non-animal protein and hydrogen using AD as a core process, helping to simultaneously address sustainability and aspects of food security (Verstraete, 2019).

In the area of environmental protection considerable progress is made in biodegradation of microplastics in thermophilic anaerobic digesters (Nielsen *et al.*, 2019) and the improved degradation of pharmaceutical compounds (Martins, M. *et al.* 2018).

Considering the variety of applications covered by anaerobic digestion, there are several research opportunities which, when followed by successful field applications, will ultimately result in a higher level of sustainability across industries. AD gives a "second life" to materials that would otherwise be considered waste, i.e. giving them value when they would have had none.

The result of using previously unwanted waste or wastewater provides a source of renewable energy in the form of biogas and organic fertiliser made from a veritable

non-fossil-fuelled production method. In order to allow anaerobic digestion to meet its full potential, we must have a process which encourages the redirection from “waste to landfill” to “waste to re-use”.

CIRCULAR ECONOMY AND RESOURCE RECOVERY VIA ANAEROBIC PROCESSES

Biogas can be considered a central pillar of resource recovery and the circular economy. Biogas is an energy carrier, and can be stored, potentially serving as a battery. Biogas can also be produced in many ways and from many different substrates, with different targets in gas quality. In addition, the contribution of biogas production to GHG emission reduction can be significant, provided biogas does not escape to the atmosphere.

In municipal wastewater treatment, AD processes play a crucial role for attaining energy neutrality in these systems, requiring further insight in the excess sludge conversion potential (Gonzalez et al., 2018).

AD applications combine the production of renewable energy with the stabilisation or mineralisation of organic waste, production of biofertilisers, minimisation of greenhouse gas emissions in agriculture, and the energy-efficient protection of surface water, ground waters, and aquifers.

The multifunctionality of the AD concept is its clearest strength. Sustainable biogas systems include processes for the treatment of residual streams (waste) for the protection of our environment, the conversion of low-value material to higher-value material, and the production of electricity, heat and/or advanced gaseous biofuel. (Fagerström et al. 2018)

AD also contributes to improved nutrient up-take efficiency in agriculture by replacing synthetic, fossil fuel-based fertilisers with biofertiliser products. Biogas can contribute to decentralised energy security through a transition to a bio-based renewable energy production system, better balancing the localised energy supply (Pabón-Pereira et al, 2019).

AD sustainably contributes to process organic waste streams across the entire food supply chain. What was previously considered waste and a liability is instead included in a production cycle where organic material and nutrients are returned to the soil to replace chemical fertilisers.

In an increasing number of AD applications, the produced biogas is upgraded to biogenic methane for vehicle fuel or as a natural gas substitute in gas-grid systems. Therefore, AD can be considered to connect decentralised biomass production to a (de)centralised gas grid.

An alternative scenario is pictured by Verbeeck *et al.* (2018), where biogas is upgraded to biomethane, injected into the existing gas grid, and used elsewhere to produce syngas. The H₂ / CO mixture is then used as feedstock for synthesis of platform chemicals and fuels. This approach could promote AD as an important driver for a future bio-based economy.

In most cases of biogas upgrading, the CO₂ is separated from the CH₄ using different types of techniques, whereafter the CO₂ is also reused for different purposes. The company Solar Foods, from Finland, is in the late stages of developing a revolutionary source of proteins, using fermentation, renewable energy and biogenic CO₂ (Vainikka, 2019). Other applications use H₂ (produced by wind energy) to reduce the biogas CO₂ to CH₄ (Angelidaki et al., Denmark), or apply increased pressures for in-situ biogas upgrading (Lindeboom et al., 2016).

MICROBIAL ELECTROCHEMICAL TECHNOLOGIES (METs)

Microbial electrochemical technologies (METs) such as microbial fuel cells (MFCs) are emerging as a promising future technology for a wide range of applications in addition to sustainable electricity generation for decentralised usage.

Electroactive (EA) biofilms produced by microorganisms are the key players in bio-electrochemical systems involving microorganism mediated electrocatalytic reactions. Therefore, genetically modifying the organism for increased production of EA biofilms and improving the extra electron transfer (EET) mechanisms may contribute to increasing the current density of an MFC.

MFCs employ the anaerobic respiration of microorganisms to convert organic materials (fuel) directly into useful electricity, which can be used to energise practical applications (Ieropoulos, 2103). At present, MFCs are not yet competitive for wastewater treatment, and the technology is under development for optimisation. However, MFC research shows interesting possibilities for product formation at the cathode side, such as hydrogen production, and reduction of CO₂ into organic products (including methane).

Recent research shows that extracellular polysaccharides (EPS) produced by the organisms attribute to both biofilm formation and electron transfer (Angelaalincy, 2018). The

integration of AD embedded in a microbial electrolysis cell (MEC) with an electromethanogenic biocathode results in increased stability and robustness of the AD process against organic and nitrogen overloads. This results in improved effluent quality and the recovery of ammonium, while at the same time the biogas is upgraded (Cerrillo *et al.* 2018).

Recent advances in microbial biotechnologies aim at converting waste materials into bioenergy and biomaterials, thus contributing to a reduction in economic dependence on fossil fuels. To valorise biomass, organic materials can be used to produce biopolymers through different microbial processes. In fact, different bacterial strains can synthesise biopolymers to convert waste materials into valuable intracellular and extracellular bioproducts, which are useful for the production of 'green' biochemicals (Pagliano *et al.* 2017).

Therefore, the development of high-performance microbial strains and the use of by-products and waste as substrates could make the production costs of 'green' biodegradable polymers comparable to those of petrochemical-derived origin. This raises the potential of creating a unique integrated system as it represents a new approach for simultaneously producing energy and biopolymers, e.g. the plastic industry, using by-products and waste as organic carbon sources.

During reductive stabilisation of organic materials, no oxygen or energy is required, and the biochemical energy is contained in the end-product. The biogas end-product is CH₄, but research shows possibilities to stop earlier in the process, e.g. producing VFA for the carboxylic acid platform.

Local conditions will determine which is most sustainable in that specific location, including offtake markets, competitive pricing of biogas compared to power and gas, waste and landfill regulations, and availability of a skilled workforce, amongst others.

BIOPROCESSING AND BIOPRODUCTION

Anaerobic digestion (AD) has to be considered in the context of the current mindsets dealing with energy, climate change and also the need for more sustainable production of chemicals and even proteins (Verstraete, 2019).

Incremental improvements in AD technology must be complemented by a set of quantum leaps, such as:

- a) harvesting the solar energy by using the inherent methanogenic capacity of deep soils;

- b) integrating decentralised biogas production in centralised bio-based petrochemistry; and

- c) opting from a strategic perspective to operate with low carbon footprint and clean technologies.

These can be achieved by combining AD with the production of clean gases, which are subsequently aerobically fermented to microbial protein. Clearly it needs to become part of a multivariant value chain, and demonstrate its potential to contribute to our transformation into a more sustainable society.

In recent years, there has been a pursuit to no longer destroy reactive nitrogen but to develop technologies to incorporate low value mineral nitrogen into protein-rich microbial biomass. The incorporation of nitrogen into microbial protein can be driven by various mechanisms such as providing organic carbon and electron donors like hydrogen and carbon monoxide.

Hydrogenotrophic microbial growth, for instance, delivers multiple benefits by incorporating ammonium, carbon dioxide, hydrogen and oxygen, thereby not only fixing carbon dioxide but also converting ammonium into valuable, protein-rich biomass in an efficient and sustainable way.

This new concept up-cycles reactive nitrogen and transforms what was considered waste into valuable products such as human food, animal feed, and organic slow-release fertiliser. The market potential for these valorisation chains are under exploration, but there is no doubt that there are substantial future opportunities.

As an example, the Finish entrepreneur and researcher Pasi Vainikka, who founded Solar Foods, presents an alternative approach, one that promises to facilitate large scale but sustainable food production of a non-animal protein (Solein) by reducing the planet's dependence on land-intensive livestock farming.

The process by which Solein is produced only requires a small fraction of the land required to produce a similar amount of beef and the modest amounts of water used can be cleaned thoroughly before being released back into the environment (Vainikka, 2019).

ADVANCED WASTEWATER TREATMENT

At present, the removal of organic micropollutants (OMPs) is one of the biggest challenges in advanced wastewater treatment, especially where direct potable reuse is being considered as part of the water supply matrix.

Biotransformation of OMPs in wastewater treatment plants ultimately depends on the enzymatic activities developed in each biological process.

Recent studies have investigated the enzymatic transformation of OMPs under anaerobic conditions (Gonzalez-Gil *et al.* 2019). These studies are unravelling biotransformation of OMPs in wastewater treatment systems, allowing for developments in the field.

Microplastics have emerged as new environmental pollutants. Biodegradation of polypropylene under thermophilic conditions was observed to be several orders higher than in any other environment investigated previously (Nielsen *et al.* 2019). The findings have shown a high potential for biodegradation of microplastics in conventional AD reactors. The results furthermore support the use of applying anaerobic digesters for the treatment of highly energetic household waste with a high content of plastics.

Biological systems aim for the highest level of efficiency to recover a maximum amount of energy, while wasting only a negligible amount of resources. Anaerobic digestion is a well-established technology for the recovery of organic carbon in the form of biogas. This is, however, a low value application.

Recovery of organic compounds as chemicals ranks higher with respect to sustainability and circular economy. Chemicals often have a higher value, which can make the recovery more interesting. In this respect the methanogenic fermentations should be halted at the level of fatty acids or alcohols from where more higher value products can be derived, whenever this is economically feasible (van Loosdrecht, 2019). This means that the ecology of fermentation processes should be better understood. The traditional approach is evaluating the microbiome and selecting the right microorganisms.

Contrary, it might be more worthwhile to select for the right metabiome. This would require a prioritising of possible outcomes; conversion instead of a specific microorganism. Recent innovative research has delved into the unravelling of the microbiome of digesters, working towards gaining a better understanding of microbial ecology aiming for better AD efficiency and biogas production capacity (Nghiem, 2019).

CONCLUSIONS

Considering the variety of applications covered by anaerobic digestion, there are several research opportunities. Successful implementation will ultimately result in an improved level of sustainability across industries. The new AD developments give ample possibilities for new businesses that strive to implement these technologies into practice.

Anaerobic digestion has secured its place as the central pillar of resource recovery and circular economy. Biogas is an energy carrier and can be stored, potentially serving as

a battery. In municipal wastewater treatment, AD processes play a crucial role for attaining energy neutrality in these systems, requiring further insight in the excess sludge conversion potential.

In addition to further processing and value add of the excess sludge (biosolids), control of nitrous emissions and others, and further developing the understanding of ecology of fermentation are areas of focused research. Next to biogas, the reductive formation of chemical building blocks or biopolymers is indeed an emerging field that may position AD more centrally in the envisaged bio-based circular economy.

Beyond wastewater treatment and energy production, findings have shown a high potential for biodegradation of microplastics and organic micropollutants in conventional AD reactors.

Anaerobic digestion is an expanding technology that offers the ideal scenario, where a continual circulation of resources can be successful in the long-term alternative to organic waste management.

This process gives a second life to materials that would otherwise be considered waste. The result of using these previously unwanted materials provides a source of renewable energy in the form of biogas, various by-products and organic fertiliser made from a genuine non-fossil-fuelled production method.

In order to allow anaerobic digestion to meet its full potential, we must have a standardisation process which encourages the redirection of “waste to landfill” to “waste to re-use”, and incentivise the use of low carbon gas sources for energy production.

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