CHEMICAL ENGINEERING TRANSACTIONS

VOL. 61, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761032

Challenges for Energy Efficiency Improvement Anaerobic Digestion (AD)

Yee Van Fan[a,*], Chew Tin Lee[b,c], Jiří Jaromír Klemeš[a]

[a]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69 Brno Czech Republic
[b]Department of Bioprocess Engineering, Faculty of Chemical and Energy Engineering Universiti Teknologi Malaysia (UTM) 81310 UTM Johor Bahru, Johor, Malaysia
[c]UTM Low Carbon Asia Research Centre, Faculty of Built Environment, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Malaysia
fan@fme.vutbr.cz

One of the major environmental issues and research challenges have been to reduce emissions and effluents without compromising the production performance. The renewable energy recovery from waste to energy is less emitting than using fossil fuels. It can compete with the other renewables if properly generated, transferred, transmitted and used. Anaerobic digestion (AD) is a potential production process to improve the security of energy supply. It also serves as a promising alternative to waste disposal. The feasibility of AD technologies for power generation has been proven in some of the technologically and agriculturally advanced countries however world-wide implementation still needs some development. Presented work focuses to overview the challenges and practices for energy efficiency improvement of AD that have been reported recently, mainly between the years of 2015 - 2016. The assessment suggests the consideration and/or attentions for substrate, pre-treatment and operation mode of digesters for a better risk minimisation and feasibility maximisation. The characteristics and supply of the substrate were suggested as the initial susceptible factor for the energy efficiency of AD. The systematic review serves as an overview of the AD development and an establishment of technically feasible technologies for further study and extended implementation.

1. Introduction

Human activities are responsible for the increase greenhouse gases (GHG) in the atmosphere. Based on the new language suggested by McDonough (2016) in highlighting that carbon can be an asset, the improper human activities create fugitive carbon. Electricity has been reported as the major source of GHG emission in many countries, including in the United States (US) (EPA, 2016). Renewable energy sources such as hydropower, wind power, biomass, geothermal power, solar power only provide 13 % of the US electricity (EIA, 2016). This suggests the demand for electricity and the urge of improving the efficiency of renewable energy for a carbon emissions positive design. Anaerobic digestion (AD) is a promising solution for waste disposal and a potential production process to improve the security of energy supply. It is capable of creating a twofold advantage to the environment through waste recycling as well as a greener source of electricity and fertiliser. The fertiliser manufacturing plants in the US was reported to release 3.26×10^7 t of GHG (an 80 % increase from 2014) (EIP, 2016). Digestate from AD process can serve as a valuable nutrient for plants after appropriate post-treatment (Vaneeckhaute et al., 2017).

AD has received increasing attention and implementation with a growing number of biogas plants, particularly in the EU region. The Czech Republic plans to provide financial support up to €19 M for biogas installation (WMW, 2016). The aim is to encourage the deployment of renewable energy installations for realising its 2020 renewable energy targets. The efforts in improving the confident of the public and investors are important to ensure the sustainability of the AD projects is not depending only on financial subsidisation. This paper presents a review of the challenges and practices (in the aspect of suitability of substrate, pre-treatment and type of digester or operation mode) for energy efficiency improvement of AD that been published in the years of 2016-

2017. The different substrate consists of different characteristics and potential biogas yield. It is important to ensure that the carbon resources (waste) end up in the right places (most suitable treatment/usage) as urges by McDonough (2016).
A big gap is reported between the theoretical yield and the actual methane production efficiency of agricultural waste as substrate (Azman et al., 2015). The low yield or underutilisation of the biomass is due to the inefficient hydrolysis of biomass. The physical (IEA Bioenergy, 2014), chemical (IEA Bioenergy, 2014), biological (Zulkifli et al., 2015), and combined (Zheng et al., 2014) technologies were used to maximise the substrate utilisation. The pre-treatment related reviews were commonly discussed within a particular technology such as the white-rot fungi pre-treatment (biological) of lignocellulosics biomass (Rouches et al., 2016) and solvent pre-treatment (chemical) of lignocellulosics materials (Mancini et al., 2016). The review on comparing the different pre-treatment strategies as performed by Zhen et al. (2017) is still lacking. In the overall AD research update by Zhang et al. (2016), the key research focus of digesters is to enhance the operational stability (by self-regulatory capability) and on the integrated system (for separating solid and hydraulic retention time).
This overview attempts to interpret the mentioned aspects for AD energy efficiency enhancement. It is important towards the offset of operation cost for an economically feasible AD process.

2. The review method

The literature search covered the studies published within the period of 2016-2017 dealing with the AD issues of substrate, pre-treatment and digester. Scopus® (2017) database is used as the search engine. The assessment was conducted by limiting the subject area to energy and chemical engineering research published in Applied Energy, Energy and Fuels, Renewable and Sustainable Energy Review, Renewable Energy and Energy. “Anaerobic digestion” is used as the main searching keywords. The flow of paper searching and the criteria for relevancy screening were listed in Figure 1 and Table 1. The search results by the date of 9.2.2017 have been included.

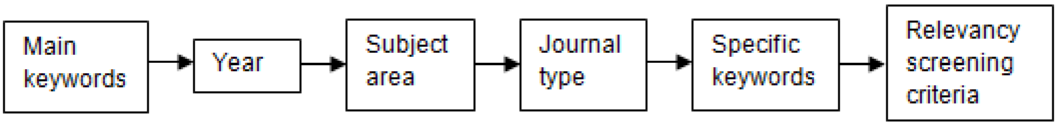

Figure 1: Flow of paper searching and selection.

Table 1: Categorised criteria for AD study.

AD Study	Specific keywords to limit the searching	Relevancy criteria*
Substrate	NA	Study on the suitability/potential of a substrate including co-digestion
Pre-treatment	Pre-treatment	Study on the substrate pre-treatment method to improve the AD process
Digester	Reactor and digester	Study and compare the effect of different type/configurations/system of the digesters.

NA=Not applicable
*The primary screening on the relevancy is mainly based on the title and abstract. The foremost inclusion criterion has more than 60 % of the paper content meets the mentioned relevancy criteria.

3. Status report

The search results lead to total numbers of 156 papers. 29 papers were classified to the study of the substrate, 23 papers as pre-treatment and 22 as the digester. So far a total of 20 papers in 2017 and 54 papers in 2016. The other 82 papers (69 in the year of 2016, 13 in the year of 2017) were excluded as they are not relevant to the mentioned criteria in Table 1.
Figure 2 summaries the number of papers for each journal that were included in the assessments. 41.4 % of the publication of substrate studies has been published in Renewable and Sustainable Energy Review. Energy and Fuels has the highest number of publications regarding pre-treatment for biogas production (7 out of 22 studies). Renewable Energy has the highest publication related to digester among the five selected journal publishers (41 %).

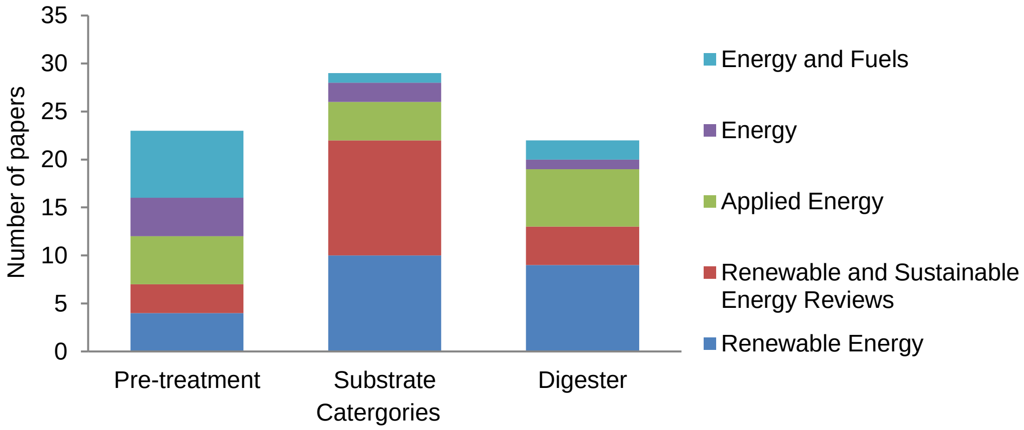

Figure 2: The number and types of journal papers.

4. Results and discussion

4.1 Substrate

The area of substrate studies (a total of 29 studies) consist of the characterisation and potential evaluation of a specific single substrate (11 studies), two or more substrates (14 studies) and evaluation of the potential substrates in a country (4 studies). The co-digestion (two or more substrates) presents the highest research interest. This was compatible with the previous findings by Mata-Alvarez et al. (2014), suggest anaerobic co-digestion as a high concern issue in the critical review of AD studies between the years of 2010 - 2013. Co-digestion offers several benefits over the single substrate AD process under certain circumstances (e.g. spare digesters capacity, low biogas yield such as manure as substrate and fluctuations of waste supply). The addition of co-substrate are able to enhance the utilisation of the plant facilities, increase the biogas yields and consequently increase electricity production, and improved the overall process economics. However, biological inhibition studies, contaminant analysis and additional technical design (e.g. homogenisation) are needed. Fundamental and feasibility studies are important prior to implementation.

The co-digestion of manure and crop residual was relatively well established and has become a standard operation technology (IEA Bioenergy, 2003). Awais et al. (2016) reported that the methane yield can increase by 20 - 24 % for the co-digestion of cattle manure and wheat straw. Co-digestion of wastewater sludge and organic waste (e.g. food waste) has gained a relatively higher momentum in recent years. Brown et al. (2016) suggested that the biogas production in co-digestion can be boosted by 78 % compared to digesting the sludge alone. However, it requires higher research attention especially at a pilot and full scale. Nghiem et al. (2017) have revealed the challenges in this area by compiling data from the full-scale facilities. This includes the issues of inert impurities (e.g. in food waste), a regulatory uncertainty of gate fee collection, a discrepancy between environmental benefits and true economic values, as well as the supply and operation of the design. To promote the co-digestion of wastewater sludge and organic waste a multi-disciplinary approach is needed.

The energy efficiency of co-digestion under the addition of an energy crop has been proven in a few studies. Maize is the popular energy crop that reports to yield 13.2 - 19.8 kWh of electricity for 1 ha of maize (IEA, 2003). However, the argument of environmental sustainability and food security exists. The suggested research direction is the life cycle assessment follow by a comprehensive overview. This is to identify the conditions where energy crops are sustainable as the AD substrate for a better decision making. For the specific single substrate, algae has the highest research attention (36 % out of 11 studies). The other was cattle slaughterhouse waste, horse manure, cotton industry waste, fruit waste, fur etc. Compared to energy crops, the cultivation of algae has no direct competition with human resources and no need for arable land.

The 4 studies of substrates evaluation for AD were conducted in Algeria, Malaysia, Mauritius and China. The potential of biogas production for different biomass was identified with the attempts to facilitate the AD implementation of the countries as shown in Table 2.

The assessment of China was in the effort to promote the underutilise substrate (agricultural residues) for further energy recovery. China, United States and Germany are the world leaders in the production of electricity from biomass (REN 21, 2015). The research direction is different with Malaysia, Algeria and Mauritius that comparatively elemental, assess the national biomass potential. Based on the results in Table 2, waste resources are ready for exploitation with electricity generation potential ranging from 603 GWh to 8,270 GWh. Urban waste is identified as the most potential biogas source with the electricity generation potential of 1,685 GWh in Algeria. In Mauritius, the energy available from AD represents 20.8 % of the total electricity generated in the island. Appropriate substrate utilisation and a stable supply are the most critical initial issue in ensuring the energy efficiency.

Table 2: The potential substrate for biogas production in the different countries.

Country	Reference	Scope of study	Potential of the biogas produces (m^3/ y)/ Electricity generation potential (GWh)
Malaysia	(Abdeshahian et al., 2016)	Identify the electricity generation potential of livestock waste	4.59×10^9 m^3/y= 8,270 GWh
China	(Li et al., 2016)	Review the available biomass resources and identify the future research and development	$3.84 \times 10^{11} m^3$/y
Algeria	(Akbi et al., 2017)	Compare the potential from waste generated in different sectors (urban, industrial and agribusiness waste)	Urban waste is the most potential source: 9.74 $\times 10^8$ m^3/y = 1,685 GWh
Mauritius	(Bundhoo et al., 2016)	Total energy potential of the major waste (agriculture, municipal and industrial waste)	603.89 GWh

4.2 Pre-treatments

The energy conversion efficiencies of AD can be limited due to the lignocellulosic composition during the hydrolysis process. The theoretical yield based on the cellulose content of agricultural waste was predicted to be about 90 % but the methane production efficiency is just 50 % due to the inefficient hydrolysis of biomass within full-scale biogas digesters (Azman et al., 2015). This highlighted the requirement of long retention time resulting in the higher capital cost for a larger digester and low energy generation efficiency. Pre-treatment capable of improving the hydrolysis of lignocellulosic biomass. Figure 3 presents the type of available pre-treatment and the number of studies.

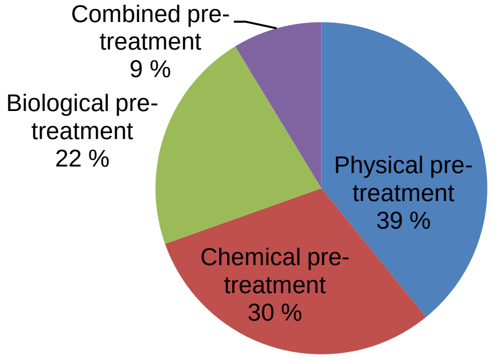

Figure 3: The type and percentage of pre-treatment.

Physical pre-treatment received the highest research interest (39 %) followed by chemical (30 %) and biological treatment (22 %). Physical pre-treatment can generally divide into mechanical, thermal and irradiation approaches. In the full-scale biogas plants, physical pre-treatment, particularly the mechanical treatment poses the highest rate of application (NNFCC The Bioeconomy Consultants, 2016). Rodriguez et al. (2016) identified mechanical pre-treatment to have the highest enhancement in energy conversion (60 %) compared to microwave, thermal, chemical and biological methods. The physical pre-treatment gives a more instant effect (compare to biological treatment) and is environmentally friendlier (compare to chemical treatment). Biological pre-treatment has the potential to increase bio-methane yield by 2.5 times higher (Yin et al., 2016) but it is not commonly used in full-scale AD plant even with the advantages of being less expensive and environmentally friendly. The experiment studied would not be feasible on an industrial scale as the biological method is sensitive. The AD conditions including the water content, aeration, temperature, nutrient of substrate and duration always need to be optimised. Rouches et al. (2016) propose white rot fungi are efficient in improving the lignocellulosic biomass but the increased biogas is not systematic due to the loss of organic matter during the pre-treatment. Every treatment has different advantages and limitations. There is no universal solution for improving the energy conversion of AD. Different scenarios require a targeted solution. This challenge highlights the need for future studies to gather research outcomes into a decision framework on a case by case basis.

4.3 Digester

AD process consists of four process stages which requiring different optimal process variables. The design of the process system of the digester could definitely maximise the energy production, efficiency and economical feasibility of the AD process. The ongoing research and development activities in EU countries are towards the promotion of decentralised energy production from biomass. In Germany, decentralised system on a farm with power capacity in the range between 100 and 2,500 kW is the most common type of AD plants. The digester consists of heating elements. The inclusion of heating components (thermophilic study) has been widely highlighted in the digester studies (31.82 %, 7 out of 22 studies). The other studies include phase separation, single and two stage digestion systems, feed controlled methodologies, digestion time, continuous systems and stirring. Akobi et al. (2016) revealed that the two stage AD process (separate of acidogenic and methanogenic) can maximise the energy recovery by an increase of 18 - 33 %**.** The most suitable digester's configuration for the AD of POME was reported to be ultrasonic assisted membrane anaerobic system (Ohiamain and Izah, 2017). This is because the high methane composition can be produced at lower hydraulic retention time and organic loading rate. The main challenge in the digester study is also the results differences between the simulation model and small-scale plants with the full-scale AD plants.

5. Conclusions

Improvement of energy efficiency is an essential scope of the study to support the AD implementation. The review efforts are conducted to look for improved AD practice with enhances biogas productivities. Considering the energy input and chemicals used for the stage of the substrate (e.g. cultivation of energy crops), pre-treatments, and enhanced digesters operation, the net benefits may not be as promising as assumed. Detailed analyses including life cycle assessment and environmental impact assessment can provide a better picture of the AD scenarios proposed. A balance/optimisation is needed between the energy efficiency, cost and environmental sustainability. The study of suitable parameters as the early underperformance indication, to reduce the risk of AD failure, as conducted by Pontoni et al. (2015) is also important. This is particularly true when one of the operated AD plants in the North America is facing the risk of shut down due to the unpleasant smell issue (The Coloradoan, 2017).

Acknowledgments

This research has been supported by the project Sustainable Process Integration Laboratory – SPIL, funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research and by the collaboration agreement with the Universiti Teknologi Malaysia (UTM) based on the SPIL project.

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