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The Update of Anaerobic Digestion and the Environment Impact Assessments Research

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An increasing number of studies on biogas as a renewable energy including the industrial implementation have been published. The important issues dealing with anaerobic digestion (AD) includes integration of the evidence into patterns, capable of illustrating the current research trend and gaps. Although AD is widely perceived as a clean technology, the assessing and reporting of its environmental impacts remain an important research scope. This work attempts to highlight the recent AD development through a systematic reviewing approach. The criteria for searching are year, type of search engine, keywords and for the selection according to the relevance of the available sources. The presented review covers a case study, mixed mode, by experiment and review. The environmental impact analysis in AD life cycle assessment is also discussed. This facilitates the future studies in improving the environmental impact of AD system. The digestate management and application were suggested as the hotspot of AD system that needs to be improved as the first priority. The AD overview that has been presented statistically proposes the other potential research direction through the interpretation of the type, amount and characteristics of available research. The key future research area is a feasibility study of AD with the consideration to optimise the energy efficiency, economic and environmental aspects which would attract the investors as well as convince the policy makers.

1. Introduction

Anaerobic digestion has attracted considerable research attention due to the emerging concern for environmental protection and energy security. A growth of 622 % (years 2010-2015) for the built AD plants was reported in the UK within the past five years (BioCycle, 2015) and 647 % (years 2010-2013) for the world leader in biogas technology deployment, Germany (Hijazi et al., 2016). The progress of the AD industry reflects the relative maturity of AD technology. However, AD is still reliant on government incentives to attract finance (Bacenetti et al., 2015). The implementation in developing countries remains low. Continuous analysing and optimising are the fundamental and significant step for promoting the AD implementation. The overview of current research trends **is** to identify the gaps of study. It is important to collect the available research outcome in individual puzzle pieces to have an integrated picture. Many reviews published the attempts to synthesise the findings at the specific area of AD system. Zhen et al. (2017) present the up to date review of the research achievement in the pretreatment technologies to improve the efficiency of AD for sewage sludge. Kamali et al. (2016) overview the AD development and suggest the improvement opportunities for pulp and paper mill wastes. The factors affecting the efficiency of general AD system (Mao et al., 2015) and AD for lignocellulosic biomass (Ge et al., 2016) were summarised. This presented work attempts to highlight the recent AD development and its environmental impact through a systematic reviewing approach. The concept was similar to the AD research updates by Zhang et al. (2016), however, their paper published in 2016 included mainly to present the qualitative research trend and discussed environmental issues. Life cycle assessment (LCA) is recognised in the study of waste management to understand the environmental impacts associated with all the process stages and compare the impacts of different waste management alternatives for decision support. The environmental profile of AD has been studied using the

LCA approach to select sustainable treatment technologies. The acidification potential (AP), eutrophication potential (EP), global warming potential (GWP) are the environmental perspectives that have been studied widely (Ahamed et al., 2016). Hijazi et al. (2016) suggested that the main environmental benefit of AD energy system compared to fossil fuels happen in term of GWP and resources consumption with no significant improvement for AP and EP. The potential environmental "hotspots" and reduction opportunities are less commonly discussed. This study summarises and interprets the hotspots of GHG emission in the recently reported AD system. The activities with high environmental footprints that have to be improved and prioritised are identified to facilitate the future study.

2. The review method

This review collected articles published in the recent years for providing a snapshot of current trends or achievement from AD research. The literature search only covered the studies published within the period of 2016-2017. Scopus® (2017) database is used as the search engine by applying "Anaerobic digestion" as the keywords. The documents by type and country of the search results by the date of 26.12.2016 were reported. The assessment on current research development of AD was conducted by limited the subject area to energy, environmental science, chemical engineering and engineering published in Bioresource Technology, Renewable Energy and Journal of Cleaner Production.

The primary screening on the relevancy is mainly based on the title and abstract. The foremost inclusion criterion has more than 60 % of the attention on AD (e.g. review papers which assess all the available type of waste management technologies will be excluded) and relevant with the objective of this paper. The selected studies were divided into eight categories as listed in Table 1. Some of the papers particularly for review were assigned to more than one category. The environmental impact for the life cycle of AD systems was also discussed based on the publication in the year of 2015 - 2017.

Table 1: Definition of each category

Category	Definition	Example
Bioreactors/ Digester	Study and compare the effect of different type/configurations of the reactors.	Jung et at. (2016)
Feasibility	Study on the energy conversion efficiency and economical aspects.	Gutierrez et al. (2016)
Pre-treatment	Study on the substrate pre-treatment method to improve the AD process	Lalak et al. (2016)
Monitoring and Characterisation	Study on process trend monitoring (E.g. kinetics, performance) to characterise and understand the mechanism of the selected method (the uses of transition metal compound or anaerobic filter; not by optimising the temperature, moisture, hydraulic retention time) in improving the biogas production. The AD studies which do not belong to the other mentioned category fall under "monitoring and mechanism".	Xu et al. (2016) Zhang et al. (2017)
Optimisation	Study on parameter optimisation to improve the biogas production, where the optimum condition is reported in the form of impact relation. E.g. "injecting A (value) mL O_2/g VS (unit) able to increase methane production by B %.	Khan et al. (2016)
Substrate	Analyse the characteristics of a selected substrate or comparing with other substrates to identify the suitability for AD.	Zarkadas et al. (2016)
Modelling	Propose framework or model for AD.	Ware and Power (2016)
Environmental/ Life cycle assessment (LCA)	An environmental related study by using LCA methodology/concept and the review studies of LCA.	Tagliaferri et al. (2016)

3. Results and discussion

The search results lead to a total number of 303 papers (22 papers in 2017 and 281 papers in 2016). Figure 1 shows the type of documents and the first ten countries with the highest reported AD studies. Chinese authors published the highest number of AD-related articles (29 %, 88 papers) within the year of 2016-2017 followed by the United Stated (11.8 %). Based on the data analysed by Scopus® (Scopus, 2017), the number of AD-related paper in China surpasses the other countries and has taken the lead the last 5 years. China as one of the world's top energy consuming countries is accelerating in the development of biogas industries among the other developing countries in recent years. The foreseen shortage of energy and government policies has induced the AD project and the AD-related studies. Germany is the largest biogas shared country, however, the number of recent studies is not as high as in China. This suggests the relatively stabilised, advanced level of biogas production, technology and policy framework in Germany. Gu et al. (2016) state that the biogas industries in Germany, Austria and Italy were in the trend of gradually stagnated. Zhang et al. (2016) reported that Germany is having an excess of AD plants installed hence the research interest is more on assessing the methane productivity of specific substrate.

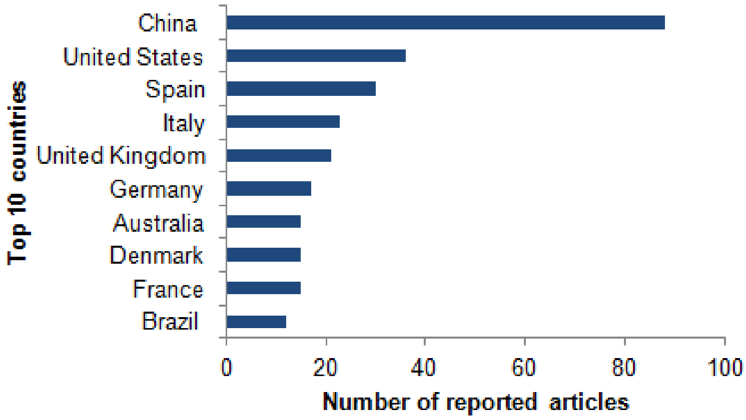

Figure 1: Top 10 countries and their reported number of AD studies (2016-2017). Adapted from Scopus®, (2017).

70 papers were excluded in the determination of recent study trend (section 3.1) according to the selection criteria as mentioned in Section 2. The final selected papers (total of 233) consist of 95.3 % of the article and 4.7 % of review papers were used in the synthesis of evidence in section 3.1. The article papers comprised of experimental (74.7 %), case study (13.3 %) and mixed mode (7.3 %) as shown in Figure 2.

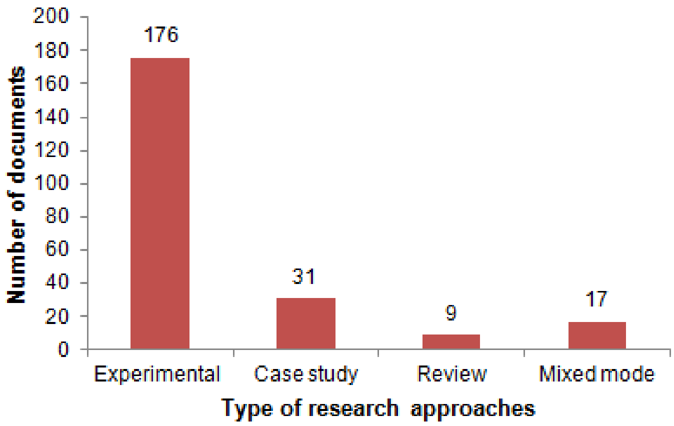

Figure 2: Type of selected article papers on AD studies

The number of review papers was relatively low. The write up of a review paper is complicated with a wide range of data collection is required for a comprehensive summary. However, it is useful for providing the more complete information or overview of the research area. More systematic and quantitative review study using the meta-analysis approach as performed by Miranda et al. (2015) is capable of critically summarising the up-to-date understanding of the investigated area, identifying the research strength, weakness and potential. There is always a gap between the full-scale application and experimental studies. The increasing number in AD research by case study could maximise the practicality of the suggested solution.

3.1 Recent study direction of anaerobic digestion

The studies in the effort of improving the AD process were assigned into eight categories as shown in Figure 3. Monitoring and characterisation are the major categories (33.6 %) where the fundamental of a novel or uncertain processes were assessed in order to understand the working principles. Different parameters were monitored and characterised for further interpretation. Most of the study evaluated the effect of changes or supplementation (e.g. trace element, biochar, inoculums, and enzymes) on the monitored parameters (e.g.

microbial communities, physical properties and biogas production). The high percentage of mechanism study suggests the demand in the biogas industry. The research is not limited to optimise the available method (13.2 %) for an enhanced performance. The distinct or localised approaches are being characterised and introduced. The case-by-case monitoring is important due to the different, natural resource endowments, climate conditions, technologies development, industrialisation development and socioeconomic status.

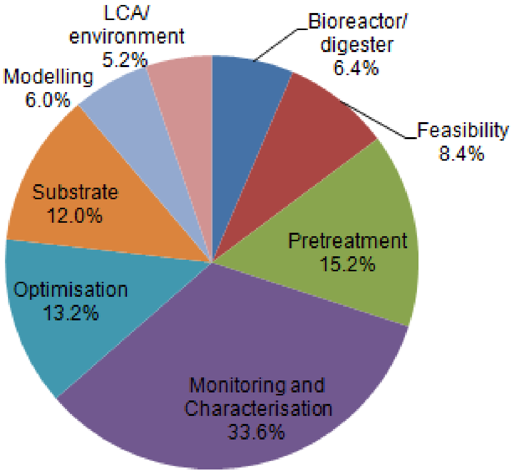

Figure 3: Recent study of AD for subject area of energy, environmental science, chemical engineering and engineering

Lignocellulosic biomass has not been widely utilised as the substrate of biogas limited by the inefficient hydrolysis of recalcitrant substances (Goswami et al., 2016). However, lignocellulosic biomass consists of high potential biogas yield (>100 m^3/t) for renewable energy generation (IEA Bioenergy, 2015) and are widely available from crop residues. This reflects the high research interest in the recent study of pretreatment method (15.2 %) as high energy efficiency is able to promote the financial feasibility for real case AD.

A high number of studies have been reported for the efficiency improvement of AD, e.g. pretreatment. The feasibility study on the operation and environmental aspect were less frequent. Pretreatment methods with high efficiency generally incurred a higher investment cost or are environmental less friendly. For example, the use of a chemical method (use of oxidative, ozonolysis, acid and alkali) and irradiation method (microwave, ultrasound, gamma-ray, electron beam) are generally less environmentally friendly and costly than the biological treatment (microorganisms). Based on Figure 3, the feasibility study is comprised of 8.4 % of the recent AD study. The feasibility study covers wider aspects to suggest the sustainability (efficiency-economic, environmental-economic, and efficiency-environmental) of the AD process from an industrial point of view. A feasibility study can be performed by assessing the available data or considering the feasibility aspect by conducting the efficiency experiment. Making a comparison across the literature, however, is complicated in the AD study as multiple influencing factors should be considered. The lack of standardised reporting (some of the factors might be ignored in the evaluation procedure depending on the researchers) remains a barrier to having an exact comparison across the literature. A feasibility study is important for decision making. The utilisation of fuzzy logic PROMETHEE approach as suggested by Lolli et al. (2016) that consider the environmental, economic and social criteria could further facilitate the process.

3.2 Hotspot determination

The environmental impacts for the life cycle assessments of AD can vary based on different biogas system and LCA methodology. The comparison can be benchmarked against the other waste management treatment or the conventional fossil fuel system. The unit of waste to be treated is used as the functional unit for LCA focusing on the waste management. Studies oriented towards bioenergy production use the unit of biogas or electricity produced as the functional unit. In general, most studies reported the positive performance of the evaluated environmental impacts.

Most of the environmental impacts reported with a negative effect for AD system were acidification potential (AP) and eutrophication potential (EP). Ahamad et al. (2016) stated that the treatment of food waste by AD has a negative impact of EP than the production of bio-oil and hydrochar. Wang et al. (2015) also suggested that the AD treatment of municipal solid waste has a better global warming potential (GWP) and AP, but a weaker EP than incineration. EP shows negative impact because of the low effectiveness of AD to remove nutrients, which were left in the treatment plant for further processing. The digestate management and the concentration of nutrients in the feedstocks also negatively affected the AP and EP when compared with the reference fossil fuel system (Lordan et al., 2016).

Based on the overview outcome, the environment hotspots have been proposed to be the digestate storage and field application as supported by the study of Yasar et al. (2017). Baylea et al. (2016) also highlighted the issues on inputs and digestate storage condition for the environmental impact as well as the health risk of operation workers. The management of the digestate is reported to have a major influence on the environmental profile of the biogas production because of the open storage practices. Lordan et al. (2016) documented that the use of closed tanks can lead to a 65 % reduction of the emission. The environmental impact from field application can be minimised through nutrient recovery technologies or digestate conversion treatment. However, the analysis performed to understand the appropriateness of both methods is still lacking. Further LCA study should be performed to delve into the impact of digestate management options.

Few studies have reported the roles of feedstock combination and energy crop substitution in reducing the environmental impact (particularly for AP and EP). Intensive exploitation of the arable land for the cultivation of energy crops yields a negative environment impact. Ertem et al. (2016) show that the substitution of energy crop and optimum feedstock loading rate (storage capacity) can save up to 10 - 45 % of GHG emissions, and reduce 10 % of impact from AP and EP. The utilisation of macroalgae can further lower the AD (83 %) and EP (41 %) (Ertem et al., 2017).

4. Conclusions

This mini-review provides some insight on the current AD study and suggests the possible research direction. The number of review study, case study and feasibility study should be increased in order to facilitate the full-scale implementation. There is a need to establish the standardisation of cost and environmental benefit optimisation tool in identifying the preferable route of AD system. The differences in the assumptions and methodologies (included scopes/aspects) for calculation should be minimised for a better comparison with the literature. The research on feedstock substitution (to replace energy crop) as well as the digestate storage, post treatment and application have been proposed for the future study to further enhancing the environmental sustainability of AD system. The information of this study was extracted from limited sources, based on the papers published in only three journals. These outcomes could be affected by the nature of the selected journals. Further assessment on the research achievement of AD can be conducted by including a wider range of sources using the meta-analysis for a more comprehensive and systematic overview. The best practices for each category (pre-treatment, characteristics of substrate etc.) can also be based on the decision tree or framework.

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