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Research article

Anaerobic digestion of municipal solid waste: Energy and carbon emission footprint

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ABSTRACT

Anaerobic digestion (AD) serves as a promising alternative for waste treatment and a potential solution to improve the energy supply security. The feasibility of AD has been proven in some of the technologically and agriculturally advanced countries. However, development is still needed for worldwide implementation, especially for AD process dealing with municipal solid waste (MSW). This paper reviews various approaches and stages in the AD of MSW, which used to optimise the biogas production and quality. The assessed stages include pre-treatment, digestion process, post-treatment as well as the waste collection and transportation. The latest approaches and integrated system to improve the AD process are also presented. The stages were assessed in a relatively quantitative manner. The range of energy requirement, carbon emission footprint and the percentage of enhancement are summarised. Thermal hydrolysis pre-treatment is identified to be less suitable for MSW (−5% to +15.4% enhancement), unless conducted in the two-phase AD system. Microwave pre-treatment shows consistent performance in elevating the biogas production of MSW, but the energy consumption (114.24–8,040 $kW_eh\ t^{-1}$) and carbon emission footprint (59.93–4,217.78 kg $CO_2\ t^{-1}$ waste) are relatively high. Chemical (~0.43 $kW_eh\ m^{-3}$) and membrane-based (~0.45 $kW_eh\ m^{-3}$) post-treatments are suggested to be a lower energy consumption approach for upgrading the biogas. The feasibility in terms of cost (scale up) and other environmental impacts (non-CO_2 footprint) needs to be further assessed. This study provides an overview to facilitate further development and extended implementation of AD.

1. Introduction

Anaerobic digestion (AD) has received increasing research attention and deployment owing to the emerging concern for waste disposal and energy security. It provides multiple environmental benefits including green energy production, organic waste disposal, environmental protection (sanitation-pathogen, air pollution, replace inorganic fertiliser etc.), biogas-linked Agrosystem (pig-biogas-vegetable greenhouse system etc.) and GHG emission reduction (Mao et al., 2015). In Europe, 17,376 biogas plants and 459 biomethane plants were registered in 2016. They are functioning with the total electricity amount of 60.6 TWh from biogas (EBA, 2016). The AD technologies or digester installation have been emerging at a fast pace in Asia as well (Lim, 2016). However, the AD is still dependent on economic incentives from governments to be sustainable (Vasco-Correa et al., 2017). Waste as feed is at no cost however the collection and processing could cost more than the value of the end product (biogas and digestate) (Jung et al., 2015). The energy balance between the input (pre-treatment, AD process, upgrading process, collection and transportation) and output energy (potential energy content of the waste) is yet to be improved. A majority of AD plants are used for sewage sludge and livestock waste (UNEP, 2015). Anaerobic digestion of Municipal Solid Waste (MSW) is comparatively challenging and in development (Clarke, 2018). The high solid content, large particle size, variability and inhomogeneous nature of the composition are subjected to the difficulty in controlling the process (UNEP, 2017). Optimising and enhancing the energy efficiency are a fundamental and vital move to stimulate the sustainability of AD implementation. It allows maximum exploitation of the renewable energy source and improves the environmental sustainability. The economic feasibility can also be maximised. This study aims to review the performance of different stages of AD process from the context of energy efficiency and carbon emission footprint. The focus is placed on MSW.

There are many published reviews that synthesise the discoveries at

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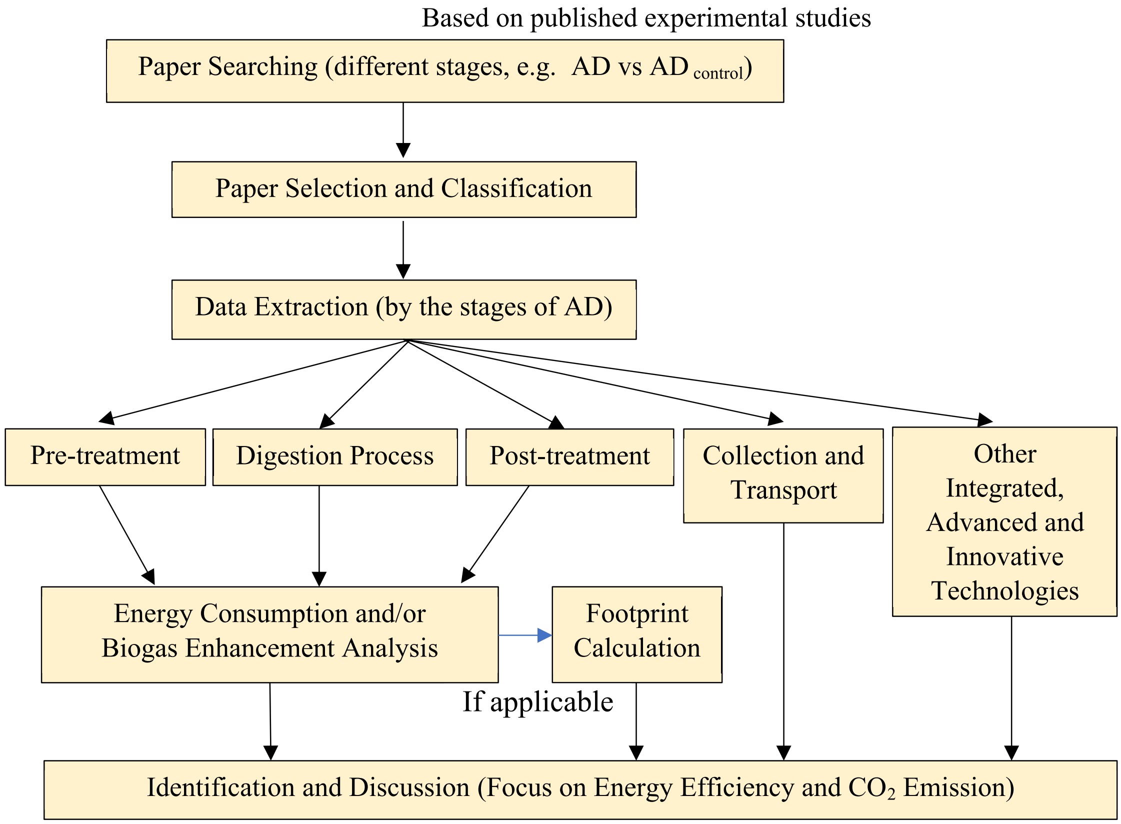

Fig. 1. The framework for the assessment of anaerobic digestion process in treating MSW.

a specific stage of the AD system. Zhang et al. (2014) study the physical, thermo-chemical, biological and combined pre-treatment as well as the co-digestion approaches to enhance the AD of food waste. Kondusamy and Kalamdhad (2014) reviewed different pre-treatment methods of food waste from a similar viewpoint. Additional discussion on the configuration of the anaerobic reactor for enhanced methane content in the biogas was provided. Mao et al. (2015) summarised the impact of different AD configurations to the methane potential but covered a wider range of substrates including the MSW, lignocellulose, livestock manure and waste activated sludge. Muñoz et al. (2015) discussed the state of the art of biogas upgrading technologies (post-treatment) and highlighted biotechnologies are superior to physical/chemical technologies. Most of the existing reviews on the AD were stage-specific (pre-treatment or operational mode or post-treatment or supply chain etc.). It is important to assemble available research outcomes so that the individual puzzle pieces can be integrated. This could facilitate the comparison among stages and enables the identification of opportunities for improving energy efficiency and environmental impact.

Life cycle assessment (LCA) identifies the environmental impacts of all process stages, including energy use and production. Life cycle studies provide information from an integrated viewpoint. Hijazi et al. (2016) suggested that the main environmental advantage of AD energy system compared to fossil fuels is the resource consumption and global warming potential. There is no significant improvement in eutrophication potential and acidification potential. Bacenetti and Fiala (2015) evaluated the carbon emissions footprint of five different AD plants by considering the energy consumption and production through LCA approach. The carbon emissions footprint savings range from -0.208 to -1.07 kg CO_2eq kWh^{-1}, contributed by the substitution of energy production from fossil fuel. However, the outcome of LCA is dependent on the system boundaries and the chosen baseline scenario, which is difficult for cross comparison. The other limitation of LCA in evaluating waste to energy has also been discussed by Zhou et al. (2018) and several extension methods have been proposed for further development. The baseline scenario in AD studies is usually the conventional method of waste disposal (landfill) or energy production (fossil fuels), but not among the different AD technologies. Comparison by referring to the worst-case scenario (conventional method) limits the further improvement in energy efficiency and environmental impact of the AD process, as the AD is known to be superior to landfill and it generates renewable energy.

This study assesses the different stages of the AD process to support the limitations of comparison by LCA and the lacking in the available review studies. The assessed stages of this study include pre-treatment, digestion process and post-treatment. The concept is similar to the work presented by Chiu and Lo (2016). However, the focus is different where Chiu and Lo (2016) emphasise on food waste, which is comparatively qualitative (discuss the mechanism) and the post-treatment stage is not considered. In this study, the energy consumption and/or biogas enhancement of pre-and post-treatment stages were extracted from various experimental studies. The different reported units are converted into common units to facilitate the comparison. The carbon emission footprints calculation were based on the energy consumption, when applicable. The basis of comparison is not referring to the conventional waste handling technologies (e.g. landfill) and conventional energy source (e.g. fossil fuel) as in most of the LCA studies, but within itself. For example, different pre-treatments, digestion systems and post treatments for AD are compared. The logistics/supply chain as well as the other integrated, advanced and innovative technologies in enhancing the AD performance are also discussed.

2. The review and assessment methods

The literature search covered publications from 2008 to 2018 dealing with the AD performance assessment of MSW. The assessed stages include pre-treatment (Section 3.1), digestion process (Section

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