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Life Cycle Assessment and Techno-Economic Assessment of Anaerobic Co-Digestion: A Short Review

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Waste-to-energy conversion such as anaerobic digestion has been widely promoted under the subsidies to decouple from fossil fuel dependence system and its inherent two-fold benefits. It could diversify the renewable energy matrix and divert the waste from the landfill. Co-digestion of two and more feedstocks could enhance bioenergy production and maximise waste recovery. However, the anticipated benefits are not absolute for all circumstances, varying across the type of co-substrate, pretreatment and other settings. The present study aims to overview the life cycle assessment (LCA) and the techno-economic assessment (TEA) of the anaerobic co-digestion processes. The results could provide an insight into the several critical parameters for sustainable co-digestion. Co-digestion of two or more feedstock is favourable since higher anaerobic digestion performances and higher profitability in TEA is shown. Cultivation of energy crops, transportation, pretreatment of feedstock and storage stage each contributes some shares to eutrophication potential (EP), acidification potential (AP), global warming potential (GWP), ozone depletion and fossil depletion. Generally, high anaerobic digestion performances and biogas upgrading can offset the negative environmental impact. Positive net present value is also observed from the co-digestion of feedstock.

1. Introduction

Global energy demand has increased over the years and depending on fossil resources.The anthropogenic emission of greenhouse gas (GHG) to the atmosphere had caused adverse effect, such as global warming. Renewables produce 54 % of electricity in Sweden, making them the world's leading country in the energy transition from fossil to renewable for four consecutive years (Harry, 2020). The use of biomass in energy applications to diversify its energy matrix is becoming increasingly important. Europeans are building bio-digesters to generate heat or power from biogas, mainly in Germany, as an alternative to waste treatment strategy and transition into cleaner energy. Other nations outside Europe also embrace the drive to improve economic and environmental benefits in biogas usage while implementing the concept of waste-to-energy (WtE) (Salvador et al., 2019)

Organic substrates' anaerobic digestion (AD) produces biogas when microbes break down the complex organic material without oxygen. New AD technology such as anaerobic membrane bioreactor are recent advancement which produce biogas while treating the wastewater (Chen et al., 2021). In China, the two primary forms of biogas usage are the upgrading to create biomethane and combined heat and power generating (CHP) (Li et al., 2020). Co-digestion is the AD of two or more different feedstocks. Cattle slurry converts to biogas at a lower rate than other types of biomass, such as energy crops during mono-digestion (Esteves et al., 2019). Thus, co-digestion of swine manure and grass silage shows increase the efficiency of biogas production by 97 CH_4/g VS rather than mono-digestion of swine manure (Zhang et al., 2021). In metropolitan Argentina, primary waste generated like municipal solid waste and sewage is co-digested to produce biogas (Morero et al., 2017). In Italy,

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swine manure and food waste generated to produce electricity using AD (Bartocci et al., 2020). Biogas production from food waste co-digestion with crude glycerol was investigated by Jensani et al. (2021). Besides that, biomass, such as agricultural waste and energy crops, is also widely used as a co-substrate in AD for biogas production (Lijó et al., 2017).

A thorough methodology like Life Cycle Assessment (LCA) is used to assess and ensure biogas generation's sustainability (Aziz and Hanafiah, 2020). According to Zhang, Jiang, Wang et al. (2021), the LCA for co-digestion of pig manure and grass silage shows increase in biogas yield and offset 94% of Global Warming Potential (GWP) compared to mono-digestion of pig manure. In addition, WtE offers one way to set up a system for a circular economy. For instance, WtE may meet energy demand, trash reduction and emission reductions (GHG) concurrently (Pan et al., 2015). Techno-economic Assessment (TEA) investigates fully integrated biomass processing processes for its overall cost of output and economic viability. For policymakers and consumers on bio-refinery markets, the TEA/LCA study might be of interest. Production costs and environmental profiling of these processes provide an overview of process economics and environmental consequences, providing a thorough overview of the process's workability and sustainability (Unrean et al., 2018). In recent years, extensive research has been done on the LCA of biogas system by researchers worldwide. Current LCA of biogas system reviews focuses on mono-digestion: LCA of biogas from manure (Esteves et al., 2019); LCA for biogas production in Europe (Hijazi et al., 2016); LCA of biogas to form electricity (Salvador et al., 2019). However, there is a lack of review done in LCA and TEA of co-digestion concurrently. This review paper summarises the life cycle assessment and synthesises the techno-economic of the several AD-based co-digestion processes. The link between the co-digestion feed of the AD process and the environmental impacts through LCA are discussed in Section 3.1. At the same time, the cost and economic indicators are outlined in Section 3.2.

2. Methodology

The approaches utilised to list the literature through research databases are presented in this section. The significant publications and trends in emphasis, techno-economic analysis and LCA of anaerobic digestion co-digestion are systematically evaluated. *Methodi Ordinatio* (Pagani et al., 2015) is employed to ensure the review is based on high impact articles. Three databases are used, namely Science Direct, Web of Science and Scopus. The time limit of 2010 to 2021 is set to ensure the studies are relevant in terms of time. The summary of the literature review steps is outlined in Figure 1. Besides, two sets of keywords are used to collect the articles.

Set 1: "Life cycle assessment" AND "co-digestion" AND "biogas"

Set 2: "Techno-economic assessment" AND "co-digestion" AND "biogas"

Two hundred twenty-one articles are found with the databases from Science Direct, Web of Science and Scopus. The reference manager employed is Mendeley. The articles are first filtered by going through the title to rule out unrelated articles then the abstract filter is applied. The article with subjects of interest not linked to this study is taken out where 64 articles remained. Some more were not linked to topics of interest in this research following a complete reading of the abstracts, so 49 remained. InOrdination was applied in this stage. The selection criteria of the article include all types of agricultural waste.

The Ordinatio Method demonstrate and reflect on the significance of the article by an equation. The number of citations from each article and the relevant journal's impact factor (IF) is weighted. The article's citation counts are found using Google scholar and the IF using the Journal Citation Reports (JCR). The InOrdinatio coefficient additionally considers the publishing year. It requests an (α) score assignee from 1 to 10, wherein the closer the α to 10, the more significant the documentation has been produced this year. A score of 7 is chosen to emphasise the relevance of time to this study. Microsoft Excel was used to calculate the InOrdination coefficient. After that, a list of weighted articles is presented, and the top 17 articles are included in this study's portfolio.

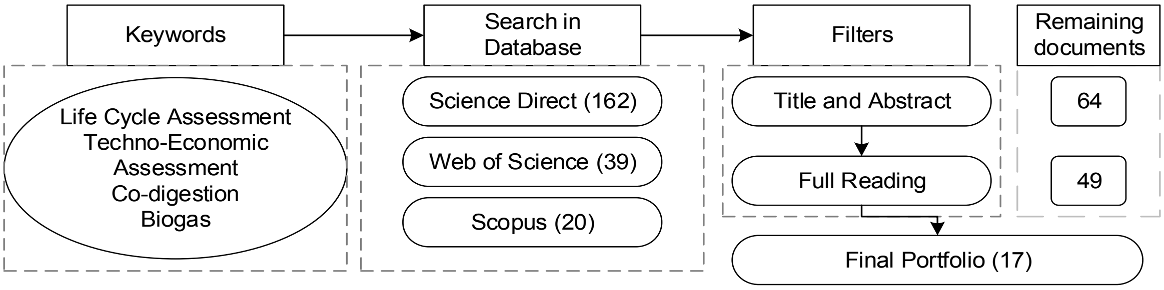

Figure 1 Summary of Literature Review steps

3. Findings

The findings of the reading are divided into two sections. The first part summarised the LCA of different feedstock that needed cultivation, transportation, or storage and the effects on the impact categories. The second part summarised the TEA done on co-digestion.

3.1 Life Cycle Assessment

Multiple types of feedstock are used in AD worldwide according to the availability of biomass resources at the biogas production location. Dairy manure is not suggested to use as a single feed because of the high nitrogen levels, which can induce partial inhibition of the AD process. The consequences of climate change can be minimised via co-digestion to the fullest extent possible (Usack et al., 2018). The emission from the co-digestion of energy crops and cow manure is observed to be lower compared to the US electrical system (540 gCO_2-eq/kWh) (Aui et al., 2019). Co-digestion of pig manure and grass silage also demonstrated the best performance in most environmental impacts assessed compared to mono-digestion of pig manure (Zhang et al., 2021), while a 17 % increase in biogas generation achieved when co-digestion of cow manure and pre-treated grass (Tsapekos et al., 2019) in comparison with the mono-digestion of animal manure. Besides, global warming potential (GWP) and resource depletion show the most effective management of co-digesting seaweed with manure and orange peel waste for biogas and nutrient production by achieving higher GHG savings. Orange peel waste is previously used as animal feed, but it is not an ideal waste treatment measure due to increased energy demand in pretreatment (Negro et al., 2017). The LCA of co-digestion using all sorts of feedstock mentioned above proven to have lower environmental impacts in general. In all the articles reviewed in this paper, manure and food waste are deemed a waste stream from the previous life cycle. The system boundary starts from the disposal stage; therefore, the associated waste did not carry any environmental burdens from the production stages.

One popular manure co-digestion feedstock used is energy crops such as maise, rye, wheat, triticale and grass, which require cultivation stage and pretreatment, for example, ensilage. Following researchers reported that the production of energy crops as a (co-)substrate and its resulting field emissions have notable contributions. Lijó et al. (2014) conducted LCA for the categories of abiotic depletion potential, acidification potential (AP), eutrophication potentials (EP), GWP, ozone depletion potentials and photochemical oxidation potential. Crops cultivation of triticale and maise producing between 52 % and 98 % of the total environmental impacts primarily due to agricultural machinery diesel needs and pollutants from combustion generated. When irrigations are needed, the impact increases and has been identified as a hotspot. In terms of AP and EP per 100 kWh of electricity produced, the application of fertilisers contributed up to 77 %. It is mainly linked to emissions of ammonia to the air and phosphate to the water. However, due to the CO_2 uptake by photosynthesis, a positive impact in GWP (142 $kgCO_2$–eq avoided impact) is reported by Lijó et al. (2014). The co-digestion is still very feasible with a lower impact compared to the energy generated.

Similarly, negative environmental impacts of crops cultivation are reported by Ertem et al. (2016). The NO_x emissions are the most significant when a higher percentage (70-75 %) of energy crops is used due to fuel consumption associated with crop cultivation (Poeschl et al., 2012b). LCA of AD co-digestion with energy crops demonstrates higher emission, adding to AP and EP impact categories. The statement is further supported by a couple of researchers who conducted comparative LCA on co-digestion by using an alternative co-substrate to energy crops. A 42 % carbon footprint reduction from biogas production is achieved by replacing the co-digestion of cow manure feedstock with 6,600 tons of food waste instead of 9,900 tons of maise (Bartocci et al., 2020). The life cycle AP impact is reduced by 82 % when energy crops are substituted with macroalgae and co-digested with chicken manure in an AD system (Ertem et al., 2016). As crops production is excluded, the emission of ammonia from fertiliser spreading is omitted.

Another co-substrate that includes the cultivation stage is glycerin derived by soybean production with a high emission factor (2.49 kg CO_2-eq/kg). The GHG emission of the AD recorded is ten times higher than the scenario co-digesting wheat, rye, corn stover and cow manure where glycerin is absent (Aui et al., 2019). Although glycerin may increase the biogas produced, where it is economically favourable (see Section 3.2), the climate change impact is not much different from conventional processes reported by the authors.

The environmental effect from the cultivation stage seems worse when producing biogas from energy crops than from other feedstock. However, the environmental impacts of the AD system can be improved by increasing power efficiency (Aui et al., 2019), decreasing resource impact or avoid energy crops if another biomass waste source is readily available (Usack et al., 2018). To reduce environmental impact, an organic farming system in crops production proposed by Ramírez-Arpide et al. (2019), by replacing inorganic fertiliser by using dairy cow manure and avoid using atrazine and insecticide as weed and pest control, where a 22.5 % reduction in GWP (equivalent to 1.72 g CO_2-eq/MJ) is obtained.

The transportation stage of feedstock should not be left out from the system boundary of LCA. Transportation and pretreatment of feedstock had appeared as one of the hotspots of the AD system, contributing to GWP, ozone depletion and fossil fuel depletion. At the same time, the co-substrate that commonly need to go through these stages are MSW and food waste. The addition of food waste in co-digestion with animal manure and crops imply higher biogas yield and higher methane content (60 %). As a result of feedstock transportation and pretreatment of food waste, positive impacts are obtained for GWP, ozone depletion and fossil fuel depletion (Lijó et al., 2017). Several studies demonstrate that fossil emissions from feedstock supplies for MSW to achieve MSW input quality requirement were 53 times higher than cattle manure (Poeschl et al., 2012b). The research is further supported by Morero et al. (2017), where transports of food waste contributed to the human toxicity (>55 %), photochemical oxidation formation (>45 %) and urban land occupation categories (>95 %).

Nevertheless, for LCA, which considers manure storage, Li et al. (2021) stated that more than 39 % and 41 % of GWP and AP contributed to ammonia emission during manure storage. Similarly, when the area required for digestate land application is much higher than the area for crops cultivation, digestate management should be prioritised. The authors further indicate that covering the digestate or manure storage tank reduces the GWP (Ramírez-Arpide et al., 2019).

Cultivation of energy crops is the main contributor of EP and AP. At the same time, transportation and pretreatment of feed significantly contribute to GWP, ozone depletion and fossil depletion and storage stage concerns both GWP and AP. It is vital to consider the system boundary of cultivation, transportation and storage stage, which could overturn the environmental sustainability of the AD process to provide a more realistic LCA on co-digestion.

3.2 Techno-Economic Assessment

Co-digestion of organic waste resulted in proportionately higher emissions when AD was overloaded due to increased digestate methane emissions, worsening the environmental impact (Usack et al., 2018). A higher load of feedstock does not equal higher yield and environmental benefits causes by decreased digester stability and performance. Techno-economic assessment (TEA) encompasses all components of economic research. A financial spreadsheet is widely utilised as a methodology.

TEA measures the viability of an AD system from co-substrates to the final products such as electricity and digestate fertiliser. Techno-economic research showed capacity variations between 2000 and 30,000 tons per annum, with Capital Investments (CAPEX) ranging from 200 to 10.9 million dollars. TEA has been made for the co-digesting of manure and energy crops (Bartoli et al., 2019), manure and food waste (Li et al., 2021), and sewage sludge and food waste (Hosseini Koupaie et al., 2014).

Net present value (NPV) is a standard economic indicator that demonstrates the profitability of a process. For the AD plant, co-digesting cow manure and energy crops as biomass, 0.44 \$/kWh of the electrical capital cost are found where it is lower than a study report in the year 2008 (0.50 \$/kWh electricity). This is mainly due to glycerin used in the co-digestion, which increase the methane yield. The NPV also shows a positive value, although the Internal return rate (IRR) obtained is lower. This research had proven that co-digestion of glycerin with manure and biomass could cut operating costs by 32 % and raise the Return on Investment (ROI) by 27 %. A considerable sum of the expense comes from the digester itself, which is the main equipment of the AD process (Aui et al., 2019). Hence, the addition of glycerin is proven to economically favourable.

The main assets of an AD system are biogas, as mentioned by Li et al. (2021), where the sales of CH_4 entitled for 80 – 91 % out of the total assets. The research by the authors shows a positive NPV (\$1,167,240) with a Total Solid (TS) value of 22 %. This results from lower equipment cost and higher methane production than semi-liquid and liquid scenarios, suggesting a negative NPV value. The digester's cost largely contributes to the capital cost, which agrees with the previous TEA done by Aui et al. (2019). Higher solid contents of feed have indicated lower maintenance cost and building cost in the digester.

Due to the feedstock's total solid and volatile solid content nature, the biomethane potential is reported to affect the AD system's revenue. Pig manure co-digesting with food waste from the food industry and supermarkets generates a positive NPV (€ 1,457,326) with a 7.6 y of simple payback period, with an energy production cost of 120.74 €/MWh. Bartocci et al. (2020) claimed that earnings of sales electricity generated from biogas are sufficient to cover the cost of collecting food waste from the food waste providers.

Due to capital cost and operational cost reduction, the net cost declined 37 % in using a co-digester rather than building two digesters. The studies are done with co-substrates fruit juice industrial waste and municipal waste sludge (Hosseini Koupaie et al., 2014). TEA is used to assess the implications of renewable energy and agricultural policies in position. In New York State, farmers are encouraged to maximise their co-substrates load rate by giving out incentives: gate fees. The studies found that the current policies should consider the performance and condition of AD while allocating subsidies to the farmers. The existing policies and framework economically favour low-strength and low-biodegradability co-substrates deemed not optimum for co-digest biogas production and posed more environmental burdens (Usack et al., 2018). Policy Mitigating Cost (PMC) is also calculated in an economic analysis to evaluate the efficacy of policies regarding agricultural biogas towards energy production and environmental impacts in Italy (Bartoli et al., 2019). The policy change ensures that biogas-based energy mitigation promotes manure for biogas generation while restricting land-based biomass usage. Policy Mitigation Cost shows a reduction in 167 - 178 €/tCO$_{2}$-eq in the post-policy scenario. The drop in unit cost is also visible due to the new policy, which saves between 65 – 75 €/MWh. The reduction observes in TEA implies the success of policy change.

TEA has been conducted in this value chain from the onsite feedstock to various products, like through CHP to electricity or biomethane (Negro et al., 2017). Co-digesting of sewage sludge (SS) and organic fraction of municipal solid waste (OFMSW) obtained total revenue from biogas upgrading is 12 % higher than a scenario with combined heat and power (CHP) unit (Morero et al., 2017). This is due to the 100 % process efficiency of biomethane and only 84 % efficiency from CHP. Biogas upgrading practices present promising income generation to the process. CHP and biogas upgrading cost is also compared in preliminary cost flow analysis (Negro et al., 2017). The profit of biogas converting to electricity is low while biomethane achieved significantly greater profit, € 77 indifference. However, because the process requires heat, biogas upgrading scenarios have led to higher operating cost. The net profit after paying off the operating cost still favours the biogas upgrading scenario.

The TEA articles reviewed proven co-digestion is economical and feasible compared to single feed counterparts due to higher AD performance, with a decrease in 32 – 37 % of the cost is observed. Biomethane from biogas upgrading is more profitable compared to a CHP system. Besides, the profit of biogas-based energy can be improved by increasing the methane yield by co-digesting glycerin. As a result of higher maintenance cost and digester cost, semi-liquid and liquid AD scenarios are less feasible economically. However, the feasibility of the AD system differs under exceptional circumstances of policies implemented by related authorities.

4. Conclusions

In conclusion, the most common co-substrates are animal manure, energy crops and food waste. Co-digestion, in general, from the LCA done, brings positive environmental performance mainly in GHG savings and higer biogas production. From the articles reviewed, the cultivation stages of energy crops and the storage stage of manure and digestate generally exhibit a higher environmental impact in mostly EP, AP and GWP. Besides, transportation and pretreatment are the prominent determining factor in overall GWP, ozone depletion and fossil depletion contributions. However, increasing power efficiency of AD plant and using biomass waste with lower resource impact may help to reduce overall impact. TEA and cost analysis of co-digestion AD system mostly show positive economic performance while biogas upgrading further improves the AD system's profitability. A reduction in 32 – 37 % of cost are observed and positive NPV values are shown in multiple co-digestion scenario, preferably at higher TS value (22%). Transparent TEA and LCA are increasingly necessary to assist policymakers and investors in taking advantage of AD's potential. Future opportunities of biogas can be drawn to circular economy practises. Closing the waste management cycle by employing AD is a possible strategy to reduce potential environmental effects and increase financial benefits.

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