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Techno-economic and life cycle assessments of anaerobic digestion – A review

Karthik Rajendran[a,*], Ganti S. Murthy[b]

[a] Department of Civil and Environmental Engineering, SRM University-AP, Amaravati, India
[b] Department of Biological and Ecological Engineering, Oregon State University, Corvallis, OR, 97331, United States

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ABSTRACT

Techno-economic analysis and life cycle assessments are crucial for any processes to be sustainable using the tri-fold metrics including technical feasibility, economic viability, and environmental sustainability. Anaerobic digestion is portrayed as one of the mature technologies for handling solid waste management and bioenergy generation. Nonetheless, a clear assessment of the tri-fold sustainability metrics is not available yet and this review attempts to address this knowledge gap. Important problems in techno-economic analysis and life cycle assessments such as assumptions used, extrapolation of research data, robustness and reproducibility of results, the openness of materials were discussed. Anaerobic digestion helps in treating organic wastes that could be used for different purposes including electricity, vehicle fuel, natural gas substituent, heating, and cooking fuel. However, sustainability in terms of technology, economics and environment remains the question for it to be industrialized.

1. Introduction

Anaerobic digestion (AD) is a biological process in which organic fractions are converted to methane and carbon dioxide by different groups of bacteria and archaea. Because of its relatively high-energy density (LCV – 23 MJ/Nm^3) compared to lignocellulosic feedstocks and ease of use, biogas has a variety of applications, including cooking, district heating, fuel, electricity generation and energy storage (Swedish Gas Technology Centre, 2012). Biogas has been used in diverse scales from household levels between 1 and 6 m^3 to industrial levels of > 10,000 m^3 (Deublein and Steinhauser, 2011). Historically, biogas production was visualized as a byproduct from WWTP (wastewater treatment plant) and only in the last few decades, the market for biogas from solid substrates has grown. The reason for this rapid growth is the recognition of two-way benefits of biogas production, i.e. reduction in a waste fraction, simultaneously generating energy and valuable fertilizers.

Many industries and investors see biogas production for energy generation as a high-risk investment due to inherent variabilities in the supply of feedstock, characteristics of feedstock, segregation of solid waste, operational problems, and profitability issues (Schmidt, 2014). To address these issues, many governments have introduced off-take agreements and favourable policy initiatives to encourage private investments in this area. Moreover, several research groups across the world continue to work on anaerobic digestion to address challenges and enable commercialization. Waste Management World (2017) reported that the global biogas market would reach $50 billion by 2026, and it is necessary for researchers to look anaerobic digestion on a systems level, including techno-economic and environmental benefits perspective. Therefore, it is imperative to conduct integrated analyses to assess the technical feasibility, economic viability and environmental impacts of anaerobic digestion technologies.

The techno-economic analysis (TEA) involves evaluation of a process/technology through process simulation approach often using software such as Aspen Plus and Intelligen Superpro Designer. Firstly, a flow sheet is developed using different unit operations to conduct mass and energy balances. The economic analysis for the simulated process is performed using user-specified values for materials used for construction, location, interest rate, labour cost, etc (Murthy, 2016b) (Murthy, 2016a). The techno-economic analysis provides insights on the feasibility of a project, which is essential for bioenergy/bio-based products. Also, it is possible to identify the bottlenecks in the process that pose challenges to technical feasibility or economic viability (Murthy, 2016b). On the other hand, life cycle assessments (LCA) are used to quantitatively compare the impact of various products/processes on the environment. Through LCA, it is possible to evaluate the environmental impacts of a process and the resources used for its entire life cycle i.e. from raw material acquisition to the waste generated and the

* Corresponding author.
E-mail addresses: karthik.1988@gmail.com, rajendran.k@srmap.edu.in (K. Rajendran).

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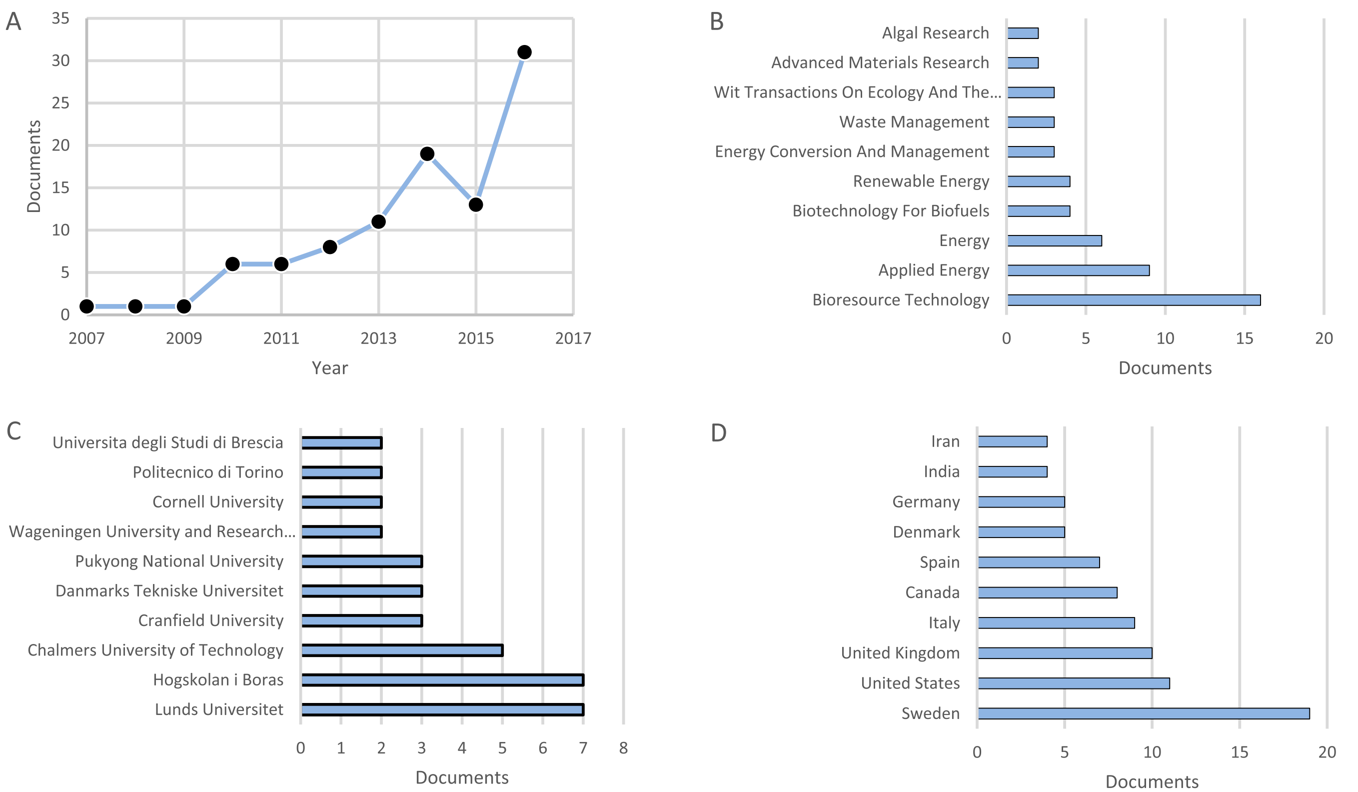

Fig. 1. A systematic review of the techno-economic analysis of anaerobic digestion based on Scopus database. (A) A number of documents published every year since 2007, (B) The journals which published the most number of techno-economic articles, (C) The universities which work the most of the techno-economic analysis of anaerobic digestion while (D) shows the countries that contribute the most to the techno-economic analysis of anaerobic digestion.

consumption of the product. LCA provides a comprehensive analysis including GHG emissions, human health, resource utilization, etc. (Murthy, 2016a).

This review article attempts to summarize the techno-economic aspects and life cycle assessments of the various AD based process including collection and transportation, processing and upgrading for end use applications. While there are several reviews in literature focusing on different aspects of AD processes, this is the first comprehensive review of the AD process that investigates the tri-fold sustainability metrics which could help in identifying challenges and opportunities in this area. Furthermore, a systematic review of the peer-reviewed literature was performed to identify most active countries, universities, and the journals in the field AD process development and deployment. Finally, a critical evaluation was conducted to compare the literature to identify common issues that pose challenges to the transferability of results from one context to another. Such information is valuable for the development of standard practices for systems analysis of AD processes.

2. Methods

This section summarises the methods used to shortlist the literature using research databases. The contents were analyzed to highlight different research parameters including journals, universities etc. A systematic review is used to identify the key journals, trends, important universities or groups which work predominantly in the focus area, in this case, techno-economic analysis and LCA of anaerobic digestion. The systematic review evaluates publication data, keywords, country-wise data in a quantitative manner for a recent period.

2.1. Content analysis

For the systematic review, Scopus database was used with a given period between 2007 and 2016. The year 2017 was ignored as the publication data is not complete. The records were collected using the following keywords:

Set 1: “techno-economic analysis” AND “anaerobic digestion” OR “biogas production”.
Set 2: “Lifecycle assessments” AND “anaerobic digestion” OR “biogas production”.

The set 1 is used for collecting publication information for techno-economic analysis while set 2 was used for LCA. The period between 2007 and 2016 was chosen to summarize the research that took place on techno-economic analysis and life cycle assessments on anaerobic digestion during the last decade. The research on the techno-economic analysis of anaerobic digestion started dates to 2003, while LCA on anaerobic digestion started in 1998. The gap between the first publication reported for LCA and TEA was around 5 years, which shows that the importance of environmental impacts was a primary concern for AD technology followed by the studies related to economic viability. Perhaps, this is also a result of prior work in AD that was done in 1970–2000 with a primary focus on decentralized AD treatment systems for waste management and household energy production in developing countries. Between Jan 2007–Apr 2017, 101 publications have been recorded in Scopus on techno-economic analysis. While on average, only one publication was published between 2007 and 2010, the publications on techno-economic analysis of anaerobic digestion showed a rapid increase since 2010. The number of documents published every year increased and in 2016 a peak of around 31 publications as recorded in Scopus. The complete literature which was used to analyze these data can be found in the supplementary file 1. The early publications reported manual calculations for economic analysis, and after 2010 use of process simulation software such as Aspen Plus and

Superpro Designer program was prevalent for TEA. The top five journals which published most articles include Bioresource Technology which accounts for 15 articles, followed by Applied Energy (9), Energy (6), Biotechnology for Biofuels (4), and Renewable Energy (4). Other journals include Energy conversion and management, Waste management and algal research. The top 5 publishing countries were Sweden (19), United States (11), UK (10), Italy (9) and Canada (8) (Fig. 1).

Regarding the universities, that contribute to the techno-economic analysis of biogas production include Lund University (7), University of Boras (7), Chalmers University of Technology (Sweden) (5), Cranfield University (UK) (3), Technical University – Denmark (3) (Fig. 1). It is worth mentioning that all the top contributors on techno-economic studies of biogas production were from EU, and which has the most number of industrial installations for biogas production supported by favourable governmental policies. Additionally, many EU nations also formulated special laws to avoid landfilling which provided additional incentives for commercialization and was reflected in the number of studies focused on making the anaerobic digestion technology economically feasible. The citation of the techno-economic studies started to kick off only since 2011 were 43 citations were reported, and in 2016 it was 362 citations which are seven times higher growth in a 6-year period. About 75% of the documents reported were original research articles, while 18% corresponds to conference proceedings. About 3% were review papers, however, those reported reviews when analyzed only had a section on techno-economics and no dedicated paper was found on summarizing the anaerobic digestion technology in terms of techno-economic analysis perhaps reflecting an evolving field.

Similarly, for LCA on anaerobic digestion was performed using the keyword in set 2. Between Jan 2007–Apr 2017 about 520 articles were published, which is five times more publications records compared with techno-economic analysis. This also shows that LCA has been carried out for a while, while TEA had emerged with the advancement in computer and software development. Compared with TEA, LCA on anaerobic digestion was well established and the peak in TEA (2016-31 documents) was reached in 2010. In 2015, about 100 publications were reported in Scopus containing LCA and anaerobic digestion or biogas production as a keyword. This shows that environmental impacts were more studied than economic feasibility and in the recent times, the profitability of the anaerobic digestion has been questioned which is why the number of TEA studies is increasing along with the LCA. In 2015, the number of publications decreased to 85, which needs to be addressed with further data points, whether the research on LCA aspects of anaerobic digestion was saturated or it represents a temporary fall (Fig. 2).

The five top most journal which published LCA aspects on anaerobic digestion technology includes Journal of cleaner production (62), Bioresource Technology (45), Waste Management (37), International journal of life cycle assessment (25), and Applied energy (21). Other top journals include Environmental science and technology, Science of the total environment, Resources conservation and recycling, Waste management & research, and Journal of environmental management. When analyzed TEA and LCA together some journals scope falls for both the aspects including Bioresource Technology, Applied Energy, Journal of cleaner production and Waste Management. Italy leads the country wise publications with 69 publications reported between 2007 and 2016, and the other countries are as follows: United States (67), Germany (45), UK (45), and Sweden (42) (Fig. 2). It is evident again that the leaders in TEA countries such as Sweden, Italy, USA, UK lead other countries in LCA aspects as well. However, Europe dominates rest of world when it comes to the LCA of AD process.

The research groups/universities which focus on LCA were slightly different from that of TEA of biogas production. Technical University – Denmark reported the highest publications on LCA aspects of anaerobic digestion (24) followed by Universidad de Santiago de Compostela, Spain (14), Swedish University of agricultural sciences (12), University of Milan (12), and Ghent University, Belgium (11). This clearly shows the difference in leaders of two different metrics of anaerobic digestion. The citation for LCA aspects on anaerobic digestion started to increase rapidly by 2009 reaching more than 100 citations, and in 2016 alone 2,111 citations were reported, and the cumulative citations add to 9,250 between the period 2007–2016. About 80% of the documents reported were original research articles followed by conference papers which add 8% of the overall publications reported between 2007 and 2016. The review on LCA aspects of anaerobic digestion corresponds to 6% and other types of contributions such as book chapters and conference reviews add the rest.

3. Techno-economic analysis

The AD process technology can be broadly divided into three areas of focus, namely, feedstock production/acquisition and transport; pretreatment and anaerobic digestion; biogas post processing/utilization and coproduct handling. Similar to these fundamental processing aspects, three sections can be identified in the techno-economic analysis of the solid waste/energy crop treatment for AD: 1. The unit operations associated with collection and transportation of feedstocks to the site of treatment. 2. The second section involves the processing of the feedstocks arriving at a treatment facility to produce biogas production. 3. The final section involves the costs associated with upgrading the biogas for different applications including electricity, liquid methane or for household cooking. This section covers the techno-economic challenges around the biogas production from solid waste. Costs associated with the complete value chain of AD for solid waste are summarized in Fig. 3.

3.1. Collection and transportation of feedstocks

Collection and transportation of feedstocks are generally accomplished using trucks/trailers or manual collection methods. The world bank reported that corporations or municipalities spend 20–50% of the budget on collection and transportation services (Daniel and Perinaz, 2012). The collection and transportation costs vary depending on the geographical location and cost of the local labour involved with it (Daniel and Perinaz, 2012). In the United States, the curbside collection and transportation cost $2.27/ton/km, while in Thailand the cost varies between $2.9 – 10.4/ton (Daniel and Perinaz, 2012; Koushki et al., 2004). The costs associated with the collection and transportation of waste are often imposed on the waste generators and are called tipping fees. The tipping fee is collected in two ways, i.e., a flat fee for every month for each household irrespective of the amount of waste produced or the fee is based on the amount of waste produced. For example, in Ireland, the cost of waste collection at household varies a flat rate between $22 – 35/month (1€ = 1.13$)(Daniel and Perinaz, 2012; Koushki et al., 2004).

It is estimated that transporting the wastes more than 25 km is not economically feasible and it is essential to decentralize the anaerobic digestion facility in high waste generation countries/cities such as India and Hong Kong (Rajendran et al., 2014). Municipalities are responsible for the waste collection, and sometimes municipalities authorize certain private companies to do door-to-door garbage collection. The waste collection efficiency varies depending on the average income within the country (Table 1). There is a wide variability in the amount of waste generated per capita, the volume of waste generated and overall collection efficiencies among different countries (Table 2). For example, Sweden, Germany, and Japan treat more than 50% of their waste using incineration, while in developing countries such as India, Nigeria, and Romania more than 80% of the wastes are landfilled (Taherzadeh and Rajendran, 2014). On the other hand, India has the lowest per capita waste generation while US has the highest total volume of the MSW generated among all countries. It is important to note that the high overall collection efficiencies and recycling are often found in the relatively low population, high-income countries with high human

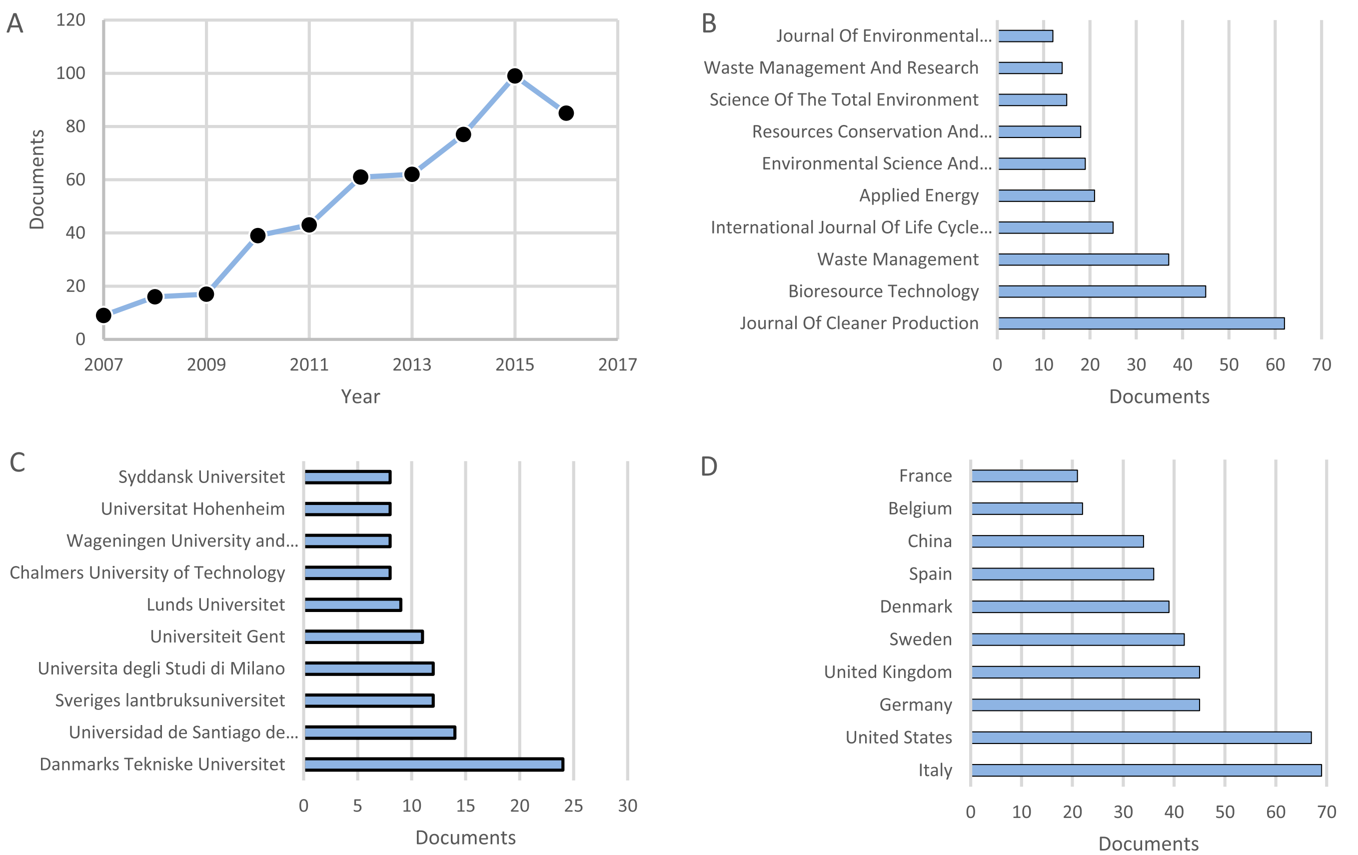

Fig. 2. A systematic review of life cycle assessments of anaerobic digestion based on Scopus database. (A) A number of documents published every year since 2007, (B) The journals which published a most number of life cycle assessments, (C) The universities which work the most of the life cycle assessments of anaerobic digestion while (D) shows the countries that contribute the most to life cycle assessments of anaerobic digestion.

development indices. In these countries, the volumes of total MSW produced are also lower and have a more organized system for collection and disposal of MSW. Translating the results from one context to the other requires careful considerations of scalability and feasibility of collection and disposal mechanisms.

Wastes are collected in trucks and some of the municipalities across the globe do not have access to trucks, and the waste collection efficiencies were less than 40%. Despite much investments by local governments and World Bank investments of $4.5 billion on 329 waste treatment-related projects in the Indian subcontinent, Africa, Argentina and Morocco, additional investments are needed for infrastructure developments. The collected wastes are transported using a small van/lorry to a temporary storage site and further transported to the final treatment sites in larger trucks (Daniel and Perinaz, 2012; Koushki et al., 2004).

3.2. Biogas production

The feedstocks arriving at the treatment facility for biogas production are usually stored in a silo or open facility. Then the substrate is

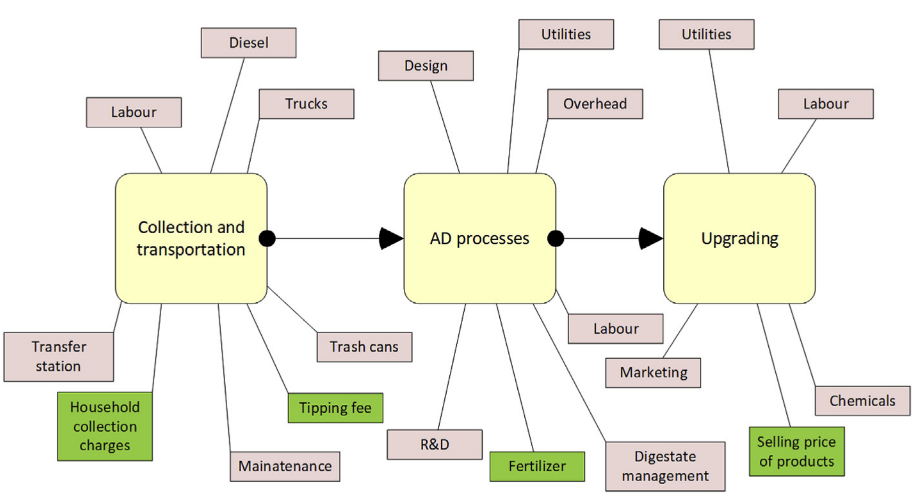

Fig. 3. Various costs associated with the value chain of waste treatment from collection to products generation. The green colour indicates the possible revenue, while the red colour indicates the possible expenses or costs associated with it. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Estimated Solid Waste Management Costs by Disposal Method adapted from (Daniel and Perinaz, 2012).

Category	Low-Income Countries	Lower Middle-Income Countries	Upper-middle Income countries	High-Income Countries
Income (GNI/capita)	< $876	< $876 - 3465	$3465-10725	$10725
Waste generation (tons/capita/year)	0.22	0.29	0.42	0.78
Collection Efficiency (percent collected)	43%	68%	85%	98%
Cost of Collection and Disposal (US $/Ton)				
Collection	20–50	30–75	40–90	85–250
Sanitary landfill	10–30	15–40	25–65	40–100
Open dumping	2–8	3–10	NA	NA
Composting	5–30	10–40	20–75	35–90
Waste to energy Incineration	NA	40–100	60–150	70–200
Anaerobic digestion	NA	20–80	50–100	65–150

size reduced using milling process and water is added before temporary storage (Sawatdeenarunat et al., 2016). The stored liquid substrates act as backup for regular feeding to the digester to avoid any technical problems during milling and ensure availability of substrate to the digester (Jeihanipour et al., 2013). The biogas production yield and rate in the main digester depend on the processing conditions such as operating temperature, organic loading rate, hydraulic retention time and feedstock characteristics (VS content, composition, and moisture content) (Aslanzadeh et al., 2014; Rajendran et al., 2012). There could be several operational problems such as dead volume accumulation, mixing issues, and pump failures among others that affect the stability of gas production. After digestion, the liquid stream rich in NPK is usually sent to post-digestion tank, where still some biogas production occurs. The biogas production in the post-digestion tank is less than 3 – 5% of the main digester, and most post-digestion tanks are not temperature controlled. The digestate is dewatered and/or sold as fertilizers to the farmers after that while the gas stream rich in methane is processed for purification and its final application (Rajendran et al., 2014).

The techno-economic studies were usually performed over this value chain from the substrate/feedstock on site to the production of different products such as CHP, vehicle fuel or electricity (Hawkes et al., 2009; Kempegowda et al., 2012). Many techno-economic analyses focused on the use of biogas as a vehicle fuel as the common product and is a leading technology indicator of the emerging applications for biogas (Morgan-Sagastume et al., 2016; Nakakubo et al., 2012). There are fewer techno-economic analyses for the combined heat and power (CHP) and electricity generation from the biogas indicating the maturity of these application areas (Akbulut, 2012; Hawkes et al., 2009). A summary of techno-economic studies including the feedstocks, operating conditions such as organic loading rate (OLR), and hydraulic retention times (HRT), methane yields, capacity, application, payback period, internal rate of return (IRR), capital expenditure (CAPEX) and Operational expenditure (OPEX) was mentioned in Table 3.

Several analyses reported in literature performed only a partial TEA focused on changing some aspect of an existing facility or considered only a part of the value chain. For example, García-Gutiérrez et al. (2016) considered the upgrading of biogas using ionic liquids as a physical absorbent and not the entire product chain. Such studies are helpful in understating the economic behaviour of the unit operations, however, they are not useful for assessing the complete process chain. Several techno-economic studies also considered biogas as a part of ethanol production, where stillage or thin-stillage post distillation of ethanol was sent to anaerobic digestion for the production of biogas (Barta et al., 2010; Bravo-Fritz et al., 2016; Frankó et al., 2016; Joelsson et al., 2016; Rajendran et al., 2015; Shafiei et al., 2011). Kontokostas and Goulos (2017) considered the TEA of gas turbines after AD for using biogas as a fuel.

Feedstocks reported in the techno-economic analysis could be classified into the conventional substrates such as MSW (Khan et al., 2016; Sills et al., 2016), manure/farm scale plants (El Defrawy and Shaalan, 2003; Salsabil et al., 2010) or municipal wastewaters (Balussou et al., 2012) and the alternative/futuristic feedstocks including lignocelluloses, energy crops (Gonçalves et al., 2016; Shafiei et al., 2011), microalgae (Zamalloa et al., 2011) etc. The capacities reported in techno-economic analysis varied between 20,000 and 200,000 tons of annual processing capacity, while the capital investments (CAPEX) ranged between 25 and 165 M$ (Table 3). The internal rate of return (IRR) ranged between 20 and 7% for the small-scale and industrial-scale facilities respectively (Table 3). Biogas, when used as cooking fuel replacing Liquified Petroleum Gas (LPG), the studies showed payback period between 5 and 10 years. This is due to the fact that, IRR is subjective where depending on the demand, application and location of the plant, as in developing countries energy demand is more, using small-scale digesters saves a large fraction of the money. Whereas industrial processes are predominant in the western world where the application is mainly electricity, heat or vehicle fuel which requires upgrading, processing, labour etc. as additional costs that bring the IRR down.

3.3. Biogas upgrading

The third section of the techno-economic evaluation deals with the

Table 2
Waste management strategies in different countries across the world, adapted from (Taherzadeh and Rajendran, 2014).

No.	Countries	GDP ($ /per capita/year)	Population (millions)	MSW generation (M tons/year)	Organics in MSW (%)	Recycling (%)	Incineration (%)	Compost/biological treatment (%)	Landfilling (%)
1	Sweden	43180	9.6	4.4	35	34	50	15	< 1
2	India	3876	1234	90	40–60			8	> 80
3	Nigeria	2661	173	25	50–60	8 *			> 90
4	USA	49965	316	389	25		7		70
5	Japan	35178	127	51	26	18	74	5	< 3
6	Indonesia	4956	237	55	55	15*		3	69
7	Denmark	42086	5.6	9.5	40	24	53	18	< 1
8	Brazil	11909	201	95	52.5	1.2			96
9	Romania	16518	20	21					> 99
10	Qatar	98,329	1.9	2	57			15	80

Table 3
Summary of different techno-economic studies on anaerobic digestion.

Feedstock	OLR	HRT (days)	T (°C)	Methane yield	Capacity	CAPEX	OPEX	Payback period (years)	IRR (%)	Application	Reference
Microalgae	20 kg VS/m^3/day	2.3	30	0.5 m^3/kg VS	70-110 Ton DM/hd/year	21–24 M$	3.4–3.9 M$	5.5–10	-7to17	CHP	Zamalloa et al. (2011)
Forest residues + OFMSW	–	20	55	0.470 Nm^3/kg VS	300000 Tons DM/year	164 M$	118 M$	–	20.70	Vehicle fuel	Teghammar et al. (2014)
Wheat Straw	29.4 t/h	20	55	70.5 Million Nm^3 /year	200000 Tons DM/year	70M$	0.63$/$m^3$	5	–	Vehicle fuel	Shafiei et al. (2013)
Paper tube residuals	26.3 t/h	20	55	70.5 Million Nm^3 /year	200000 Tons DM/year	72M$	0.76$/$m^3$	5	–	Vehicle fuel	Shafiei et al. (2013)
OFMSW	150 m^3/day	19	55	9600 m^3/day	55000 tons/year	34.6 M$	–	10	–	Vehicle fuel	Rajendran et al. (2014)
OFMSW	1.4 kg VS/m^3/day	75	20	570 L/kg VS/day	4–6 kg/day	100 $/m3	10 $/year	3.27	30–40	Cooking	Rajendran et al. (2013)
olive mill pomace and pig slurry	3.68 kg VS/m^3/day	24	37	150–275 L/kg VS/day	8750 t/year	1.31 M$	0.17 M$	6.7	–	Vehicle fuel	Orive et al. (2016)
Forest residues	2.5 t/h	20	55	0.23–0.34 m^3/kg VS	20000 tons/year	56–60 M$	–	< 8	12	Vehicle fuel	Kabir et al. (2015)
Dairy waste	2.29 DM/m^3/day	33	40	300 m^3/t DM	29200 t/year	11.5 M$	–	3.4	–	CHP	Akbulut (2012)

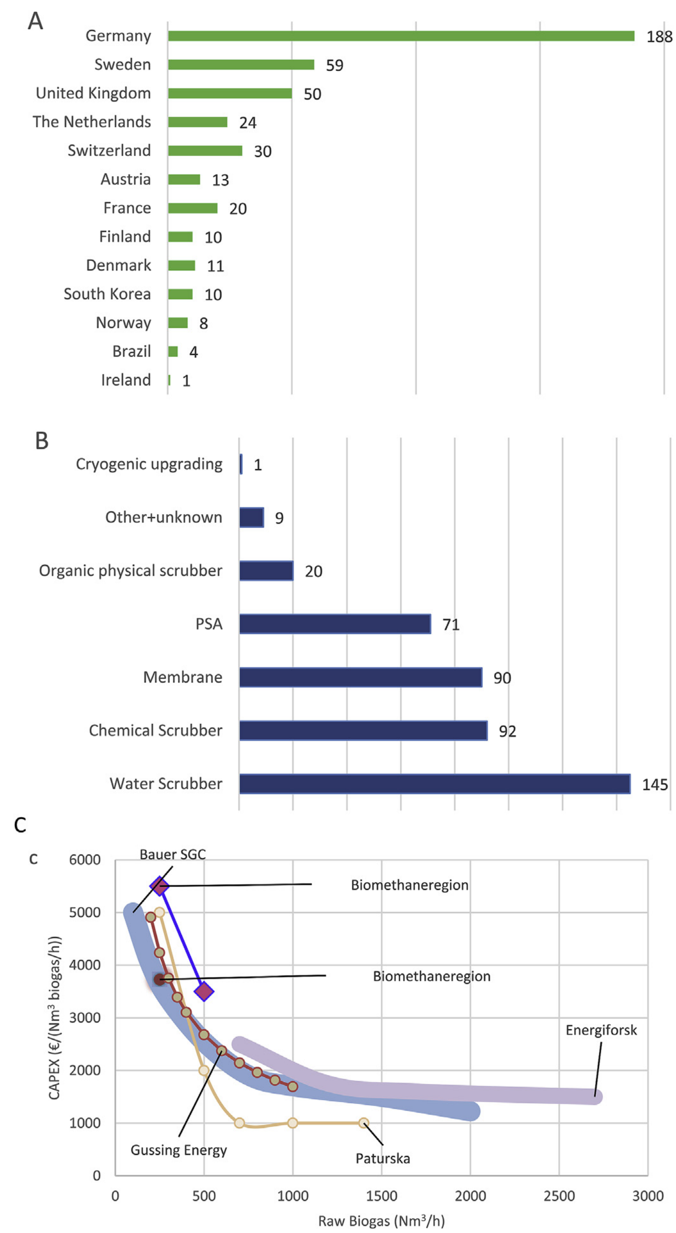

Fig. 4. A number of biogas upgrading sites installed within Task 37 countries of IEA based on countries (A), based on upgrading technologies (B), costs of different technologies based on their scale (C) adapted from (Bauer et al., 2013; International Energy Agency, 2015).

costs involved in biogas purification for different application including electricity, the power-to-gas or vehicle fuel. There are different biogas upgrading technologies available including water scrubbing, amine absorption, pressure swing adsorption, membrane separation, organic solvent scrubbing, and cryogenic separation. In the early 2000s, only 20 biogas upgrading facilities were built and this number had increased significantly since then especially in Europe due to government subsidies and support. Until 2015, more than 428 biogas upgrading facilities have been reported according to IEA Bioenergy Task 37 (International Energy Agency, 2015). Germany (188), Sweden (59), UK (50) (Fig. 4A) were the global leaders in installing biogas upgrading facilities for liquid fuel production. These three countries correspond to more than 67% of biogas upgrading facilities installed in the world. The three main types of upgrading technologies commissioned include water scrubbing (34%), chemical scrubbing (21%) and membrane separation (21%) (Fig. 4B). While membrane separation had gained high

Table 4
Summary LCA studies related to anaerobic digestion since 2016.

Reference	Goal and Scope	Functional Unit	System Boundary					Coproducts and allocation strategy	Impact Assessment Method	Sensitivity Analysis	Feedstock type	Country
			Feedstock production and Collection	Anaerobic Digestion	Biogas Upgradation	Product use	LUC					
Ciliberti et al. (2016)	Compare areal productivities of AD and wind farms	1 MWh	No	Yes	NA	Yes	Yes	NA	NO	Yes (Milk prices and farm costs)	dairy waste water	USA
Di Maria et al. (2016b)	Co-digestion of sewage sludge and fruit and vegetable wastes	1 MT WMS +80 Kg Fruit and vegetable wastes on a wet basis.	No	Yes	NA	Yes	No	Yes, System expansion	ILCD Metrics	Yes (OLR and HRT)	Co-digested fruit and vegetable waste with waste mixed sludge from municipal wastewater treatment plants.	Italy
Edwards et al. (2017)	Co-digestion of sewage sludge and municipal food waste	Annual quantity of the sewage sludge and food waste at local city government level.	No	Yes	Yes	Yes	No	Yes, System expansion	CML-IA	Yes	Sewage sludge and sorted food waste	Australia
Blanco et al. (2016)	AD of sewage sludge	37 tons/Day of dewatered Sludge	No	Yes	No	Yes	No	Yes, System expansion	ReCiPe v.1.08 (midpoint)	No	Sewage sludge	Spain
Collet et al. (2017)	AD of sewage sludge and methanation	1 MJ of Methane	No	Yes	Yes	Yes	No	Yes, System expansion	GHG Emissions; ReCiPe v.1.08 (endpoint)	Yes (Change in electricity mix)	Sewage sludge	France
Eriksson et al. (2016)	AD of food waste and sewage sludge	Annual quantity of the sewage sludge at local city government level.	No	Yes	No	Yes	No	Yes, System expansion	CML 2001 (GHG results only)	No	MSW	Sweden
Ertem et al. (2016)	Electricity production from agriculture feedstock	1 kWh electricity	Yes	Yes	Yes	Yes	No	No	ReCiPe v.1.06 (midpoint) and CED v.1.08	Yes (OLR)	Co-digestion of maize (or sunflower, horse manure and biogenic waste), grass, rye silage, and chicken manure	Germany
Ertem et al. (2017)	Electricity production from microalgal feedstock	1 kWh electricity	Yes	Yes	Yes	Yes	No	Yes, System expansion	ReCiPe v.1.06 (midpoint)	No	Co-digestion of marine microalgae or maize, grass, rye silage, and chicken manure	Germany
Jensen et al. (2016)	Compare organic waste management systems	1 MT of organic waste	No	Yes	No	No	No	NO	A method with similar indicators as specified in ReCiPe midpoint metrics	No	Organic waste	Danish-Germany border region
Kral et al. (2016)	Biogas from pretreated maize silage	1 kWh electricity	Yes	Yes	No	Yes	No	NO	ReCiPe v.1.08 (mid-point) and ILCD 2011	Yes	Maize Silage	Austria
Igos et al. (2016)	Assessing rye cover crop for bioenergy production	1 MJ of bioenergy (36% electricity and 64% heat)	Yes	Yes	No	Yes	No	Yes, System expansion	ILCD Metrics	Yes	Ryegrass	Belgium
Iordan et al. (2016)	AD of co-digested sewage sludge and organic wastes	1 MJ of electricity	No	Yes	No	Yes	No	Yes, System expansion	A method with similar indicators as specified in ReCiPe midpoint metrics	Yes	Sewage sludge and organic wastes	Norway

(*continued on next page*)

Table 4 (*continued*)

Reference	Goal and Scope	Functional Unit	System Boundary					Coproducts and allocation strategy	Impact Assessment Method	Sensitivity Analysis	Feedstock type	Country
			Feedstock production and Collection	Anaerobic Digestion	Biogas Upgradation	Product use	LUC					
McNamara et al. (2016)	LCA of wastewater treatment plants	0.2 m3 of wastewater	No	Yes	No	No	No	No	CML 2001	No	Sewage sludge	Ireland
Morero et al. (2016)	AD of co-digested sewage sludge and MSW	21000 MT sludge	No	Yes	Yes	Yes	No	Yes, System expansion	CML 2001	No	Sewage sludge	Argentina
Naroznova et al. (2016)	Compare AD and Incineration of household organic wastes	1 kg of waste	No	Yes	No	Yes	No	Yes, System expansion	ILCD 2011	Yes	Domestic organic waste	Denmark
Nayal et al. (2016)	AD of Agricultural farm waste	10680 MT waste/year	No	Yes	No	Yes	No	Yes, System expansion	EDIP 2003	No	Agricultural Wastes	Turkey
Oldfield et al. (2016)	Food wastes and food residues	126749 MT waste/year	No	Yes	No	No	No	Yes, System expansion	A method with similar indicators as specified in ReCiPe midpoint metrics	Yes	Food wastes	Ireland
Pierie et al. (2016)	Spatial analysis of AD potential	GJ/Km2	No	Yes	Yes	Yes	No	Yes, System expansion	GHG Emissions: EROI	Yes	Mixed feedstocks	Netherlands
Postacchini et al. (2016)	Comparative analysis of activated sludge, trickling filter and high rate anaerobic-aerobic digestion	11,680,000 L/day wastewater	No	Yes	No	No	No	Yes, System expansion	IMPACT 200 + and TRACI 2.0	No	Wastewater	USA
Rana et al. (2016)	GHG emissions of Agro-biogas energy system	1 MW	Yes	Yes	No	No	No	No	RED methodology	No	Mixed feedstocks	Italy
Righi et al. (2016)	LCA of lignocellulosic biomass pyrolysis with AD	1 MT of dried corn stover	No	Yes	No	Yes	No	Yes, System expansion	CML 2001	No	Corn Stover	Italy
Shimako et al. (2016)	LCA of microalgae AD	1 MJ of energy	Yes	Yes	Yes	Yes	No	Yes, exergy-based allocation	ReCiPe 2008	No	Microalgae	France
Styles et al. (2016)	Consequential LCA of AD in the UK	1 MT of feedstock	Yes	Yes	Yes	Yes	Yes (ILUC)	Yes, System expansion	CML 2010	Yes	Mixed feedstocks	UK
Tagliaferri et al. (2016)	Comparison of two AD strategies	1 MJ methane and 1 kg MSW	No	Yes	No	No	No	Yes, System expansion	Not specified	No	MSW	UK

popularity in a short span of time, there are challenges such as demonstration of stable operation for a long period of time, in reality, economic viability, and a lifetime of the membranes that impede their adoption. A lifetime of membranes is commonly assumed to be between 5 and 10 years, however, reality doesn't support this assumption (Bauer et al., 2013).

The investment cost for the biogas upgrading facilities is primarily based on the throughput of the gases based on the economies of scale principle. For example, amine scrubbers are expensive when operated at lower throughputs however, they become comparable to other upgrading technologies at higher processing capacities (Bauer et al., 2013; Bishnoi and Rochelle, 2000). When the raw biogas processing exceeds 1,500 m^3/h it was found that there was very little difference between the capital costs of scrubbing and pressure swing adsorption (PSA) technologies (Starr et al., 2014) (Fig. 4C). Membrane separation is an appropriate choice in the mid-range category (1200–1300 m^3/h) but is not the most economical choice at high processing capacity due to lower benefits from economies of scale (Bauer et al., 2013; Tomei et al., 2016; Zhang et al., 2001).

In general, the energy consumption during AD reduces with an increase in the throughput of the biogas while site-specific values are dependent on ambient temperatures and operating conditions. The energy efficiency of water scrubber is not affected by the composition of the biogas, whereas for PSA the energy consumption is dependent on the carbon dioxide concentration (Alonso-Vicario et al., 2010). The energy consumption in water scrubber ranges between 0.20 and 0.30 kWh/ m^3 for 400 – 2000 m^3/h gas throughput. The reported values for energy consumption in PSA was also similar between 0.2 and 0.3 kWh/ m^3, these values are similar to membrane separation systems, though actual values are dependent on the type of membrane and operational aspects (Santos et al., 2010). Amine scrubbers consume the lowest energy of the different upgrading methods reported between 0.12 and 0.14 kWh/ m^3, however, it also requires heat in the about 0.55 kWh/ m^3. The heat is used to recover the amine regeneration and the rejected low-quality heat can be used for other applications such as heating the digester (Alonso-Vicario et al., 2010; Bauer et al., 2013; Santos et al., 2010).

Apart from energy consumption, depending on the type of the biogas upgrading method certain consumables such as anti-foaming agents were necessary for water and amine scrubbing method. Similarly, in the water scrubbing method, not all water can be recycled and freshwater inputs (20 – 200L/h) are needed to the system to avoid buildup of particulates and trace compounds. Hydrogen sulphide removal is essential and activated carbon is used for sulphur absorption in most upgrading techniques. However, water scrubbing method can remove both hydrogen sulphide and carbon dioxide and so activated carbon might not be essential for this upgrading method (Bauer et al., 2013).

Different techno-economic assessments have been reported on various biogas upgrading technologies including power to gas (Collet et al., 2017; Parra et al., 2017), upgrading using CO_2 facilitated membrane (Deng and Hägg, 2010), biogas to liquid fuel using Fischer-Tropsch synthesis (Okeke and Mani, 2017), a hybrid process employing gas permeation membrane with normal upgrading equipment (Scholz et al., 2013; Shao et al., 2012), CHP (Barta et al., 2013), hydrogen sulfide removal using sewage sludge for adsorption as a upgrading method (Aguilera and Gutiérrez Ortiz, 2016), ionic liquids as absorbents for upgrading biogas (García-Gutiérrez et al., 2016), hythane upgrading (Huang et al., 2017), syngas from biogas (Haro et al., 2016).

4. Life cycle assessments

Life Cycle assessment has been used as a valuable tool to evaluate the environmental impacts of the AD technologies. Since the AD was primarily looked upon as a waste management and decentralized energy production technology in the last few decades, the emerging LCA techniques were applied to the AD. AD technology has been practised for over 100 years and the impetus for reducing GHG emissions and renewable energy production spurred application of LCA methods to assess environmental impacts of AD technologies under various settings. With an explosion in the number of papers related to LCA of AD systems in the last two decades, there have been several reviews focused on summarizing the efforts of past decade. These LCA reviews emphasized different aspects of the AD technologies such as using AD for co-digestion of food wastes (Chiu and Lo, 2016; Piao et al., 2016; Righi et al., 2013); community scale applications (Tiwary et al., 2015); agricultural residues (Bacenetti et al., 2016); utilization of municipal solid and liquid wastes for bioenergy production with a focus on algal biomass/biofuel application (Chen et al., 2016); biogas production in Europe (Hijazi et al., 2016). A detailed summary of the LCA studies not covered by the above review papers is presented in Table 4.

AD plants in operation can be classified into two main areas based on their primary focus on waste remediation or bioenergy production. Most of the plants in Europe are focused on bioenergy production while in the rest of the world, the primary focus of AD technologies is waste remediation. The difference in focus is reflected in the functional units, system boundary, size of plants and the feedstock production processes in the LCAs. While the functional units in case of bioenergy focus are primarily energy produced through the AD process, the functional units are defined in terms of the waste handling capacity for the waste management focus LCAs.

The LCA standards are described in ISO-14040–14044 (International Standard Organization, 2006) and are typically followed by most studies although not to the fullest extent. Most of the LCA studies are focused on attributional LCA while only a limited number of consequential LCAs are performed in the literature (Bacenetti et al., 2016; Tagliaferri et al., 2016). Perhaps, this is due to the fact that the policy drivers incentivize the environmental impact assessment for an individual farm which is addressed by the attributional LCA. The impact assessment methods used in the LCA studies varies and is primarily dependent upon the geographical region. European LCA studies tend to use ReCiPe, CML and ILCD while studies from the USA also use TRACI.

Variability in the LCA has been a recognized problem and reasons for the variations have been variously attributed to different goal and scopes, functional units, system boundaries, reported units, data quality and location specificity of many assumptions (Cherubini and Strømman, 2011; Tufvesson et al., 2013). This poses severe challenges for deriving generalizable trends from particular LCAs performed for a particular location under a given set of assumptions and extending the results to another study area. Despite several standardization initiatives such as ISO-14040-14044 (2006), the variations remain. A possible solution to address this challenge and collate LCA studies for deriving generalizable results is the use of Monte Carlo based sensitivity analyses (Laurent et al., 2014a, 2014b). report that only 50% of the 200 LCA studies included sensitivity analyses. While sensitivity analyses were not common in earlier LCA studies they are more common and are included by default in recent LCA studies (Table 4). It is important to identify the sources and understand the impact of various uncertainties in LCA inputs. Di Maria et al., 2016a, 2016b was one of the first reports for AD technologies that looked into the propagation of uncertainties in the LCA using the inputs specified as average values with a variance. The authors used Monte Carlo simulations and compared the uncertainties for two bio-waste management strategies. Some sources of variability associated with input data or model parameters can be reduced through better data collection and higher quality data. However, some sources of uncertainties such as the uncertainties associated with field emissions due to soil variability and weather variability cannot be controlled and will have to be accounted in any LCA study (Tabatabaie and Murthy, 2017). This is especially important for studies that focus on using AD for bioenergy production using dedicated energy crops as feedstocks.

Di Maria et al. (2016a) conducted a detailed LCA for co-digestion of sludge from wastewater treatment plants with fruit and vegetable wastes. Their study concluded that the environmental benefits associated with renewable energy and the fertilizer value of coproducts were critical to the positive environmental impacts. Edwards et al. (2017) performed a detailed comparative analysis of conventional municipal wastewater treatment with co-digestion of sewage sludge with sorted food waste in an anaerobic digester. They found that while the AD technologies offer a significant advantage compared to conventional municipal wastewater treatment technologies, the coproduct credits have a significant influence on the final results. Interestingly, their sensitivity analysis indicated that with the improved household sorting of food waste, the benefits of AD compared to regular Municipal Wastewater Treatment Plant (MWWTP) could decrease by about 25%. This can be attributed to the decrease in the available food waste feedstocks for AD process due to improved segregation of food waste at source. Their results are similar to other LCA studies that point (Bacenetti et al., 2016) out that there is a significant contribution of the coproduct credits to the environmental benefits associated with AD technologies. This is especially important for processes that use dedicated agricultural feedstocks for dedicated bioenergy and are driven by policy imperatives to reduce environmental impacts (Edwards et al., 2017).

Ciliberti et al. (2016) compared to wind farms and AD technologies and concluded that the cost-benefit ratio of wind farms was 2.15 while for AD facilities this was 1.2. Additionally, they also found that both energy and revenue generated per hectare of land for wind farms were almost two times larger compared to AD facilities. They also identified that incentives in the range of 16 – 39% of capital costs need to be provided to bring the AD electricity on par with wind farm generated electricity. Lack of policy drivers was suggested as a primary reason for non-adoption of the AD technologies.

4.1. Emerging issues

While attributional LCA are used to characterize the performance of an individual facility, the importance of consequential LCA for formulating the policies cannot be overemphasized. This is especially the case when seen in the context of uncertainties during the feedstock production stage for bioenergy focused AD technologies which are primarily driven by policy imperatives rather than the process economics. Another critical issue that has been virtually ignored in almost all LCA studies is that they consider feedstocks such as food waste as having zero upstream environmental impacts. For example, if a consumer purchases 10 kg of food and only 7 kg of the food are consumed producing 3 kg of food waste, the entire burden of the upstream LCA impacts for food is attributed to the 7 kg of consumed food and the 3 kg of food waste is considered to have zero impacts. Therefore, conducting a simple cradle to gate attributional LCA of an AD facility would suggest that increasing food waste, thus producing more ‘zero’ cost feedstock for AD facilities will be environmentally beneficial. In the above example, it is similar to a consumer who consumes only 5 kg and produces 5 kg of food waste thus increasing the ‘zero’ cost feedstock for the AD facility. However, the environmental burdens of food production are significant and food waste reduction is an imperative to meet the needs of the growing populations. This implies that consequential LCA studies must be conducted to assess the true burdens of using food waste for energy production. Therefore, there is a critical need to perform system analysis of AD technologies from cradle to grave and identify strategies that would be truly beneficial to the environment and formulate policies that would encourage such pathways.

5. Critical analysis, discussions and perspectives

Though techno-economic analysis had gained importance in the recent times, there are a lot of uncertainties in the way it has been calculated. Non-standard set of procedures, assumptions and use of data sets with varying quality pose difficulties for comparing literature values with each other and draw conclusions in a rational manner. Several assumptions are used when calculating TEA such as type of financing (equity or debt), cost and space of land acquisition, cost of the feedstock, yield of the methane from feedstock's, lifetime of the plant, time of construction, labor costs, cost of the product (methane or electricity), utilities cost however, these assumptions doesn't reflect reality which affects the calculations. Increasing transparency about the procedures and the assumptions used for TEA analyses will facilitate reproduction of results and also allow researchers to use prior work in a rational manner.

For lignocellulosic ethanol production, the NREL report is often used as a standard base scenario for researchers to compare the technical and economic details (Humbird et al., 2011). Whereas for AD, no such standard thoroughly reviewed and standard reports are available. Since biogas productions are gaining adequate attention, there is a critical need for such a detailed evaluation with extensive documentation. Within the biogas production, sources of uncertainty in the TEA and LCA revolve around the availability of feedstock, operational issues and retrofitting costs. There is a research gap which needs to be addressed focusing on the above-mentioned areas. There are certain studies which consider a large volume of the plant or increase the lifetime of the plant which makes the results look positive on the methane production, however, the underlying assumptions are not realistic. For example, Zamalloa et al. (2011) used 20 and 30 years as a lifetime of the plant, based on previously reported literature. However, the cost of replacing pumps and other equipment in the plant during such a long lifetime was not included in the calculations, which reduces the reliability of the net present value obtained after 30 years of operation. Whereas Akbulut (2012) considered the costs associated with replacing pumps, and their repairs after 10 years of operation and the results are therefore more realistic (Shafiei et al., 2013). considered in the base case, the capacity of the plant as 200,000 tons wheat straw/year which requires a 70,000-acre farm to support the feedstock needs. The availability of such a big size farms is rather limited in the world raising questions about the validity of this assumption. Additionally, It is crucial that the transportation of the feedstocks should not be more than 20 – 30 km (two-way) and increasing the distance affects the economics which is why decentralized plants are necessary than large-scale facilities for biogas production (Rajendran et al., 2014).

Most studies do not report the assumptions used to carry out the techno-economic evaluations or the provide access to simulation files which severely limits the reproducibility and replicability of the results. To standardize TEA and LCA studies, studies with standardized assumptions and greater transparency are needed to reduce/identify sources of uncertainty and advance the state of the art. It is recognized that the TEA and LCA analyses will be site specific and depend on operating conditions, therefore it is essential to describe the assumptions clearly and transparently with adequate justification. Moreover, it is critical in TEA and LCA to perform sensitivity analyses to determine the important factors. For example, a study assumed 99.5% recycle rate of NMMO a solvent, which is unrealistic considering that achieving such high recovery rates in a commercial facility is expensive and not practical (Teghammar et al., 2014). Performing a sensitivity analysis over the recovery rate could have provided more information on the overall feasibility of the process and increased the value of the study many folds (Teghammar et al., 2014). It can be concluded from many study results that unlike ethanol plants, for biogas decentralization approach would only be profitable and considering a large facility for biogas production, in reality, is worse due to the transportation costs. One could argue that centralized plants work better in EU, however when capacities or transportation distance is considered, transporting more than 40 km wouldn't be economically feasible (Rajendran et al., 2014).

6. Conclusion

Anaerobic digestion is a mature technology where many industries are unable to commercialize this technology due to market and policy drivers. This review summarized techno-economic analysis and life cycle assessments of anaerobic digestion using qualitative and quantitative approaches. The important findings from this review include variability in the assumptions used, unavailability to access data or simulation files, and inconsistent indicators across different publications led to incomparable and unreproducible results on techno-economic and life cycle assessments of anaerobic digestion. Standardization of both techno-economic and life cycle assessments including process mapping, database development, profitability indicators, and regional considerations are necessary. There is a growing need for realistic and transparent techno-economic and environmental impact analysis, that will help the policy makers and investors understand the potential of Anaerobic Digestion.

Abbreviations

AD	Anaerobic digestion
GHG	Greenhouse Gasses
IRR	internal rate on investment
LCA	life cycle assessments
LCV	Lower calorific value
NPV	net present value
PBP	payback period
ROI	return on investment
TEA	Techno-economic analysis
WWTP	Wastewater treatment plant

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bcab.2019.101207.

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