INVESTIGATING ENERGY AND ENVIRONMENTAL ISSUES OF AGRO-BIOGAS DERIVED ENERGY SYSTEMS: A COMPREHENSIVE REVIEW OF LIFE CYCLE ASSESSMENTS

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Contents

1. Introduction

~~Currently, fossil fuels continue to be widely used energy sources (Volpe et al., 2014), although they are responsible for problems associated with their production and utilisation (combustion), like: the exploitation and subsequent decrease of the natural reserves; the emission of Greenhouse Gases (GHGs) and other pollutants causing impacts to environmental aspects such as: climate changes; human health; and reduction of ecosystem quality (Collet et al., 2017). These and related problems are more and more increasing societal concern about, and are fostering efforts towards, development of new technologies, policies, commitments, and ethical principles to obtain increasing percentages of energy from renewable, clean energy sources and processes (Volpe et al., 2014; Karray et al., 2017); not to mention causing political unrest in the world, which is supporting the need for diversification of energy sources (Volpe et al., 2014).~~

~~Furthermore, for economic development sustainability, there is an urgent need to make dramatic transitions to post fossil-carbon societal systems, in as short a time as possible, due to climate changes and their present and anticipated ecological/social/economic disruptions. Therefore, it is essential to accelerate the transition to equitable, sustainable, liveable, post fossil-carbon societies, which are efficient, and equitably and accessibly priced (Chiricosta et al., 2014; Ingrao et al., 2016; Ingrao et al., 2018a).~~

~~Additionally, the scarcity of some resources and the increasing demand for materials and energy are drivers for implementing and transitioning towards equitable, sustainable post fossil-carbon societies (Ioppolo et al., 2014; Ingrao et al., 2016; Selvaggi et al., 2018). To that end, it is essential for all societies to shift from fossil fuels to renewable energy sources and from linear to circular economies, centred on closed-loop of material's management (Ioppolo et al., 2014; Ingrao et al., 2018b).~~

~~It is essential to reinsert '*quality of life*', *equity, ethics* and *future generations* into the real-world political/corporate/educational/NGO and family decision-making processes. Otherwise, it will not be possible for humans to make the urgently needed changes, soon enough.~~

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~~A growing interest is evolving for implementation of numerous renewable energy sources. Based upon the Paris Climate Change Accord of 2015, many regions, countries, cities, businesses, universities, private householders have established and are implementing ambitious targets, as such sources are abundant and environmentally friendly (Yasar et al., 2017).~~

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Biomass is considered as a valuable renewable energy source and is expected to provide more than a half of the energy demand in the near future (Ertem et al. 2017). Biomass is regarded as carbon neutral, since the share of carbon dioxide (CO_2) that is emitted through combustion is balanced by the CO_2 fixed by photosynthesis in the recent past (Karray et al., 2017).

Conventional disposal of biomass from farming and livestock activities in sanitary landfills is well known to be of high economic cost for the growers and, at the same time, generates high environmental impacts. Such could be avoided if that biomass was utilised for generation of thermal and electrical energy, also with self-consumption purposes, through production and utilisation of biofuels (Cotana et al., 2014). By doing so, both the dependence from fossil fuels and the related GHG emissions could be reduced, so favouring the transition towards equitable, sustainable, post fossil-carbon societies (Volpe et al., 2016; Ingrao et al., 2018a).

Biofuels are fuels obtained from biological resources whether they are made directly or indirectly through the well-known photosynthetic process (Yasar et al., 2017). Three generations of fuels should be addressed in this context:

a) First-generation biofuels produced, utilising edible feedstock like corn, soybean, sugarcane, and rapeseed (Karray et al., 2017). When used for energy production, those crops are regarded as '*energy crops'*. Several studies documented that the intensive exploitation of arable land for cultivation of those crops can have negative effects in terms of direct and indirect land use changes (d-, i-LUC), as other land areas need to be used for food production. Therefore, there may be a negative impact upon the global stock and increases of prices of food, and an increase of the amounts of GHGs that are emitted to the atmosphere (Ertem et al., 2017). The potential risks and attributions of iLUC affect planning for and usage of biofuels, which are still largely debated by the environmental impact assessment community. However, for the purpose of making ways to mitigate iLUC related problems the European Commission has defined a precautionary threshold of 7% for the share of first-generation biofuels that can be used in transportation. (Rana et al., 2016).

b) Second-generation biofuels are made from agriculture and food-industry residues, and from dedicated lignocellulosic feedstocks. These fuels have several advantages over the first-generation ones. They give major benefits in terms of higher stock yields and the lower land requirements in terms of quality and quantity. However, there are some economic disadvantages, at large scale, which have been observed for lignocellulose conversion to biofuels due to its strong resistance to degradation (Karray et al., 2017).

c) Feedstock for third generation biofuels is represented by micro- and macro-algae, which present further advantages compared to the previous categories (Karray et al., 2017). Algae are known to be characterised by high photosynthetic effectiveness, fast biomass growth with no arable land required and resistance to contamination from heavy metals. This makes them highly competitive compared to energy crops and second-generation fuel feedstocks (Ertem et al., 2017; Karray et al., 2017).

In this context, this paper was designed to review energy and environmental issues connected with the utilisation of those types of biomass for energy generation through application in Anaerobic Digestion (AD) plants.

Finally, after this introductory piece this paper is articulated as follows: *Section 2*, to discuss the technological and energy merits of AD and biogas production, also as the base for clearly backgrounding and reasoning this study; *Section 3* - which is the key part of this manuscript, to review environmental assessments in the agro-biogas energy field by giving details on their objectives and findings; *Section 4*, to discuss and build upon lessons learned from review of those studies; and finally *Section 5*, on conclusions and future trends related to the whole study conducted.

2. The background and reasoning for this comprehensive literature review

Energy generation is among the possible biomass applications: it can be done through a set of methods, like pyrolysis, combustion, gasification, hydrolysis, and fermentation. AD is a widely used biological process to produce biogas from biomasses containing high levels of organic matter (Nayal et al., 2016). Two end-products are generally released from biogas plants: biogas; and a nutrient rich digestate. Biogas is a mixture of methane (CH_4), CO_2 and others compounds such as hydrogen sulphide (H_2S), carbon monoxide (CO) and hydrogen (H_2). CH_4 and CO_2 contents are strictly reliant upon the feedstock used and the plant operating conditions; they generally range between 50-60% and 40-50%, respectively (Negri et al., 2014).

Digestate is a stabilised material (Nayal et al., 2016) that is generally subjected to a centrifugation treatment leading to production of a solid and a liquid fraction. The former is used as organic soil fertiliser, as a soil conditioner or as animal bedding, while the latter is partially recycled within the AD plant to feed the digester, and the other part is utilised for fertigation activities (Ingrao et al., 2015; Nayal et al., 2016). So, it is understood that, with proper application to the soil, digestate can contribute to reduction of costs for both production and usage of energy intensive fertilisers (Yasar et al., 2017).

Generation of electricity from biogas in countries, which are part of the Convention on the Organisation for Economic Co-operation and Development (OECD) grew from 3.7 TWh in 1990 to 78.8 TWh in 2015. This represented the third fastest growing renewable electricity source after wind and solar energy (Nayal et al., 2016).

As highlighted by Nayal et al. (2016), that growth was driven by OECD Europe accounting for almost 80% of the entire OECD production in 2015. Nearly, 14 ktoe of biogas primary energy was produced in the European Union (EU) in 2013: 69% of that energy was generated in decentralised agricultural plants, facilities for production of methane from Municipal Solid Waste (MSW), and centralised co-digestion plants. In their paper, Nayal et al. (2016) reported that approximately 72% of the biogas plants operating in the EU were installed in farms utilising agricultural wastes, manures, and energy crops.

Biogas production has expanded dramatically in Europe during the last 20-25 years, but it has also increased in other parts of the world, but not as rapidly. In this regard, Nayal et al. (2016)

documented that in 2013 the world biogas production increased to 59 billion m^3, which was a 5.5% increase over the previous year. This should be attributed to biogas from agricultural feedstock because AD of agricultural by-products is recognised by the EU as one of the renewable sources that can be used to produce 20% of the energy needed in Europe by 2020 (EU, 2009). In addition to this, electricity generation from AD-derived biogas was stimulated by subsidies at the regional, national and European level. Currently, Germany has the highest number of AD plants (about 9000), according to the German Biogas Association (2016), followed by Italy (1800 plants) (Negri et al., 2014; GSE, 2017).

In 2016, the installed capacity of AD facilities achieved 4166 MW in Germany and 1406 MW in Italy corresponding to an electricity production of 29.41 TWh in Germany and 8.12 TWh in Italy: the latter represented 2.56% of Italy's total national electricity-consumption (GSE, 2017). Lower production volumes were recorded in Poland, due to a much lower number of installations compared to Germany and Italy. According to Polish reports as of 25/08/2014, there were 54 operating agricultural biogas plants, with an overall installed power of 63.34 MW_e and 65.05 MWt in 2014 (Piwowar et al., 2016). On average, during the period 2011-2014, approximately 200GWh electricity and 215.75 GWh heat were produced annually in Poland from a consumption of 100 million m^3 per year.

The feedstock used in AD facilities was generally a mixture of animal manure, energy crops, and agricultural residues. The ratios of the inputs were designed to maximise biogas production, based upon the biogas potential of the mixture (Rana et al., 2016; Igos et al., 2016). Nayal et al. (2016) highlighted that 70% of biogas plants operating in the EU were installed in farms using agricultural wastes, manure, and energy crops.

Most AD plants in Europe are fed with cereal and grass silage and grain crops: among them cereal silage is favoured because of its high specific biogas production, high energy density and the ease of storage. Approximately, 50–55% of EU biogas plants´ feedstock is derived from energy crops despite the growing concern about using food crops to produce energy. In 2012, Germany used 2.5 x 10^6 ha of land for production of energy crops. Maize often provides highest yields, which makes it the preferred feedstock for bio-energy generation; thus, 90% of biogas plants in Germany run, at least partially, with maize as the primary feedstock.

In Poland, based upon data from Piwowar et al. (2016), during 2011-2014, liquid manure represented 38%, on average, of the feedstock to AD plants and was the most used substrate. Maize silage represented an average of 21.84 % of the whole feedstock used, due to the higher energy yield (in the range 87-145 GJ ha^{-1}) compared to other energy crops, was the most frequently used energy crop feedstock (Piwowar et al., 2016).

About 10% of the agricultural area dedicated to maize in Italy is used to supply biomass to feed agricultural AD plants (Negri et al., 2016; Selvaggi et al., 2018). Unfortunately, producing biogas using dedicated energy crops gives rise to environmental, social, and economic concerns due to the competition between food and non-food products regarding soil consumption. Therefore, due to environmental criticisms related to their cultivation, energy crops like maize and triticale are increasingly being replaced by agriculture and food industry residues (Valenti et al., 2018a). Co-digestion of those residues together with zoo-technical effluents (animal manure and sewage) enables achieving a better nutrient balance in AD, and provides optimum carbon-to-nitrogen ratios, while decreasing the risk of ammonia inhibition (Nayal et al., 2016). Different types of residues from the same geographical areas can be utilised, thus, supporting the creation and expansion of integrated waste management systems (Nayal et al., 2016; Valenti et al., 2018b; 2018c). This generates considerable environmental gains, in terms of energy saving, reuse and recycling of residues within agriculture, and the reduction of CO_2 emissions (Pagés-Díaz et al., 2014; Nayal et al., 2016).

Life Cycle Assessment (LCA) could be coupled with energy analyses and used subsequently to investigate the energy and environmental issues associated with agro-biogas supply chains: from feedstock production and management, to biogas production in AD plants and digestate treatment, until electricity and heat cogeneration (Ingrao et al., 2015).

Several LCA studies in Europe and worldwide were focussed upon environmental assessment of biogas production systems, thereby, creating a solid knowledge base for stakeholders like LCA practitioners, farmers, engineers, company owners, policy- and decision-makers to contribute improvements to the efficiency of the AD systems and reduction of the related environmental impacts. At the same time, comparing different LCAs was challenging due to differences in scopes, methodologies and findings, as well as due to the lack of proper documentation. However, highlighting those differences could stimulate and provide the basis for creation of guidelines and regulations for application of LCA's in the bioenergy field.

In this context, Bacenetti et al. (2016a) compared results of LCAs of agricultural AD plants at the world level by considering both methodological and operational aspects: studies considered by Bacenetti et al. (2016a) were published before 2016.

This article builds upon those studies and, integrates Bacenetti's et al. (2016) findings by selecting and reviewing papers published subsequently, thereby, they contributed to: enhancing the relevant literature in the field and to the understanding and appreciation of readers worldwide. They highlighted methodological issues and impact indicators that are appropriate indicators for environmental assessment of agro-biogas derived energy systems. Among those indicators, GHG emissions and related climate change impacts were considered, as they are the environmental impact indicators used globally (Ingrao et al., 2018 a,b). Therefore, that paper is valuable as a reference in the field, compared to Bacenetti et al. (2016), to help readers deepen the technological, operational, and environmental subjects related to biomass-AD derived biogas supply chains. In addition, highlights included in this review paper, related to environmental assessment methodology, contribute to forming the platform of relevant information for analysts to strengthen knowledge about new applications of LCA concepts and tools in the bioenergy field.

Another reason why this study was developed was that AD is a well-established, eco-friendly way to manage organic-matter rich biomass, which is increasingly being implemented as a renewable energy generation technology (Nayal et al., 2016; Fusi et al., 2016; Ingrao et al., 2018b). Additionally, AD offers environmental benefits related to: odour control; improved air and water quality; improved nutrient management; flexibility; and GHG emission reduction. Furthermore, properly designed, operated and monitored AD systems help to reduce the release of phosphorus and of copper and zinc into surface waters, when the solid and liquid fractions of digestate are properly integrated into sustainable agricultural practices (Nayal et al., 2016). Furthermore, AD of agricultural feedstocks is well documented as integral to the generation of renewable energy in rural areas where it is used locally, while the heat cogenerated with the electricity is also effectively utilised.

Therefore, the authors of this review are confident that it is important and useful to continue investigating this bioenergy production technology by addressing the related operational and energy-environmental issues.

In this context the paper authored by Piwowar et al. (2016) presented the current state-of-the-art of and the prospects for the development of the market of agricultural biogas production in Poland. The authors performed a comparative assessment of technical potentials of the existing agricultural biogas plants in Poland. Although it was limited to the Polish context, the paper deepened knowledge on AD for agricultural biomass treatment, by addressing the merits of the related technological, operational and economic issues. In contrast with other European countries like Germany and Italy, the authors reported that the market potential of the biomass-derived energy in Poland (600.167 TJ) was not fully exploited due to: organisational barriers; lack of technical and substantive consulting advise; economic barriers (inter alia, deficiency of financial aid programs for construction of agricultural biogas plants); and legal barriers (Piwowar et al., 2016).

Considering the area of agricultural land and the development of the agribusiness sector, the production potential could provide opportunities for Poland to be among the most important producers of bio-energy generated from substrates from EU agricultural products (Piwowar et al., 2016). Therefore, in agreement with Piwowar et al. (2016), actions are needed to overcome those barriers and concerns, and to stimulate production of biomass-derived energy.

In this respect, the availability of biogas markets for products from AD plants paved the road to diverse possibilities for the recovery of its energy content, starting from electricity production to more sophisticated uses, such as feeding it into the natural gas network or using it to produce biomethane for transport (Grosso et al., 2012; Ingrao et al., 2018b): these and related issues were reviewed in this paper.

3. Review of the latest environmental assessments in the agro-biogas energy field

This section was dedicated to reviewing papers, which addressed environmental assessment of biogas supply chains for energy generation. Based upon the review, six papers published in 2016, and eight in 2017, were selected: all of them focussed upon assessment of AD plants, thereby underscoring the academic and societal attention that are increasingly being shown towards such bioenergy production systems.

Nayal et al. (2016) investigated methane production in Turkey and considered a feedstock mixture comprised of slaughterhouse wastes, vegetable wastes from cultivation and harvesting, poultry and cattle manure, and grass from cultivation. The researchers performed LCA to compare two options (AD vs. combined-cycle gasification) for production of the same amount of energy. The Functional Unit (FU) of the study was, focussed upon 8599 GJ of electricity provided to 865 houses for one year and produced from a 10.68 kt/year feedstock mixture. The system boundaries included the phases of: feedstock production and utilisation for production of the electricity. Digestate usage as organic fertiliser was also considered in the assessment.

The authors documented that both plants provided sustainable options compared to the use of hard coal (the most abundant fossil fuel in Turkey), but the environmental impacts associated with the AD option were 50% lower than those from the gasification option. This was attributed to the environmental gains resulting from the utilisation of the digestate as organic fertiliser and to the resultant reduction in usage of mineral fertilisers. However, the largest impact to global warming among all the life-cycle stages was from the emission of dinitrogen monoxide (N_2O), related to the digestate application.

Pierie et al (2016) assessed the overall renewability, sustainability, and possible energy yields of biogas production pathways operating on locally available biomass waste flows in the Netherlands. These authors considered questions regarding the achievability, efficiency, and sustainability of the biogas production pathway when utilising biomass from energy crops, especially if they were transported longer distances. Considering 20kt of fresh matter used per year and the same setup for the AD plant, three different pathways were considered: *green gas* (part of the produced biogas was used in a small boiler to produce the needed heat for the digestion process), *combined heat and power* (CHP), and *waste treatment*. Concerning the multi-functionality issue, the digestate was documented to replace equivalent quantities of inorganic fertilisers while, in the scenario in which the biogas was fed into a CHP engine, the produced electricity and heat were fully exploited and a one km pipeline to transport it was integrated into the calculations.

To quantify efficiency and sustainability, two reference scenarios were considered. The first one was the fossil fuel reference scenario based upon natural gas and the average grey electricity mix of the Netherlands, while the second scenario was the “maize reference scenario” in which maize silage used as a feedstock was especially cultivated for usage in the biogas production pathway.

Although the literature indicated that there was sufficient bio-energy potential in local waste streams to reach the renewable production goal set for the year 2020, the authors stated that the average useful energy finally produced by the AD production pathway was significantly lower, often due to poor quality biomass and due to difficult harvesting conditions.

In regard to application of the LCA tools, the authors concluded that the choice of feedstocks, technologies, and the operational values of AD pathways (e.g. feedstock, transport, process) have significant influences on the environmental impacts. Moreover, the increased usage of biomass for production of methane can require the usage of valuable arable land and, therefore, compete with food production and negatively impact regional biodiversity.

In another study, Collet et al. (2017) designed a methane production system by combining AD and Power-to-Gas (PtG) technology, which consisted of the utilisation of electricity to convert water into H_2 by electrolysis, and then to synthetize CH_4 from CO_2 and H_2. Several applications used CH_4. In this study, the authors investigated its combustion for heat generation, by considering three alternative plant options: biogas upgrading and CO_2 conversion into CH_4 via methanation; biogas upgrading into CH_4 through its direct methanation; and biogas upgrading without methanation.

The authors performed a techno-economic and environmental assessment of the whole methane supply chain, considering those plant options. The FU was regarded as 1MJ heat produced, and the system boundaries included all the middle unit operations of which the system was comprised, from biogas production to CH_4 combustion and heat generation. The authors claimed that PTG technology was documented to be a promising and competitive approach~~According to the authors, the PtG technology was documented to be a promising and competitive approach~~. However, the authors recommended using renewable electricity and/or a different electricity mix to feed the electrolysis process, so increasing the economic and environmental performance of this technology.

In another study, Ertem et al. (2016) analysed the environmental performances of an agricultural biogas plant of a capacity of 500 kW comparing environmental impacts of flexible and the traditional baseload operation. The authors found that a flexible biogas supply is vital to balance the power generation and can be realised by biogas storage or by flexible biogas production management systems. LCA was performed in this study to detect the environmental impacts of the variety of feedstock in co-digestion scenarios by substitution of maize and of the loading rate scenarios with a focus on flexible feedstock utilisation.

In Ertem's et al. (2016), the AD plant was operated with the co-digestion of maize, grass, rye silage, and chicken manure. The selected FU was 1 kWh of produced electricity and the system boundary included all phases from crop production - purchase, ensilage, storage to biogas combustion and supply of the generated electricity into the grid and heat utilisation for temperature control at the fermenters and poultry housing. All steps in between, such as AD, storage of residues and application of digestate for agricultural production, transport between multiple stages of the anaerobic digestion were assessed.

As in other studies (Pierie et al., 2016; Bacenetti et al., 2016a; Lijó et al., 2017a) concerning the animal slurry, only the collection and storage of the produced digestate were considered by Ertem et al. (2016) and modelled as a mineral fertiliser substitute. The amounts of mineral fertiliser replaced by the application of digestate were calculated, based upon the digestate composition and fertiliser replacement values. Primary data were collected by surveys at the AD plants over two years, while background data related to the production of construction materials, agricultural tractor, CHP unit, energy, fuels, fertilisers and pesticides were taken from the Ecoinvent 2.2 database.

Based upon findings from the study, the Global Warming Potential (GWP) was affected by the type of feedstock, and thus the nutrient content of the digestate, while acidification and eutrophication potentials (AP, EP) were mainly related to digestate spreading due to high nitrate and phosphor emissions. For GWP, significant impact reduction comes from utilisation of the heat output from the CHP unit.

Finally, the authors concluded that: demand-driven biogas production resulted in 48%, 20%, and 11% lower GWP, AP and EP due to lower emissions and feedstock loading rate but involved higher values of (+16%) Cumulative Energy Demand (CED). Increase in CED was related to higher energy consumption rates at both the fermentation and CHP steps (related to changes in feedstock composition and adaptations in electricity generation), as well as to higher energy demand for transport and storage. About the substitution of maize silage with other feedstock, the use of waste can reduce GWP and AP up to 10%, due to the reduction in the emissions of N-compounds related to fertilisation.

Iordan et al. (2016) investigated a Norwegian biogas plant where sewage sludge and other organic wastes (i.e. fats from food industry, sludge from septic tanks and other biological substrates) were co-digested for production of biogas to be converted to electricity. In their study, the authors performed LCAs for evaluation of the environmental sustainability of such an electricity production choosing 1 MJ as FU. Since the feedstock was composed of waste substrates only, a zero-burden approach was adopted, thus, they neglected the upstream impacts. The system boundaries included: the transport of the feedstock substrates to the plant, the capital infrastructure and its end-of-life, the use of biogas in a CHP plant for electricity generation and the proper management and utilisation of the digestate.

The final distribution and usage of electricity were accounted for in the assessment and were considered as falling outside the aim and scope of the study. Since the waste heat and the digestate were not economically exploited, all impacts were attributed to the electricity production and no allocation was needed. Regarding the digestate, the authors did not perform the allocation because the digestate market in Norway is still evolving and the biogas plants receive no revenues from utilising the digestate in agricultural applications. The analyses were based upon primary data from a biogas plant, supplemented with data from the literature. Primary data were combined with background ones as extrapolated from the Ecoinvent 2.2 database. The environmental performance of the biogas system was benchmarked against a conventional fossil fuel system. Results revealed how better performing the biogas system was for the acidification and particulate matter formation potentials, compared to the fossil-fuel-based reference system. Moreover, the sensitivity analyses performed, documented that the most sensitive parameter was the storage of the digestate.

A study done by Uusitalo et al (2016) that was focussed upon the environmental assessment of the potential benefits arising from the exploitation of surplus heat by means of an Organic Rankine Cycle (ORC). Although heat is a typical co-product of all AD plants producing electricity via the combustion of biogas in a CHP engine, it is important to find feasible ways to fully exploit it, thereby, avoiding its emission as waste. In fact, the surplus heat available for exploitation has a huge variation, during seasons, depending upon the variation of the air temperature and, consequently, the amount that is recirculated within the AD plant itself. Furthermore, the heat demand in agriculture is typically concentrated in winter. During winter, most of the heat produced is reused to feed the digestion chamber, therefore, small quantities of heat are left for other applications.

In this context, the study performed by Uusitalo et al. (2016) assessed the potential reduction of GHG emissions by using Organic Rankine Cycle (ORC) turbine for recovering exhaust gas heat of biogas engines. The authors found that ORC is a suitable technological option for converting low-grade heat into electricity with relatively high efficiency. They developed two scenarios (the first where only electricity from a gas engine was utilised, the second where electricity and heat from a gas engine were utilised) with four cases for each scenario, were studied.

The four cases were: A) additional electricity was produced using typical current methods; B) additional electricity was produced using marginal methods; C) additional electricity was produced using biogas; and D) the ORC process was used. The comparison among the different cases was modelled using the system expansion method according to the ISO/TR 14049. According to system expansion, a similar number of products was produced in different cases to enable a fair comparison. Therefore, the authors considered a similar amount of electricity and heat in all cases. Because, more electricity was produced through the ORC process, for cases A and C additional electricity had to be produced using other electricity production methods. Results from the study documented that GHG emissions can be reduced (from 16% to 35% depending on the considered biogas plant) if the thermal energy embedded in the exhausted gases, otherwise lost during the process as heat waste, was utilised for additional electricity production by means of the ORC. The largest decrease in GHG emissions occurred when ORC was used to replace the marginal energy produced by coal, while the lowest decrease was recorded when ORC was used to replace the electricity produced using the biogas output from the AD plant. However, when the heat was used in the form of heat power, the use of ORC does not necessarily lead to GHG emission reductions. The final results documented that working fluid leakages and production, as well as the ORC construction materials and production, have only marginal effects on the results from the GHG perspective. The authors concluded that ORC is an effective option for converting the surplus heat produced by the CHP into electricity and, consequently, could improve the environmental performances of AD plants where this thermal energy was not otherwise fully exploited. From the perspective of GHG emissions, the benefit related to ORC depends upon whether heat was exploited along with electricity; if heat was already utilised, the usage rate plays a significant role when considering GHG emission reduction with ORC.

Sometimes Cover Crops (CCs) are used as co-substrates in the feedstock mixture. The CCs are crops that are planted on the field during part of the year when the land is usually be left fallow. The main objective of this is to reduce erosion and to improve the structure and water retention capacity of the soil (Igos et al., 2016). Furthermore, management of cropping systems with CCs provides benefits related to soil characteristics, such as adding increased humus to the soil, that reduces compaction, improves water holding capacity, improves biological weed and pest control and improves nutrient cycling through reduced leaching and enhanced nitrogen sequestration (Igos et al., 2016).

Previously, CCs were mainly cultivated as “green manure”, which meant that they were not harvested, but incorporated into the soil before the main crop was sown. If, on one side, this contributes to higher yields of the main crop, on the other side, new biomass is needed for energy production, due to the growing scarcity and the societal dependence from fossil fuels, as well as the increasing biomass demand (Igos et al., 2016).

This aspect was investigated by Igos et al. (2016) who evaluated the environmental repercussions of planting rye as a winter CC after maize cultivation, and its utilisation as a co-substrate along with maize and manure in an AD plant. This scenario was considered by the authors as an alternative to leaving the land fallow during the winter and using maize in co-digestion with manure. An LCA was conducted for this purpose. The FU of the system was chosen as 1MJ energy. The system was split into three main sub-systems related to: feedstock production and management; feedstock supply to the AD plant and processing into biogas and digestate; biogas conversion into energy. This phase of feedstock production was represented by crop cultivation and manure management. Rye and maize, or maize only, depending upon the scenario considered, were co-digested with pig manure.

The resultant biogas was used for co-generation of electricity (36%) and heat (64%), which were used to supply the facility’s demands. The digestate was used as an organic fertiliser for cultivation of the maize.

The researchers found that the usage of rye as a winter CC resulted in significant environmental benefits on the local scale, mainly due to: reduced nutrient demand and nitrate leaching; optimised land use; and avoided use of herbicides (Igos et al., 2016). However, the lower rye productivity and specific biogas potential compared to maize, caused an increase of indirect environmental impacts due to the higher consumption of materials and energies for 1MJ bioenergy production (Igos et al., 2016). Therefore, according to the authors (Igos et al., 2016), trade-offs are possible between mitigation of local environmental impacts and lower energy productivity. Alternative types of energy production modes, like the integrated generation of solid fuel and biogas from biomass as studied by Bühle et al. (2011) and/or of CCs, like the promising role of planting wheat highlighted by Kim et al. (2005) could contribute to optimisation of CC valorisation as an energy product.

Biogas from biomass AD can be used as fuels for Solid Oxide Fuel Cell (SOFC) systems, that represent alternative solutions to conventional power generation systems (Rillo et al., 2017). SOFCs are devices that convert the chemical energy of a gas like the biogas outlet from the AD directly into electricity and, also, make available thermal energy for cogeneration usage, because they operate at high temperatures. In such systems, conversion efficiency was higher than the energy systems fed with the same fuel that used traditional combustion processes (De Lorenzo and Fragiacomo, 2015). Despite this, LCAs and related assessments should be conducted on such complex systems of biomass transformation and energy generation to document ways to improve their efficiency and reliability.

This was done by Rillo et al. (2017) who performed LCAs to address the environmental issues associated with a SOFC based system, where the biogas outputting from sewage-fed AD was used as fuel for the SOFC. The selected FU was production of 1 kWh by the plant. A comparison was performed with conventional technologies, like Internal Combustion Engines (ICEs) and microturbines, biogas combustion. The system boundaries were at the plant gate and encompassed the biogas production in the AD stage, and the phases of manufacturing, operation and maintenance of the SOFC plant. As part of the system investigated, CO_2 was recovered through a tubular photoreactor which enabled fixing carbon via production of micro-algae.

The findings revealed that manufacturing via SOFC systems has major impacts due to huge electricity consumption volumes. Regarding the operation of the SOFC-system operating phase, the highest environmental burdens were found in the biogas production step from sewage.

The energy consumption in the photobioreactor was found to be greater than the production, as well as the carbon emissions were documented to be greater than the amount fixed in the algal biomass. However, the authors found that such an apparently surprising result was verified in the whole system, which was at a proof-of-concept level, and so significant improvements are expected when upscaling the system at the industrial level. Overall, SOFC was documented to be a valid alternative to conventional systems, such as internal combustion engines and micro gas turbines. Hence, it is an ecologically and economically promising cleaner production process of bioenergy generation and usage.

Biogas production can be a valid option for smallholder farmers utilising waste products from household, farming and animal breeding activities. In most cases, biogas is produced and processed onsite through conversion into electricity and heat or through upgrading into high-value gas like (bio-)methane, as shown by the studies reviewed in this section, as well as in those reviewed by Bacenetti et al. (2016a). Biogas production can play multiple roles in the development of new rural energies, because it is well suited for small-deployment in rural areas where it can be integrated into farm systems and managed with relatively little operation and maintenance effort (Hou et al., 2017). In fact, this form of biogas, known as Rural Household Biogas (RHB), has been increasing in popularity in areas where smallholder farmers predominate, such as in Southeast Asia, China, and Africa (Hou et al., 2017). However, there is increasing concern about the real economic and environmental performance of RHB based systems: as a result, an increasing number of these systems are being abandoned in China (Hou et al., 2017). These and related issues were assessed by Hou et al. (2017) who performed LCA of the net GHG mitigation effects of RHB systems integrated into small household farms. In their study, the authors tracked RHB system deployment in different areas in relation to driving forces, and proposed policy recommendations to improve the effectiveness of biogas GHG mitigation solutions.

Through their study, the authors documented that RHB systems can lead to a series of environmental benefits, mainly related to reduction of: fossil fuel consumption; GHG emissions from manure storage and management; and chemical fertiliser inputs. However, it should be underscored that, when poorly operated, RHB systems can cause increased GHG emissions, aggravate nutrient surpluses on farmland, increase labour inputs, and cause economic losses. This emphasises upon the fact that the design of those systems must be carefully matched to local conditions and farmers' needs with respect to manure management and energy requirements (Hou et al., 2017). Technical options such as small pumps to extract digestate from digesters could improve operational efficiency and reduce labour requirements for the RHB systems. Moreover, widespread adoption of more precise nutrient management planning would help to improve digestate utilisation efficiency and thereby, achieve enhanced fertiliser substitution benefits (Hou et al., 2017).

Biogas is increasingly produced from marine algae, mainly due to higher rates of CO_2 fixation, greater potential for carbon dioxide remediation and higher production yields per unit of area, compared to terrestrial biomass (Karray et al., 2017). In this context, Ertem et al. (2017) performed an LCA to investigate the energy efficiency and environmental sustainability of biogas production when the energy crops are partially sourced from microalgae as feedstock to an industrial-scale AD plant. Two feedstock scenarios were tested by the authors: chicken manure with macroalgae; and chicken manure with energy crops. In line with the previous studies, the boundaries of the analysed system included: manure collection; macroalgae and energy-crop cultivation; storage and handling of the three substrates; storage, treatment and handling of the digestate produced, co-generation of electricity and heat from biogas; and lastly the transportation.

Two FUs were chosen by the authors in their study, so that it could be highlighted whether and how results from comparison of the two scenarios were affected by methodological issues like the choice of the FU. Considering the function for which AD plants are generally designed, the FUs chosen by the authors were: 1kg feedstock mixture; and 1MJ produced energy. The combustion of biogas (biomethane) was considered climate neutral. Assuming that methane is completely oxidised during biogas combustion the carbon dioxide released after combustion was excluded by the system boundary.

The researchers documented that, when energy production was considered, and the FU was 1MJ energy production, the substitution of energy crops with macroalgae generated 67%, 95%, 65% and 73% lower impacts related to global warming, acidification, eutrophication and natural land transformation, mainly due to the avoidance of digestate spreading. By contrast, when the authors considered the amount of feedstock for energy production and, hence, the FU was 1kg feedstock fed into the AD, macroalgae would lead to 22% and 15% higher impacts in terms of eutrophication and global warming.

In summary, the authors documented that different FUs generate different results, thereby underlining the importance of duly considering and selecting FUs in ways that they are consistent with the objectives and necessities related to the study and which best represent the systems being investigated.

The study done by Lijo et al (2017a) was designed to compare the eco-efficiency level of fifteen agricultural biogas plants located in Northern Italy. For this purpose, LCA and the Data Envelopment Analysis (DEA) methodology were combined to investigate and compare the efficiency of the plants considered and propose improvements those being identified as inefficient. The fifteen AD plants were fed with different feedstocks: energy crops (maize and triticale silage), maize flour, the Organic Fraction of Municipal Solid Waste (OFMSW), food waste, animal slurry, and glycerol. The FU was selected to be 1MJ electricity production. In line with the standard practice of LCA applications in this field, the system boundaries were set to include: the cultivation of energy crops; the transport and handling of all input materials; the AD process; the use of biogas in the CHP system; and the digestate management.

The production of organic wastes such as manure, food and industrial wastes was excluded since they were considered waste streams from other production systems. Therefore, in line with other authors, such as Iordan et al. (2016), a zero-burden approach was used in this study for the modelling of the waste stream acquisition. Concerning the digestate, the authors considered that some plants produce more digestate than what is required for the cultivation of their own crops. In this case, the avoided mineral fertilisation using ammonium nitrate was estimated according to the nitrogen replacement value of 65%: 1kg of nitrogen (N) from digestate corresponds to 0.65kg N from mineral fertiliser.

With regard to the heat cogenerated by the CHP, it was considered wasted except for one biogas plant located near a greenhouse: in this case, avoided production of the same amount of heat from natural gas was considered. With regard to main results of the studies, the authors documented that: i) the production of electricity from biogas in all plants provided environmental benefits compared with the average electricity production in the Italian grid; ii) to improve the environmental performances of electricity from AD plants, special attention should be given to feedstock composition, because it plays multiple key roles in the overall energy efficiency, economic convenience and environmental sustainability of the plant. For this purpose, substrates need to be properly selected, based upon their origins, chemical and biological features and biogas yield, so that the overall energy performance of the plant could be maximised as the result of the balance between energy spent and energy gained; iii) reduction of GHG emissions and other substances impacting upon human health and ecosystem quality, derived from digestate storage and usage, feedstock production and were the main environmental hotspots.

The authors highlighted that 60% of the plants operate efficiently and reduction targets were applied for inefficient ones (virtual plants). The comparison of original and virtual plants showed that the potential environmental gains differ among impact categories. Furthermore, the study highlighted that the joint implementation of LCA and DEA was an effective solution to identify the plants showing the worst performances, as the starting point for identification of the possible improvement solutions.

A second LCA of Lijò et al. (2017b) was performed to identify the environmental consequences of feedstock selection in biogas production by investigating OFMSW utilisation. For this purpose, two biogas plants were assessed and compared from a life cycle perspective. The first plant performed the co-digestion of energy crops (78%) and animal waste (22%), while the second one plant used energy crops (4%), food waste (29%), and OFMSW (67%). The selected FU was 1 MWh of electricity produced and the system boundary included maize and triticale cultivation, feedstock transport, bioenergy production, digestate management and use of surplus digestate. Waste production was considered outside of the system boundaries and only the transportation was considered for this assessment.

With regard to the digestate, the following items were included: transportation and spreading on agricultural land; life cycle of the agricultural machines utilised; the diesel fuel used and the related GHG emissions from the application of digestate. In their assessment, the authors recorded cases in which an additional amount of digestate was produced with respect to that recirculated within the system investigated for cultivation of the energy crops used as feedstock in the AD plant. In those cases, as documented by Lijò et al. (2017a), the authors considered that the surplus digestate was properly used in other agricultural systems, thereby further reducing usage of mineral fertilisers and maximising the related environmental benefits. In both of their studies (Lijò et al., 2017 a,b), the authors modelled digested matter as mineral fertiliser substitutes, so accounting for the resulting avoided environmental impacts in a substitution approach perspective. Nevertheless, different from the other articles reviewed in this paper, like Pierie et al. (2016) and Ertem et al. (2016), as well as the review performed by Bacenetti et al. (2016a), only avoided N fertilisers was considered as environmental credits. This was done because the agricultural soil in the area around the AD plant (Northern Italy) contains high contents of phosphorus (P) and potassium (K), which makes the addition of P- and K-based fertilisers unnecessary. Among the different inputs and outputs, feedstock production and emissions from digestate storage were identified as the main hotspots for the AD plants fed with agricultural biomass. As for Lijò et al. (2016), despite the application of digestate as organic fertiliser, no changes in the soil organic carbon content were considered.

The research performed by Arodudu et al. (2017) found that previous LCAs for agro-bioenergy production rarely considered some agronomic factors with local and regional impacts. Based upon results from previous LCA studies, the authors highlighted that depending upon the assumptions made in the studies, the environmental impacts of producing bioenergy on arable land cannot be considered sustainable. In contrast, other researchers considered the production of electricity from biogas to be one of the most effective, direct emission reduction and fossil fuel replacement measures.

In this context, Arodudu et al. (2017) improved the LCA methods to examine the individual and combined effects of often overlooked agronomic factors (e.g. alternative farm power, seed sowing, fertiliser usage, tillage and irrigation options) on life-cycle energy indicators. The system boundary considered in the evaluations involved cultivation of energy crops (ploughing, harrowing, ridging, seed sowing, fertiliser application, pesticide application, liming, irrigation, harvesting etc.), transportation (e.g. from farm to input market, input market to farm, farm to bio-refinery, bio-refinery to farm etc.) and conversion of biomass to energy. The manufacturing of the production factors directly consumed over the production processes such as fuels, fertilisers, herbicides, lime etc. was included too. Manufacturing, start-up and maintenance of machinery (e.g. tractors, irrigation systems, biorefineries etc.) were excluded from the system boundary. In line with other studies reviewed for this paper, digestate was accounted for as fertiliser (N, P and K) and lime substitutes without considering real soil requirements.

The main aspects related to industrial plant investigated and methodology applied were extrapolated from the papers listed in Table 1.

Table 1

The table contains article classification based upon methodological choices and results from the studies reviewed in this paper

Study	*Geographic area*	*Technology*	*Functional Unit*	*System Boundary*	*LCIA method*	*Feedstock*	*Main GHG-emission related findings*
Arodudu et al. (2017)	Tropic, sub-tropic and the temperate landscapes	AD for biogas	1 Joules of energy from maize ethanol and maize biogas	From cradle to AD plant gate	Energy Return on Energy Invested (EROEI)	Maize silage	As the study is focussed upon EROEI, no computation of GHG was developed by the authors. EROEI was found by the authors as ranging from 1.8 to 2.5. However, the study was reviewed the same in this study, because EROEI is highly connected with GWP. In fact, it can be asserted that the higher the EROEI is the higher is the energy efficiency of the plant and the lower is the GWP value.
Ertem et al. (2016)	Northeast region of Germany	AD for biogas	1 kWh of electricity	From cradle to AD plant gate	Recipe 2008	Maize, rye grass silage, chicken manure	The range 0.093-0.127 kg CO2-eq per kWh el, was found by the authors to be dependent upon the FS mix.
Ertem et al. (2017)	Northeast region of Germany	AD for biogas	1 t feedstock mixture; and 1 MJ produced energy	From cradle to AD plant gate	Recipe 2008	FS1: Macroalgae and chicken manure; FS2: chicken manure and energy crops.	13.9 - 28.9 g CO_2-eq per MJ of energy (electricity and heat) produced; 160 – 140 g CO_2-eq per t of processed feedstock Ranges should be attributed to the different FSs used: whether chicken manure was fed along with macroalgae or energy crops.
Collet et al. (2017)	France	AD for biogas and PtG technology	1MJ heat	From cradle to AD plant gate	IPCC (2007) + Recipe 2008 E/H	Maize, grass, rye silage, and chicken manure	GWP_{100} resulted as to range from nearly 20 to slightly more than 45 g $CO_{2\ eq}$ per MJ heat injected in the gas network, depending upon the price of electricity and the plant operating time.
Hou et al. (2017)	China	Rural Household Biogas	1 Rural Household	From cradle to grave	IPCC (2006)	Animal manure and kitchen garbage	The authors documented CO_2 eq emissions as ranging from 173 to 2489 kg CO_2 eq per household and year considered, depending upon the village

							considered and the way RHP systems were operated.
Igos et al. (2016)	Flanders (Belgium)	AD for biogas	1 MJ energy (36% electricity and 64% heat)	From cradle to AD plant gate	CML 2002	Maize silage, rye, manure	In their study, the authors documented that using rye as feedstock substrate generates a 12% increase in GHG emissions (GWP_{100}), compared to the no-rye utilisation case, where nearly 5E-2 kg CO_2 eq were recorded per MJ of energy produced.
Iordan et al. (2016)	Norway	AD for biogas	1 MJ of electricity	From cradle to grave	IPCC, 2013	Sewage sludge and sludge from industry	As in many of papers reviewed, the feedstock composition variability makes way for the GWP_{100} to be in the range 63-100 g CO_2eq/MJ.
Pierie et al. (2016)	Netherlands	AD for biogas	GJ of energy/km^2	From cradle to grave	Recipe 2008	OFMSW	Not reported
Lijo et al., (2017a)	Italy	AD for biogas	1 MWh of electricity	From cradle to AD plant gate	Recipe 2008	Energy crops (maize and triticale silage), maize flour, OFMSW, food waste, animal slurry, and glycerol	A range of GWP_{100} values were found (194-286 kg CO_2eq/MWh), because a set of 15 AD plants was investigated in the study.
Lijo et al. (2017b)	Italy	AD for biogas	1 MWh of electricity	From cradle to AD plant gate	Recipe 2008	Two feedstocks, in two different AD plants: FS1: energy crops and animal waste; FS2: energy crops, food waste, and OFMSW.	The GWP_{100} was documented by the authors to be equal to 152 and 619 kg CO_2eq/MWh, depending upon the feedstock (FS) considered.
Nayal et al. (2016)	Turkey	AD for biogas vs. combined-cycle gasification	8599 GJ of electricity	From cradle to AD plant gate	EDIP 2003	Slaughterhouse wastes, vegetable wastes from cultivation and harvesting, poultry and cattle manure, and grass	Not reported

Rillo et al. (2017)	Not indicated	Solid Oxide Fuel Cell fed with biogas	1 kWh of electricity	From cradle to AD plant gate	Recipe midpoint	Rye and maize, or maize only, depending upon the scenario considered, were co-digested with pig manure	GHG emissions were found in this paper as ranging between 0.2-0.36 kg CO_2 eq per kWh of electricity produced
Uusitalo et al. (2016)	Europe	AD for Biogas, plant with ORC	MJ of biogas year^{-1}	From cradle to AD plant gate	Not reported	Not indicated	GWP reduction was documented by the authors as to be in the range 16-35%, with respect to reference scenario
Yasar et al. (2017)	Pakistan	AD for Biogas	1 ton of digestate	From gate to gate (only digestate management is included)	Not reported	cow-dung, potato pulp,	Not reported

Fig. 1 was developed to represent the conventional AD system investigated in the studies reviewed plus, within yellow boxes, the additional/innovative technologies were presented that were assessed by: Uusitalo et al. (2016), for the ORC-based plant; Rillo et al. (2017) for the SOFC; and Collet et al. (2017) for the PtG technology.

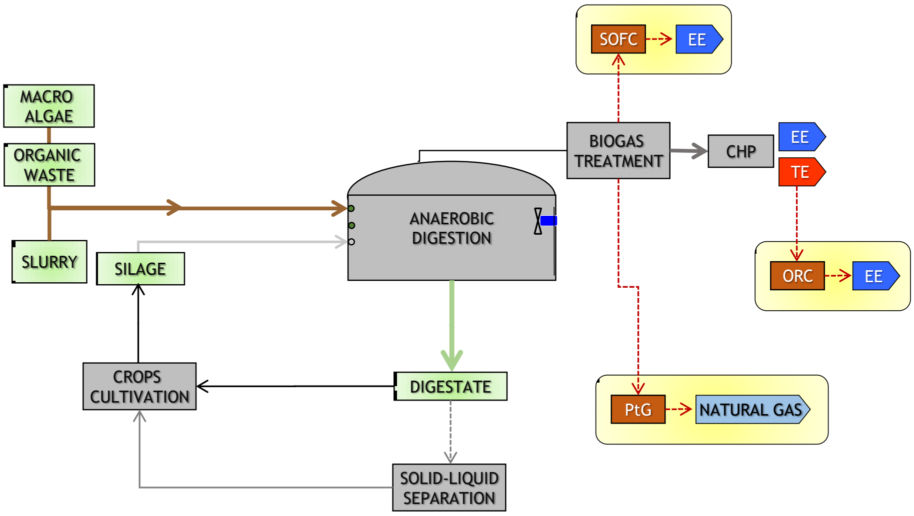

Fig.1. The figure shows a representation of the AD system investigated in the studies reviewed. Within the yellow boxes are the innovative systems that were integrated and ~~tested~~ evaluated by LCA~~by authors: ORC (Uusitalo et al., 2016); SOFC (Rillo et al., 2017); and PtG technology (Collet et al., 2017)~~.

4. Discussion about lessons learned

The authors of this comprehensive literature review achieved their objective, namely the review and building upon relevant papers dealing with environmental assessment of agro-biogas derived energy systems that were based upon LCAs. In those studies, LCAs were often combined with other methods, such as estimations of the in-field emissions due to agricultural activities, or of the energy balances associated with the AD plants. According to the authors, this emphasises that LCAs are a valid tool for environmental assessments of bioenergy supply chains.

The systems investigated were based upon AD, which were sometimes integrated with other technologies to form more complex energy production systems, such as was done by Collet et al. (2017), and Rillo et al. (2017), thereby, highlighting AD flexibility, multifunctionality, and adaptability of application.

In this regard, Bacenetti et al.'s (2016a) review highlighted that because of those advantages, AD is a very useful technology for producing methane-based renewable energy, because they can convert many biomass streams into useful products and, as documented by Ingrao et al. (2018b), can contribute to Circular Economy (CE) by helping to close some organic matter cycles.

In all the AD plants investigated, zoo-technical effluents (sewage and manure) were an important substrate of the biomass stock used to feed the plant, representing around 20% (Nayal et al.,

2016) to 100% (Collet et al., 2017; Rillo et al., 2017). The inputs used in AD plants were selected and modelled using a zero-burden approach, by considering their collection, transportation to, and handling within, the plant. As observed by Ingrao et al. (2018b), this is a well approved practice in LCAs of bioenergy systems, which utilise animal and agricultural wastes.

Different feedstock mixtures were tested and compared with objective of gaining insights into the benefits and trade-off options between biogas yields and broader impacts upon regional agricultural sustainability. Most of the authors used mixtures of manures with other types of biomass residues, which were found to be reliable and ecologically/economically sound ways for helping to mitigate many of the environmental impacts associated with the bioenergy supply chain. The choices of feedstocks, technologies, and the operational values of AD plants were documented, to significantly affect the resultant energy yields and reductions in environmental impacts. In this regard, this literature review made it possible for the readers to understand that usage of substrates like maize, rye, cover crops, algae, waste, manure and sludge slurry clarifies how feeding of AD plants investigations are addressing ways for process improvement. Much attention is being given to potential environmental benefits from the substitution of cereal silages (maize silage above all) with other types of biomass from crops with low input requirements (e.g., cover crops) or from waste and alternative biomass (e.g., algae). Marine macroalgae were tested for usage in replacement of land-based energy crops. The authors using algae found that there is higher biogas potential and lower environmental impact (per MJ energy produced) compared with the most commonly used silages such as rye, maize and grass (Ertem et al., 2017).

Another valuable finding pertained to the trade-offs between the usage of cover crops as cover crops, vs using them as feedstocks for AD plants. These competing elements must be more deeply investigated in diverse regional, agronomic and climatological contexts, because, to date, few authors were found who addressed the energy and environmental issues associated with both feedstock types (Igos et al., 2016; Ertem et al., 2017). Such a result emphasises the need for LCAs and other assessments for further investigation and improvement of those issues, to contribute to more sustainable regional agriculture.

Based upon the systems investigated in the papers reviewed, biogas production from AD plants were used for co-generation of electricity and heat, or for conversion into bio-methane.
For all studies, the system boundaries were designed to include the main unit operations that mainly addressed the ranges; from feedstock production, transportation and handling to energy generation and utilisation.

In regard to the emissions of CO_2 related to the combustion of biogas (or biomethane), few studies (e.g. Ertem et al., 2017) explicitly excluded them from the system boundary; however, this approach was commonly applied. The combustion of biogas (biomethane) was considered as climate neutral, based upon the assumption that the methane was completely oxidised during biogas combustion. After combustion, CO_2 is released back into the atmosphere with no net addition of fossil-carbon, as it is consumed during plant growth (photosynthesis) and converted back into biomass. Although this assumption is reasonable, until now there have been no studies, which documented the amount of C that is not released as CO_2 but as CH_4 and CO. If methane is fully oxidised and the emissions of methane and CO are also accounted for, there could be the risk of double accounting.

Attention was given, by some authors, to computation of the in-field emissions resulting from soil management and to those of N_2O, ammonia (NH_3) and nitrates (NO_3) released due to the application of mineral and organic fertilisers, like the digestate produced in the AD plants.
In addition to this, uncovered storage of digestate before and after treatment was found to be responsible of large impacts due to N_2O and CH_4 emissions. The covering of digestate storage tanks enables abatement of emissions of those GHGs up to 80%. For this reason, several authors, including Whiting and Azapagic (2014), Bacenetti et al. (2016c), Fusi et al., (2016), Lijò et al. (2017 a,b) and Bacenetti et al. (2016a) identified it as an effective mitigation solution, with respect to the impact categories related to the emissions of:

- CH_4: global warming potential and, although with a lesser extent, photochemical ozone formation;
- N_2O: global warming potential; and
- NH_3: acidification, eutrophication and particulate matter formation). Besides the benefits related to the reduction of emissions, additional benefits can be achieved by the increase of electricity production related to the methane recovery in the digestate covered tanks.

Several authors (Philippe et al., 2011; Bacenetti et al., 2016b; Carozzi et al., 2012) documented emissions from application of organic fertilisers, such as digestate emissions from AD plants can be reduced depending upon the timing of applications (e.g., in coldest hours during the day, in days with low wind), as well as the mechanical solutions for storage and spreading of those fertilisers. For the storage, acidification of the slurry or covering with granules of expanded clay seemed to be feasible solutions for reduction of loses to the atmosphere, while injection into 5-7 cm depth furrows, band spreading, and fast soil incorporation could be considered for digestate spreading to reduce losses to the atmosphere. However, those solutions have gained little attention, which strengthens the need for research addressing the related technological, economic and environmental issues and their impacts upon the sustainability of the entire biogas supply chain.
Allocation was performed by the authors when needed, based upon the system investigated, which was mainly focussed upon allocation between biogas and digestate, and between the heat and electricity produced by the co-generation plants. Some authors did not perform allocations due to the absence of a real market for the digestate from the AD plants, and to biogas plants receiving no revenues from re-cycling the digestates.

Concerning digestates, the articles in this literature review revealed increasing attention being given by researchers to the environmental consequences related to different utilisation methods, as well as to the peculiar methodological challenges that the production and proper utilisation and assessment of benefits from their usage. More in detail, the use of digestate as organic fertiliser was usually modelled considering:

- its usage for cultivation of the crops by which the AD plant is fed;
- the substitution of mineral fertilisers considering its nutrients composition in NPK;
- the substitution of mineral fertilisers considering only the real requirement of the different agricultural areas (e.g., considering only the N content if digestate is spread in soil with high content of P and K).

This modelling did not address the benefits such as improved soil microbiological health and quality of the soil, increased organic matter which enhances the soil's water holding capacity, reduction in erosion and improvements in plant yield and improvement in nutritional quality of the plants produced on soil properly improved with added digestates.

Primary data were used in those studies in combination with secondary data that were extrapolated from databases like Ecoinvent and/or from the subject literature. Primary data were collected onsite by performing multi-year surveys and/or, for some studies, derived from the design phase of the whole systems whether the latter had not been implemented yet, like in Collet et al. (2017) and Rillo et al. (2017).

Other differences among the studies reviewed were found in the application of the methodology, regarding the study background and set-up, the data inventoried, and the environmental impact assessment methods used. Some authors limited their assessments to the midpoint approach, while others extended it to the endpoint approach. Some authors considered a set of impact categories to best represent the system investigated, mainly related to global warming, non-renewable energy, acidification, eutrophication, particulate matter formation, and land transformation. For contrast, others (i.e. Nayal et al., 2016; Hou et al., 2017) focussed only upon GHG emission estimation.
One big difference documented was related to the functions of the system investigated and to the objectives of the study. It was clear that all authors selected the FU, that best represented the focal aspects being investigated in their research. This resulted in FUs being different from study to study, thereby making comparisons among the results of the different researchers difficult or impossible to be made.

As illustrative of this, Ertem et al. (2017) chose two different FUs for assessment of the same system and showed that different FUs caused quite dramatic differences in the apparent results.
If the objective was to produce higher amounts of energy per unit of energy input, substitution of energy crops with microalgae was found to be an ecologically and economically viable option because it helped to solve the dilemma between energy and food production. In this way, bioenergy production yields could be optimised and the iLUC related problems could be reduced or avoided. In contrast, when the attention was focussed upon the AD feedstock, it was found to be essential to analyse the whole system based upon the kg of feedstock produced and the

quantities of methane produced. In this case, utilisation of energy crops other than macroalgae could be more favourable to mitigate the environmental impacts associated with the AD plants (Ertem et al., 2017).
In line with Bacenetti et al. (2016), differences were found in the feedstock mixtures and the regions in which: the AD plants were located, and the feedstock mixture substrates were produced/obtained, managed, and supplied. Differences were found to be related to the ways the energy produced was utilised, whether it was input to the national grid, and/or it was utilised within the AD system. In this regard, an interesting aspect was found to be related to the potential environmental benefits that can result from efficient utilisation of the surplus heat by means of an ORC (Uusitalo et al., 2016; Bacenetti et al., 2019).

All those differences provided numerous valuable insights into the rich diversity of lessons learned and to an array of problems to be investigated to make more efficient/effective and sustainable usage of a wide array of organic materials in AD and in related technological/sociological/ecological contexts.

5. Conclusions and Future Trends

During the last 20+ years, application of LCA to agricultural biogas production technologies enhanced global scientific understanding and knowledge of environmental costs and benefits related to this renewable energy source. It helped practitioners, researchers, academics, decision- and policy-makers and other stakeholders to better understand the interconnected mitigation strategies that area needed to improve AD efficiency, effectivity, reliability and sustainability.
The authors of this literature review paper, documented that much progress has been made but that there are many unsolved challenges and methodological choices (e.g., about solving of multi-functionality, use of secondary data regarding emissions, selection of information from databases) that should be researched to improve and to strengthen the robustness of relevant LCAs and the integration of other modelling tools in assessing the effectivity of AD for helping societies to make improvements. Progress in these areas will help to develop results, which are increasingly close-to-reality and reliable, thus helping to ensure that LCAs and other supportive tools will be more effective in helping researchers to help societies to accelerate the transition to equitable, sustainable, liveable, post fossil-carbon societies.

To best model feedstock production, primary data should be collected by considering the wide geographic and temporal variability of cultivation practices and biomass yields. For this reason, the use of secondary data may affect the reliability of the results, especially if they are not duly adjusted. Concerning digestate emissions occurring not only during spreading on the land but also during storage in uncovered tanks, primary data collection is expensive and time-consuming. Therefore, LCA practitioners often resort to secondary-data sets from which they extrapolate emission values, with the resultant risk that the values are not fully representative of the system-specific digestates. This is because those emissions are deeply affected by soil and climatic conditions, as well as by other factors, which in this literature review’s author’s opinions are not easy to be standardised because they often depend upon the ways the digestate

management related activities were performed. When secondary data about emissions related to fertilisation and/or slurry and digestate storage are estimated using models, the LCA practitioner should keep in mind that geographic/weather/cultivation parameters should be carefully calibrated.
The choice of the Life Cycle Impact Assessment approaches should be carefully evaluated considering the goal of the study and the selection of impact categories. When the study aims at assessing AD plants fed by energy crops, an impact assessment method designed to properly quantify the impact categories affected by fertiliser related emissions (e.g., acidification and eutrophication) should be used. Other methods, possibly different from these, should be considered when a comparative LCA of different size biogas plants is conducted to highlight differences in terms of plant construction building, operation and maintenance.

Finally, in line with Bacenetti et al. (2016), environmental LCAs are increasingly relevant for supporting the development and implementation of marketing strategies, supply chain management, and political decision-making. A higher level of transparency and a harmonisation of the preparation of biogas LCAs is essential to improve the comparability of LCA results. This could help to stimulate the creation of biogas-specific technical standards to guide and regulate the assessments, and communications, of the energy and environmental performances of biogas-derived energy systems. The authors of this literature review, solicit reader feedback and input for follow-up research and development in this evolving and important field.

Acronyms

- AD: Anaerobic Digestion
- AP: Acidification Potential
- CC: Cover Crop
- CE: Circular Economy
- CED: Cumulative Energy Demand
- CHP: Combined Heat and Power
- d- and i- LUC: direct and indirect Land Use Change
- DEA: Data Envelopment Analysis
- EP: Eutrophication Potential
- EROEI: Energy Return on Energy Invested
- EU: European Union
- FS: Feedstock
- FU: Functional Unit
- GHG: Greenhouse Gas
- GWP: Global Warming Potential
- GWP_{100}: 100-year Global Warming Potential
- ICE: Internal Combustion Engine
- LCA: Life Cycle Assessment
- MSW: Municipal Solid Waste
- NGO: Non-Governmental Organisation

- OECD: Convention on the Organisation for Economic Co-operation and Development
- OFMSW: Organic Fraction of Municipal Solid Waste
- ORC: Organic Rankine Cycle
- PtG: Power-to-Gas
- RHB: Rural Household Biogas
- SOFC: Solid Oxide Fuel Cell

Nomenclature

- CH_4: methane
- CO: carbon monoxide
- CO_2: Carbon dioxide
- H_2. Hydrogen
- H_2S: hydrogen sulphide
- K: potassium
- N: Nitrogen
- N_2O: Dinitrogen monoxide
- NH_3: ammonia
- NO_3: nitrates
- P: phosphorus

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