Valorizing Agro-Industry Residues to Improve the Environmental Sustainability of Frozen Products

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Abstract. Considering the paradigm shift towards renewable energy due to the high ecological impacts associated with fossil fuels, generating biogas energy from agricultural residue for electricity is a smart use. However, the sustainability of biogas production can be limited by several factors along its production. Thus, this study evaluated the environmental sustainability of electricity generation from a biogas plant fed with maize silage, animal manure, and agri-food residue at Osimo (Marche region) in Italy. We conducted the study using the life cycle assessment methodology (ISO 14040/14044). The selected functional unit (FU) was 1 MWh of electricity produced from the biogas, and the impact assessment was carried out based on the ReCiPe method (2016). Results show a constant daily biogas yield (12,000 Nm^3) and electricity production (23 MWh). The slight variations were due to adding different quantities of agri-food residues. The global warming score obtained was 429 kg CO_2 eq./FU, with maize cultivation contributing more than 90% to the total impact. Thus, substituting maize silage with more agri-industrial residue can significantly improve the overall environmental sustainability of the biogas plant.

Keywords: Biogas, Renewable energy, Life cycle assessment (LCA), Anaerobic digestion, Digestate, Electricity.

1 Introduction

Biomass is one of the renewable energy sources with the potential to reduce the carbon footprint per unit of electricity generated and provide energy for domestic use and transportation [1–3]. Generally, biomass is the biodegradable fraction of products, wastes, and residues from agriculture, forestry, and related industries [4]. It is a versatile source that can generate heat, electricity, and liquid biofuels [[5]. Biogas is produced by the anaerobic digestion of biomass via the breakdown of complex organic matter by various anaerobic microorganisms during fermentation [6]. As a result of the challenges associated with organic waste management, biogas generation represents a means of valorizing agri-food residues, which is in line with the circular economy concept. Compared to other waste treatment technologies, such as landfilling and incineration, anaerobic digestion of biowaste is deemed more cost-effective [7,8]. Biogas has average methane and carbon dioxide content of 60%

and 40%, respectively, making it suitable for combustion to generate heat and electricity and as a transportation fuel [9]. The remaining digestate also finds application in agricultural production as organic fertilizer, plant-growing media, and soil amendment [10]. However, to advocate for extensive biogas use as an energy source, it is crucial to assess the ecological impacts of the operation of a biogas plant, considering the source of biomass, energy use, the efficiency of the plant, and related emissions.

Environmental sustainability assessment is mainly conducted using the life cycle assessment (LCA), which provides a holistic approach to evaluating a product's or service's ecological burdens [11]. LCA is an internationally recognized tool based on the ISO 14040 and 14044 standards, which helps quantify the environmental aspects of materials, energy, and emissions associated with a product or service [12]. Recently, the LCA approach has been widely applied to analyze biogas production's pros and cons in the surrounding environment, especially in Europe [13]. Despite being considered a sustainable energy source, biogas production, especially from organic waste, may be threatened by environmental concerns such as biomass cultivation, transportation, digestate treatment, and combustion emissions [6]. Therefore, these LCA studies were conducted primarily to assess biogas production's ecological sustainability and to identify hotspots along the production process for improvement [10,14]. The sustainability assessment of energy performance in terms of energy balance (production and consumption) has also been well studied [15]. Recycling organic waste for biogas production also confers economic advantages when feedstock includes a significant amount of waste, such as animal manure, agri-food waste, and municipal solid waste. Thus, several LCA studies have included the economic aspects of operating a biogas plant as part of the study's goals [6,16].

The environmental performance of biogas production is affected by several factors, such as the quality of biomass raw materials, cultivation system (energy crops), transportation of biomass, pre-treatment processes, purification of biogas gas, the efficiency of the technology employed, digestate and waste treatment, and related greenhouse gas emissions [6,13]. In Europe, maize silage is the most predominantly used feedstock for anaerobic digestion due to its high bioenergy content, with an estimated biogas yield of up to 0.35 m^3CH_4 per kg VS (after silaging) [17]. Biogas production using dedicated bioenergy crops has raised environmental, social, and economic concerns due to the competition for soil use between food and non-food products. Overexploitation of bioenergy crops such as maize silage can pose a significant threat to the environment by encouraging the creation of mono-crops to meet the energy demand [18–20]. To mitigate this challenge, agriculture and food industry residues are replacing these energy crops that have been criticized for their environmental impact. Commercial energy crops are often mixed with lower energy biowaste, such as animal manure (cattle, pig, and poultry) and agri-food waste, to decrease over-dependence on bioenergy crops. However, this can also affect the biogas yield and quality and the overall sustainability of biogas production. Therefore, this study aimed to assess the environmental and energy performance of a biogas production system belonging to a big agro-industrial producer, considering including different horticultural residues from a life cycle assessment perspective.

2 Methodology

We used the life cycle assessment (LCA) to calculate the impacts of a 1 MW biogas power plant, following the ISO 14040/14044 standards [21,22]. The standard LCA has four interrelated phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation of results. Further details are provided in the sub-sections below.

2.1 Goal and scope definition

This LCA study aims to evaluate the environmental performance of an agricultural biogas plant that produces biogas from anaerobic co-digestion of maize silage, animal manure, and agri-industrial residues for power generation. We assess the energy performance using agri-industrial waste typologies from frozen horticulture production chains to generate biogas. The study's results aim to provide an overview of the current environmental sustainability of electricity production from this biogas plant and identify hotspots to improve the company's overall environmental footprint.

The biogas plant is in Osimo, Marche region in Italy, and was set up due to the government's financial incentivization to encourage renewable energy production. However, due to the environmental concerns associated with using bioenergy crops, biogas plants have to reduce the use of bioenergy crops like maize silage to continue benefitting from the profitable tariff. Thus, there has been a need for collaboration between the biogas plant and agri-food processing companies to obtain a reliable source of residual organic material as a substitute for maize silage.

The selected functional unit was 1 MWh of electricity produced from biogas combustion considering the plant's primary function is to produce electricity. The entire system encompasses both the agri-food and bioenergy production systems. Due to the complexities of allocation, while assessing both systems simultaneously, the ISO standards recommend splitting the different phases and evaluating them individually. For this reason, this study focuses on the part related to the bioenergy production system though linked to the valorization of the residues from the agri-food production chain. Therefore, the system boundary includes upstream activities like maize cultivation, feedstock collection and transportation to the biogas plant. Core activities included the mixing feedstock, anaerobic digestion of feedstock and combustion of biogas. Downstream operations also include digestate separation and spreading. Due to the lack of economic exploitation for the heat produced, all impacts are attributed to electricity production and no allocation is required.

2.2 System description and inventory

The system model is based on a biogas plant with an average daily capacity of 23.5 MWh of electricity for 2021 from the co-digestion of 60-ton daily feedstock. The modelling of the different lifecycle stages was based on primary plant data from the plant, supplemented where necessary by secondary data. Fig. 1 shows the study's system boundary with the biogas production's flowchart.

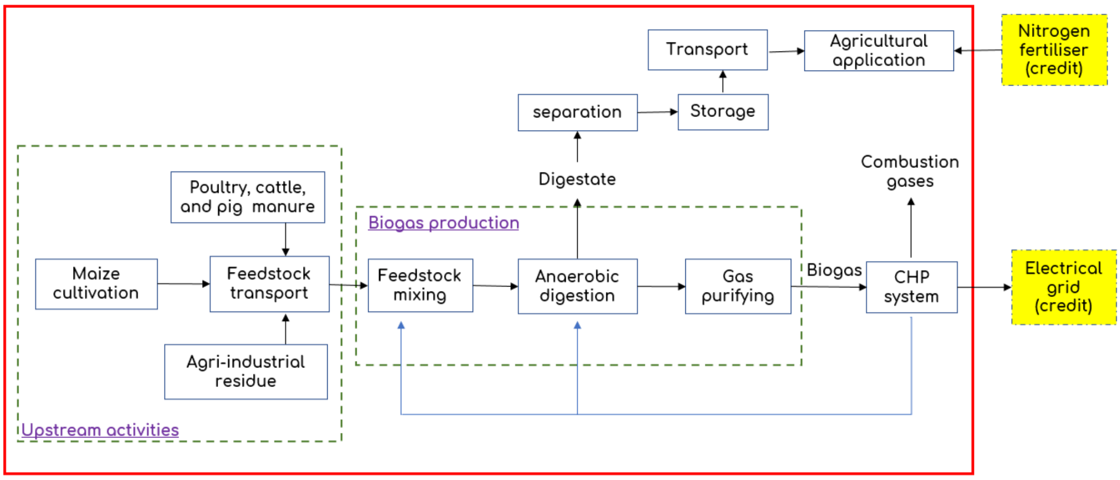

Fig 1: The system boundary of the phases considered.

The maize silage is obtained from cultivated fields close to the biogas plant and other regional commercial fields. Chicken manure is obtained from commercial poultry producers within 15-30 km of the biogas plant, while the agro-industrial residue comes from a large horticultural consortium (55 km away). Anaerobic digestion of the feedstock takes place in three special reactors between 70-90 days, mainly to reduce the volume of the feedstock. The biogas obtained is purified and filtered to remove residual sulfates using iron compounds. The combined heat and power (CHP) internal combustion engine generates electricity and heat from the biogas. About 5% of the electricity is consumed internally for conveying and mixing feedstock, while part of the heat is used to maintain the temperature of the digestors. The remaining electricity is exported to the main grid to provide households and small-scale industries with electricity. After digestion, the digestate (estimated 20,000 tons) is separated with a mechanical screw press into a solid/dry fraction and a liquid fraction. Both digestate undergo further storage in a vast tank (liquid fraction) and a pit (solid fraction). The digestate is transported and spread directly on the fields as organic fertilizer and soil amendment.

Regarding the data quality for the life cycle inventory (LCI), primary data on the feedstock quality and quantity, biogas produced, electricity generated, direct emissions (NO_X, CO, TOC, CH_4, and NMHC) from gas combustion, and digestate volume were obtained directly from the company through questionnaires, official documents, interviews, and results of the analysis conducted to meet regulatory mandates. Where the data were unavailable, we relied on secondary data obtained from the Ecoinvent databases v3, which were used to model the maize silage cultivation, digestate intended for fertilizer, and background processes (material and energy production). The efficiency of electricity generation from the CHP system is 41%. The inventory data is summarized in Table 1.

Table 1: Inventory data for bioenergy production per 1 MWh of electricity via AD

Input	**Quantity**	**Data Source**
Maize silage	2.01 t wb	Secondary
Poultry manure	0.21 t wb	Primary
Pig slurry	0.15 t wb	Primary
Cattle manure	0.06 t wb	Primary
Agri-food residue	0.25 t wb	Primary
Electricity	0.05 MWh	Primary
Output		
Electricity	1.00 MWh	Primary
Digestate	2.44 t	Primary
Emissions to air		
Methane	3.03 g	Primary
Carbon monoxide	1.10 g	Primary
Nitrogen oxides	1.33 g	Primary
NMVOC	0.20 g	Primary

2.2 Impact assessment

The life cycle impact assessment (LCIA) results were modelled using the ReCiPe method 2016 (H) with the SimaPro software version 9.4 to determine the environmental impacts. The study focused mainly on midpoint impact categories directly affected by airborne emissions for the sake of brevity: global warming (GW), stratospheric ozone depletion (OD), terrestrial acidification (TA), marine eutrophication (ME), ozone formation, human health (OF), and fine particulate matter formation (PMF).

3 Results and Discussion

The results obtained show that both the biogas produced and electricity generated were constant throughout the year with little variations (as shown in Fig. 2). The slight variation is due to the inclusion of different agri-food residues as and when they become available. Between January and March, the biogas produced included bioenergy from residual processed tomatoes added as feedstock three months prior. April to June contains bioenergy and biogas from spinach and other leafy vegetable residues. Biogas from pea residues between July and August, and fresh tomatoes between September and December. It is worth noting that the biogas produced is also due to the quantity of the agri-food residue added, which affects the overall ratio of the co-digested feedstock. The similar electricity output from the co-digestion of different feedstock suggests that the biogas plant is well managed.

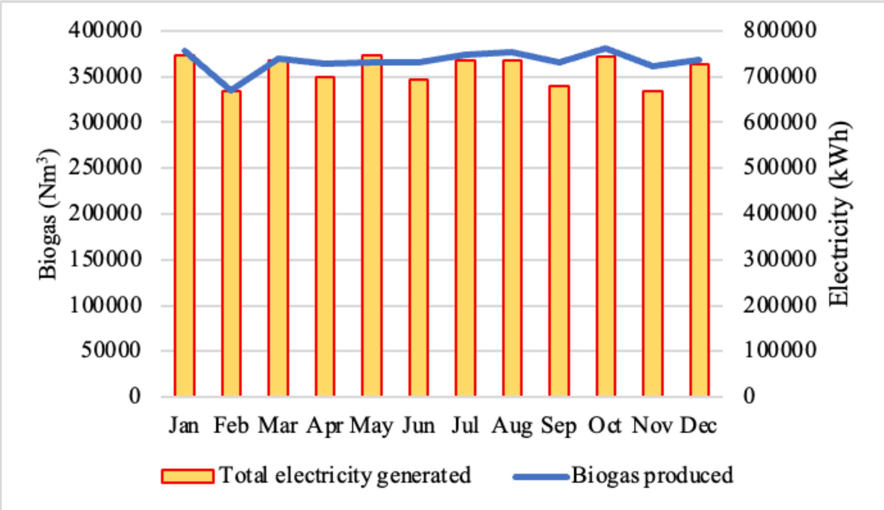

Fig. 2. Monthly biogas produced vs electricity generated.

The midpoint characterization results per 1 MWh of electricity produced in the biogas plant show a climate change score of 429 kg CO_2 eq. Other midpoint results are shown in Table 2. More than 85% of all the impacts for the various impact categories assessed were associated with maize cultivation. Anaerobic digestion and the CHP system contributed less than 2% across all impact categories. This is also due to the low direct emissions (NOx, CH_4, CO, and NMVOC) generated by the CHP unit and the avoided impact from the auto-consumption of electricity generated by the biogas. Feedstock transport contributed less than 5% across the impact categories due to the relatively short distance and the efficiency of the transport means. Credit was also awarded for using digestate as a substitute for urea in maize cultivation and the surplus used in other crop production systems based on the estimated total nitrogen content of the solid (6% d.m.) and liquid (14% d.m.) digestate.

Table 2: The midpoint characterization results per MWh of electricity produced.

Impact category	**Total**	**Maize cultivation**	**Feedstock transport**	**Bioenergy production**	**Electricity consumption**	**Urea**
GW (kg CO_2 eq.)	429	465	3.8	0.1	-20.2	-19.4
OD (kg CFC-11 eq.)	9.72×10^{-3}	9.74×10^{-5}	8.58×10^{-7}	0.0	-1.64×10^{-5}	-7.13×10^{-6}
TA (kg SO_2 eq.)	12.05	12.2	0.02	0.0	-0.07	-0.06
ME (kg N eq.)	0.36	0.36	0.001	0.0	-0.0006	-0.0008
OF (kg NOx eq.)	2.61	2.65	0.03	0.0	-0.04	-0.03
PMF (kg PM2.5 eq.)	2.04	2.08	0.004	0.0	-0.02	-0.02

The contribution analysis of maize cultivation shows that direct nitrogen emissions in the digestate were the main contributor (54%) to climate change.

Chopping/harvesting of the silage was also a significant contributor across all impact categories except marine eutrophication. The planting material contributed over 80% to ME. The highest credit from avoided urea was obtained for OD (26%) and CC (19%). Fig. 3 shows the relative contribution of maize cultivation for the various impact categories assessed.

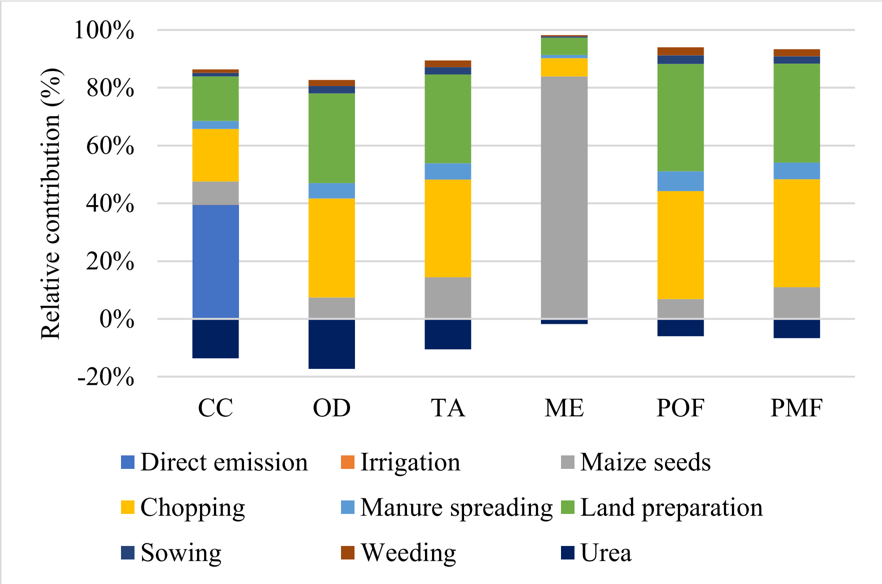

Fig. 3. Relative contribution for maize cultivation.

Although it is challenging to compare LCA results due to possibly wide variations in phases included in the system boundary, allocations, assumptions, and temporal and geographical differences, our climate change result was comparable to some of the LCA results reported for other biogas plants in Italy. Table 3 summarizes the selected LCA studies on biogas production in Italy. Most of the studies were carried out in the Lombardy region, which has more than 40% of all biogas plants in Italy [23]. This is due to the large flat area in Po Valley, which is a hub for agricultural activities with a higher maize cultivation yield per hectare (over 70 tons/ha) than in the Marche region (50-55 tons/ha). Some studies reported feedstock production and transport, especially bioenergy crops, as a major contributor to global warming potential (GWP) [23,24], while others reported bioenergy production as the most impacting [25,26]. Other studies also considered digestate management and reported considerable contributions from direct emissions in open storage systems, typical of large plants [23,25,27]. However, due to the unavailability of primary data, we excluded digestate management.

Table 3. GWP scores per MWh of electricity produced from some agricultural biogas plants in Italy

Author (s)	Year	Results (kgCO_2 eq.)	Feedstock	Number of plants	Region
This study	2022	429	Maize silage, poultry manure, cattle manure, pig slurry, agri-food residue	1	Marche
Mistretta et al. [28]	2022	394 - 566	Maize, triticale, sorghum, bovine manure	2	Piedmont and Lombardy
Cusenza et al. [24]	2021	1223	Olive pomace, whey, chicken manure, bovine manure, sulla, citrus residue	1	Sicily
Lijo et al. [26]	2017	194 - 286	Maize silage, triticale, chicken manure, pig slurry, food waste, municipal solid waste	2	Lombardy
Lijo et al. [23]	2017	152 - 619	Energy crops and residues	15	Lombardy
Fusi et al. [27]	2016	37 - 408	Maize silage, cow slurry, pig slurry, agri-food waste	4	Lombardy

Conclusion

We evaluated the environmental impacts of electricity generation from a biogas plant fed with maize silage, animal manure, and agri-food residue. The results show that the selected feedstock type and origin were critical to biogas production's sustainability. Maize cultivation was the most impacting phase, accounting for more than 90% of the total impacts across all categories. Thus, substituting maize silage with more agri-food residue like horticultural residue, livestock manure, and other organic waste from the locality will significantly improve the efficiency and sustainability of electricity production, depending on the energy potential of these residues. However, the right balance of feedstock is essential to ensuring a good biogas yield. Improved sustainable maize silage production through valorizing biogas digestate as an inorganic fertilizer substitute can also be environmentally and economically beneficial. In addition, valorizing the excess heat produced by the CHP unit, such as for heating greenhouses and district heating, can also reduce the overall impacts associated with biogas production. Horticultural value chains can also be made more sustainable by incorporating agri-residue treatment strategies, such as mushroom rearing and insect biowaste treatment, to obtain other valuable products.

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