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Determination the Environmental Performance of Biogas Production from Cattle Manure via Life Cycle Assessment

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Abstract

This study aims to evaluate the environmental impacts of biogas production from cattle manure in an anaerobic digestion plant (ADP) using the Life Cycle Assessment (LCA) methodology. The LCA analysis adopts a cradle-to-gate system boundary, with the functional unit defined as “1 m³ of biogas produced” in the ADP. Life cycle inventory data for this functional unit was obtained from the Ecoinvent database (v3.10). Life cycle impact assessment were carried out using two methods: CML-IA v3.10 and ReCiPe 2016 Midpoint (H) v1.09, within the licensed SimaPro 9.6.0 PhD software. A sensitivity analysis was also performed to examine the influence of varying transportation distances for cattle manure collection on the overall environmental impacts. The LCA analysis results indicate that operational activities in the ADP and the associated energy requirements significantly contribute to impact categories such as GWP, AP, and EP. Furthermore, it has been observed that the construction phase of the ADP has significant impacts on all ecotoxicity impact categories examined in the CML-IA and ReCiPe impact assessment method. The sensitivity analysis highlights that increasing the renewables energy source usage in the electricity generation mix profile has reduction effect on environmental impacts. Finally, relevant practitioners need to focus on reducing greenhouse gas emissions and ecotoxicity impacts to improve the environmental sustainability performance of biogas production systems.

Keywords: Anaerobic digestion, Biogas production, Cattle manure, Life Cycle Assessment.

Sığır Gübresinden Biyogaz Üretiminin Yaşam Döngüsü Değerlendirmesi ile Çevresel Performansının Belirlenmesi

Öz

Bu çalışma, sığır gübresinden anaerobik çürütme tesisinde (AÇT) biyogaz üretiminin çevresel etkilerini Yaşam Döngüsü Değerlendirmesi (LCA) yöntemi kullanarak değerlendirmeyi amaçlar. Çalışmanın sistem sınırları, hammaddenin temininden biyogaz üretimine kadar olan süreci kapsayan beşikten-kapıya yaklaşımıyla belirlenmiş olup, çalışmanın fonksiyonel birimi “1 m³ biyogaz üretimi”dir. Bu fonksiyonel birim için yaşam döngüsü envanteri verileri, Ecoinvent v.3.10 veri tabanı kullanılarak elde edilmiştir. Yaşam döngüsü etki değerlendirmesi, CML-IA v3.10 ve ReCiPe 2016 Midpoint (H) v1.09 değerlendirme yöntemleri ile lisanslı SimaPro 9.6.0 PhD yazılımında gerçekleştirilmiştir. Ayrıca, sığır gübresi teminindeki taşıma mesafelerindeki değişimlerin genel çevresel etkiler üzerindeki etkisini incelemek amacıyla bir duyarlılık analizi yapılmıştır. LCA analiz sonuçları, AÇT’deki operasyonel faaliyetlerin ve ilgili enerji gereksinimlerinin, küresel ısınma potansiyeli, asidifikasyon potansiyeli ve ötrofikasyon potansiyeli gibi etki kategorilerine önemli ölçüde katkıda bulunduğunu göstermektedir. Ayrıca, AÇT’nin inşaat aşamasının CML-IA ve ReCiPe etki değerlendirme yönteminde incelenen tüm eko toksisite etki kategorileri için önemli etkilere sahip olduğu gözlemlenmiştir. Duyarlılık analizi, yenilenebilir enerji kaynaklarının elektrik üretimindeki karışım profilinin artırılmasının belirli çevresel etkileri azaltıcı etkisi olduğunu göstermektedir. Son olarak, ilgili uygulayıcıların biyogaz üretim sistemlerinin çevresel sürdürülebilirlik performansını iyileştirmek için sera gazı emisyonlarının ve eko toksisite etkilerinin azaltılmasına odaklanması gerekmektedir.

Anahtar Kelimeler: Anaerobik çürütme, Biyogaz üretimi, Sığır gübresi, Yaşam Döngüsü Değerlendirmesi.

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1. Introduction

The demand for livestock products has experienced a two-fold increase over the past four decades, primarily driven by rapid global population growth (Han et al., 2023). This surge in demand has also led to significant rise in manure production. Between 2016 and 2019, over 1.4 billion tons of manure were generated annually by the European Union and United Kingdom (Köninger et al., 2021). Globally, the livestock industry accounts for approximately 20% of nitrous oxide, methane, and fluorinated compound emissions. Of these, livestock manure contributes roughly 45% of total N_2O emissions and nearly 50% of global ammonium emissions (Alba-Reyes et al., 2024).

Improper manure management causes additional environmental issues such as soil contamination from heavy metals, nutrient leaching, and pathogen proliferation beyond greenhouse gas emissions. These challenges underscore the importance of sustainable manure management, as specified in European Union (EU) legislation. Addressing these concerns not only mitigates environmental risks but also opens opportunities for valorizing livestock manure, particularly in renewable energy generation. Reducing dependency on fossil fuels-which currently supply approximately 80% of global energy demand (URL-1), is crucial for achieving long-term energy sustainability, mitigating climate change, and transitioning to a low-carbon economy. Fossil fuel-based energy production is a major contributor to carbon dioxide emissions, which drive climate change and underscore the urgent need for a transition to sustainable energy alternatives.

From this motivation, the EU has committed to ambitious renewable energy targets through initiatives like the Paris Climate Agreement and the European Green Deal, aiming for a minimum 42.5% share of renewable energy by 2030 (URL-2). Biogas production from organic waste, including livestock manure offers a promising pathway for achieving these targets. By means of the Anaerobic Digestion (AD) process, biogas is an important biofuel, is flammable gas that can be produced which is mainly composed of CH_4, (50%–80%), CO_2 (25%–50%), nitrogen (0%–10%), hydrogen sulfide (H_2S) (0%–3%), hydrogen (0%–1%), oxygen (0%–2%), NH_3 (0%–3%), and traces of siloxanes (Kaynarca and Onay, 2024; Fernandes et al., 2023). This process not only mitigates environmental impacts associated with manure management but also contributes to circular economy principles and multiple Sustainable Development Goals including Climate Action and Affordable and Clean Energy.

To evaluate environmental impacts of the production of biogas, LCA methodology has been utilized. Certain LCA studies on biogas production systems have been conducted in Europe and worldwide. These studies provide a solid knowledge base for both policymakers and engineers to enhance the efficiency of such systems and reduce their environmental impacts. Other hand, several studies have evaluated the environmental impacts of biogas production from different substances via AD processes using LCA methodology. For instance, Van Stappen et al. (2016) analysed the environmental implications of treating various organic wastes, including algae (Wei et al., 2023), sludge (Poeschl et al., 2012a), and co-digestion of different substrates (Poeschl et al., 2012b). However, these studies often focus on specific feedstocks or isolated aspects of the AD process. Comprehensive evaluations that identify environmental hotspots across the entire life cycle of biogas production are still limited, particularly regarding cattle manure, which constitutes a significant portion of AD feedstocks (Tufaner and Avşar, 2019). Additionally, the reviewed studies (Hijazi et al., 2016; Paolini et al., 2018; Elizabeth Sinsuw et al., 2024) on the LCA of biogas production in AD plants, mainly focus on impact categories such as global warming potential, cumulative energy demand, acidification potential, eutrophication potential, and ozone layer depletion. However, among them only a few studies assess human toxicity and ecotoxicity categories within scope of the different impact assessment methods.

This study aims to address these gaps by conducting a detailed evaluation of the environmental impacts associated with biogas production from cattle manure. Two different life cycle impact assessment methods as CML-IA and ReCiPe Midpoint, were applied to identify critical environmental hotspots of the AD process. The CML-IA v3.10 method includes eleven different impact categories, while the ReCiPe 2016 Midpoint (H) v1.09 method consists of eighteen impact categories. Additionally, this study examines the compatibility and differences between the two methodologies and evaluates the impact of varying electricity generation mix profile for operation of anaerobic digestion plant (ADP) through sensitivity analysis. This comprehensive approach aimed to provide actionable insights for optimizing the sustainability of biogas production.

2. Materials and Methods

In this study, LCA methodology was employed to evaluate environmental impacts of biogas production in AD plant. The study follows the LCA framework outlined in ISO 14040 (2006a) and ISO14044 (2006b) standards, which consists of four steps: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. The LCA analysis was conducted using the PhD licensed version of SimaPro 9.6.0 software program.

2.1. Goal and Scope Definition

This study aims to conduct an environmental assessment of biogas production from a life cycle perspective. Regarding this objective, the contribution of processes to the environmental performance in anaerobic digestion processes was determined using two different life cycle impact assessment methods. Subsequently, the compatibility of these assessment methods, considering various impact categories, was discussed. Additionally, a sensitivity analysis was conducted to assess the effects of changes in transportation distance.

Figure 1 shows the system boundaries considered in this study. The system boundaries start from raw materials acquisition and energy production, covering the construction phase of ADP. In this study, livestock manure is considered as the feedstock which is collected from farms and transported to the plant facility, where it is used to produce biogas during the operation of the ADP. The operational phase includes manure storage, anaerobic fermentation, and the storage of digestate after fermentation. Biogas is assumed to be the main output. However, the utilization of biogas and further use of the digestate are not included within the system boundaries due to the scope of the study. The functional unit for this study was chosen as 1 cubic meter (m^3) of biogas produced, due to the system boundary ending at biogas production.

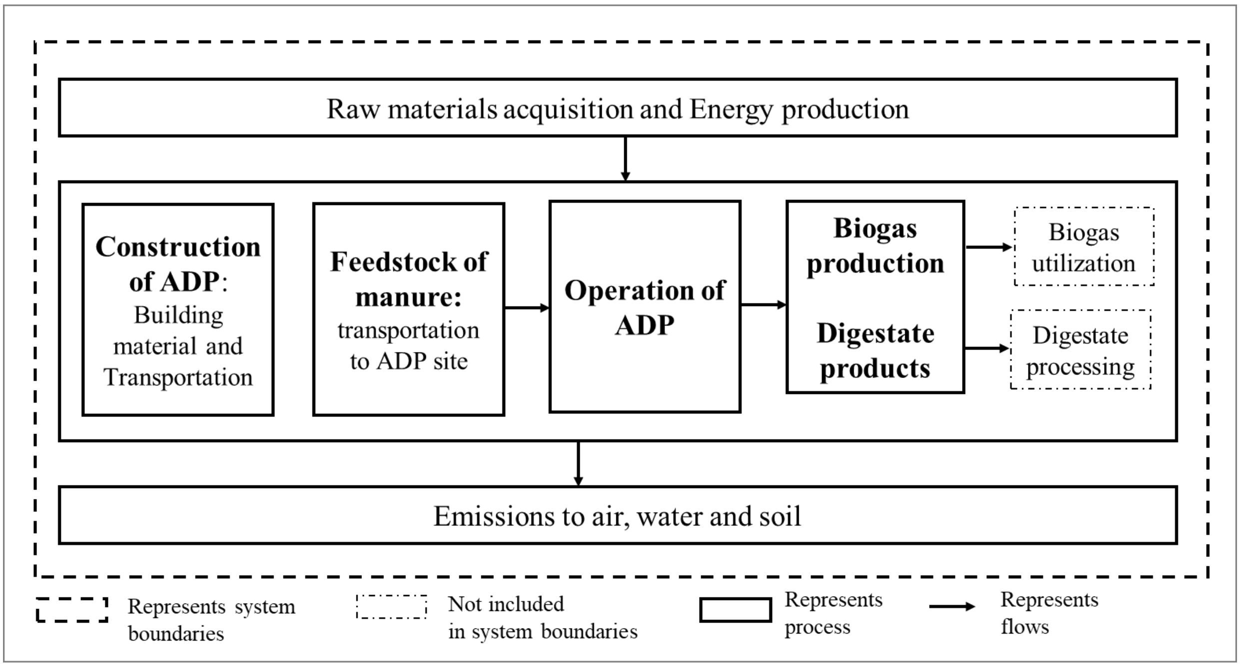

Figure 1. The system boundary of the study.

2.2. Life Cycle Inventory

The life cycle inventory for 1 m^3 biogas production were occurred and detail given in Table 1. The input data of the biogas production is mainly contributed by the transportation of manure, the infrastructure of the ADP (for instance, required construction materials within the installation stage) and operation of the plant (such as required the electricity and the heat energy consumption). The storage of the substrate before the AD process is assumed to be an undercover system. Additionally, the data of outputs are considered emissions to air. These emissions (ammonia, biogenic based carbon dioxide, dinitrogen monoxide, hydrogen sulphide, biogenic based methane was calculated according to the below Eqs. (1)-(4).

$$ES_{NH_3} = 17/14 \text{ x } C(N_{TOT}) \text{ x } 62\%\ EF_1 \text{ x } P_1 \quad (1)$$

Here, the emission of NH_3 means that the ammonia emissions in kg ES_{NH3}/t of wet substrates, $C(N_{TOT})$ is the mean total nitrogen content of the substrate in kg N/t of wet substrate. In this study, this value is assumed about 3.45 based on the manure. EF_1 represents emission factor for ammonia, as 13.5%, P_1 value is the percentage of the time that the substrate is stored at the biogas producers, and its value assumed as 10% (Dauriat et al., 2012).

$$ES_{CO_2} = 44/11 \text{ x } C(C) \text{ x } EF_2 \text{ x } P_2 \quad (2)$$

Here, ES_{CO_2} represents in kg carbon dioxide emissions kg CO_2/t of wet substrates, C(C) is the mean carbon content of the substrate in kg C/t of wet substrate, EF_2 is the carbon dioxide emission factor, and it is assumed 7%. Besides, the carbon dioxide emission is calculated by considering a basis of the methane emission, and it assumed that 30% of the carbon is released in the form of methane and 70% in the form of carbon dioxide based on Frischknecht et al. (2007).

$$ES_{N_2O} = 44/28 \text{ x } C(N_{TOT}) - (14/17) \text{ x} ES_{NH_3}\ EF_3 \text{ x } P_1 \quad (3)$$

Where, emission of N_2O in kg N_2O/t of wet substrates, $C(N_{TOT})$ is the mean total nitrogen content of the substrates in kg N_2O/t of wet substrates. Here it is calculated 3.45 kg N/t of wet substrate based on the manure. EF_3 is 0.5% is nitrous oxide emission factor from (Dauriat et al., 2012; URL-3).

$$ES_{CH_4} = 0.670 \text{ x } B_0 \text{ x } C(OM) \text{ x } EF_4 \text{ x } P_1 \quad (4)$$

Here, ES is the methane emissions in kg CH_4/ton of wet substrate, Bo is assumed as 0.345 is the substrate methane emissions potential in m^3 methane/kg organic material (OM), C(OM) means that the average organic matter content of the substrate in kg OM/ton of wet substrate, this value is calculated about 65 based on the manure substrate. EF_4 is the methane emission factor.

These emissions of CO_2, CH_4, NH_3, and N_2O to the air, resulting from the storage of the substrates before the anaerobic digestion process as well as from the storage of the digestate after the anaerobic digestion process, leads to environmental impact. The values of these emissions were calculated based on the literature study by Dauriat et al. (2012) and data obtained from the Ecoinvent database v3.10 (URL-3). In this study, the operation and infrastructure of the ADP were mainly gathered from the Ecoinvent database v3.10 (URL-3). Hence, the digestate was assumed that carbon content, non-fossil of have 0.45 kg C/kg dry mass, with a dry mass of 1.18 kg. The biogas, which is sourced from the anaerobic digestion of manure, is a non-fossil fuel with a net calorific value of 22.73

MJ. This calorific value of the biogas only considers for the methane content excluding the H_2S presence in it (URL-3). The operating temperature was assumed as 35°C, which is the optimal temperature for the mesophilic range.

The plant was considered that its lifetime is almost 20 years. Hence, the total production volume of gas in the plant is expected to 5E+07 m^3 and this plant is assumed constructed with a concrete fermentation system. The pit is 90 m^3 and the fermenter has a capacity of about 500 m^3, this plant was assumed with a methane recovery system and detailed information is available datasheet in Ecoinvent database v3.10 (URL-4).

In the case of electrical energy consumption, the electricity was assumed from a mixed-generated electricity profile, for its contribution of various energy sources to electricity generation. The electricity profile is composed of a mix of resources, including 20% hard coal, 17% lignite coal, 22% natural gas, 20.5% hydropower, 11% wind, 6% solar, and 3.5% geothermal. The background of electricity generation mix profile data was obtained a specific dataset in Ecoinvent database v3.10 "Electricity low voltage (TR) market for electricity". The transportation of manure was assumed to cover 5 km from the collection site to the AD plant. This freight transportation is assumed to conducted by a lorry with a capacity of 7.5-16 metric tons, operating with EURO6 standards.

Table 1. The life cycle inventory for 1m^3 biogas production.

Process	Amount	Unit	Remark
Anaerobic digestion plant	2.86E-07	product	Detail information are available at URL-4
Manure from cattle, liquid	32.72	kg	Assumed as substrate materials
Manure from cattle, solid	4.46	kg	
Electrical energy consumption	0.16	kWh	This amount assumed with a fixed factor per m^3 biogas produced
Heat energy	3.47	MJ	
Transport	185.92	kg.km	Transportation of manure.
Ammonia	1.75E-03	kg	Calculated based on eq.1
Carbon dioxide	7.09E-02	kg	Biogenic emission, and it calculated based on eq.2
Dinitrogen monoxide	2.49E-04	kg	Calculated based on eq.3
Hydrogen sulphide	4.13E-05	kg	Dauriat et al. (2012)
Methane, biogenic	1.98E-02	kg	Calculated based on eq.4

In this study, CML-IA v3.10 and ReCiPe 2016 Midpoint (H) v1.09 methods were employed to calculate environmental impacts corresponding to biogas production. These methods are widely recognized for their comprehensive and reliable assessment of various environmental impact categories, providing a robust framework for evaluating the sustainability of biogas production processes. The hierarchist perspective is based on the scientific consensus about impact mechanisms' time frame and plausibility. These both methods are available in the library of SimaPro 9.6.0 PhD licensed version. Characterization and normalization results of both methods were collected and interpreted in the following sections. In the CML-IA v3.10 method includes eleven different impact categories as abiotic depletion potential for fossil fuels and elements (ADP_{ff} and ADP_{e}), global warming potential (GWP_{100}), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity (FAETP), marine aquatic ecotoxicity (MAETP), terrestrial ecotoxicity (TEP), photochemical oxidation potential (POP) acidification potential (AP), eutrophication potential (EP). Other hand, ReCiPe 2016 Midpoint (H) v1.09 method also consists eighteen impact categories such as global warming potential (GWP), ozone depletion potential (ODP), ionizing radiation potential (IRP), particulate matter formation potential (PMFP), photochemical oxidant formation potential ecosystems (EOFP), photochemical oxidant formation potential: humans (HOFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), human toxicity cancer and non-cancer potential (HTPc and HTPnc), terrestrial ecotoxicity potential (TETP), freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP), land use potential (LUP), water consumption potential (WCP), mineral resource scarcity potential (SOP), fossil fuel potential (FFP). The normalization results were considered for CML-IA v3.10 and ReCiPe 2016 Midpoint (H) v1.09, EU25 and World (2010) H, respectively.

Sensitivity analysis is a significant aspect of LCA, because it helps identify how variations in key parameters impact the overall environmental and energy performance of a system. Sensitivity analysis examines different scenarios to provide insights into the robustness and reliability of LCA results under varying conditions. In biogas production systems, electrical energy mix generation profile is a significant factor influencing greenhouse gas emissions, toxicities, and fossil fuel resource consumption. Therefore, assessing the impact of electricity generation during the transition from fossil fuels to renewable sources offers valuable guidance for optimizing environmental performance in biogas plants. In this study, a sensitivity analysis was conducted to examine the impact of producing the mix electricity used in the operation of the ADP plant from different fossil and renewable energy sources. In the sensitivity analysis, electricity generation mix profile I consisted of a combination of energy sources, including 18% hard coal, 15% lignite coal, 17% natural gas, 25% hydropower, 13% wind, 8% solar, and 4% geothermal. Electricity generation mix profile II included 14% hard coal, 13% lignite coal, 13% natural gas, 30% hydropower, 15% wind, 10% solar, and 5% geothermal. In electricity generation mix profile III, the energy sources considered 10% hard coal, 10% lignite coal, 10% natural gas, 33% hydropower, 18% wind, 13% solar, and 6% geothermal.

3. Findings and Discussion

The characterization and normalization results of 1 m^3 of biogas produced in the ADP process were obtained using the CML-IA v3.10 and ReCiPe 2016 Midpoint (H) v1.09 methodologies, which are widely recognized frameworks for life cycle impact assessment. These characterization and normalization results are given in Table 2. Table 2 shows that impact categories, such as GWP100 – GWP; AP – TAP; and have a consistent and comparable results across both methods. This compatibility means that the reliability of the methodologies in evaluating key environmental impacts and provides a solid basis for interpreting and comparing the environmental performance of biogas production processes. Other hand, the results of the ecotoxicity impact category show difference in both assessment method. This is because each method considers different time horizons in the HTP – HTPc and HTPnc impact category (Monteiro et al., 2021) and different geographical scopes in the TEP – TETP impact category (Carvalho et al., 2019).

Table 2. The characterization and the normalization results 1 m^3 biogas production in the CML-IA and the ReCiPe imethods.

Impact category	**Characterization results**			**Normalization results**	
	CML-IA	**ReCiPe**	**Unit**	**CML-IA**	**ReCiPe**
ADP_e	1.3E-06	n.a. [a]	kg Sb eq.	1.5E-14	n.a. [a]
ADP_{ff}	4.1E+00	n.a.	MJ	1.3E-13	n.a.
GWP_{100}	9.7E-01	1.1E+00	kg CO_2 eq.	1.9E-13	1.4E-04
ODP	4.5E-09	2.9E-06	kg CFC-11 eq.	5.1E-17	4.8E-05
HTP	1.0E+00	n.a.	kg 1,4-DB eq.	1.3E-13	n.a.
FAETP	6.3E-02	n.a.	kg 1,4-DB eq.	1.2E-13	n.a.
METP	3.7E+02	n.a.	kg 1,4-DB eq.	3.1E-12[b]	n.a.
TEP	8.5E-03	n.a.	kg 1,4-DB eq.	1.8E-13	n.a.
POP	2.3E-04	n.a.	kg C_2H_4 eq.	2.7E-14	n.a.
AP	3.9E-03	n.a.	kg SO_2 eq.	1.4E-13	n.a.
EP	8.5E-04	n.a.	kg PO_4^{3-} eq.	6.4E-14	n.a.
IRP	n.a.	5.2E-04	kBq Co-60 eq.	n.a.	1.2E-06
EOFP	n.a.	8.6E-04	kg NOx eq.	n.a.	4.1E-05
PMFP	n.a.	1.5E-03	kg $PM_{2.5}$ eq.	n.a.	6.0E-05
HOFP	n.a.	9.3E-04	kg NOx eq.	n.a.	5.1E-05
TAP	n.a.	4.3E-03	kg SO_2 eq.	n.a.	1.1E-04
FEP	n.a.	1.7E-05	kg P eq.	n.a.	2.7E-05
MEP	n.a.	3.2E-06	kg N eq.	n.a.	1.3E-06
TETP	n.a.	4.3E+00	kg 1,4-DCB	n.a.	9.0E-05
FETP	n.a.	2.8E-04	kg 1,4-DCB	n.a.	1.2E-05
METP	n.a.	4.6E-03	kg 1,4-DCB	n.a.	2.8E-05[b]
HTPc	n.a.	1.2E-03	kg 1,4-DCB	n.a.	n.a.
HTPnc	n.a.	7.3E-02	kg 1,4-DCB	n.a.	n.a.
LUP	n.a.	7.9E-02	m^2a crop eq.	n.a.	1.4E-04
SOP	n.a.	9.9E-04	kg Cu eq.	n.a.	4.8E-05
FFP	n.a.	9.7E-02	kg oil eq.	n.a.	n.a.
WCP	n.a.	1.7E-03	m^3	n.a.	n.a.

[a] n.a means that this impact category is not applicable to the applied impact assessment method.
[b] n.i means that not included. During the calculation impact percentage of impact categories in the normalization results, MAETP impact category excluded in total assessment due to its uncertainties (Shen and Patel, 2010).

The normalization results were calculated to transform impact categories into unitless values, facilitating a meaningful comparison between them. These normalization results indicate that impact categories with a percentage greater than 5% were selected for further analysis, particularly focusing on process contributions and inventory pollutants or substances. As a result, the impact categories ADP_{ff}, GWP100, TEP, AP, and EP were chosen for in-depth analysis within the CML-IA v3.10 method. In contrast, the ReCiPe 2016 Midpoint (H) v1.09 method highlighted the need for a more detailed investigation of the GWP, PMFP, HOFP, TAP, TETP, HTPc, and FFP impact categories, as these also showed significant contributions to the overall environmental performance.

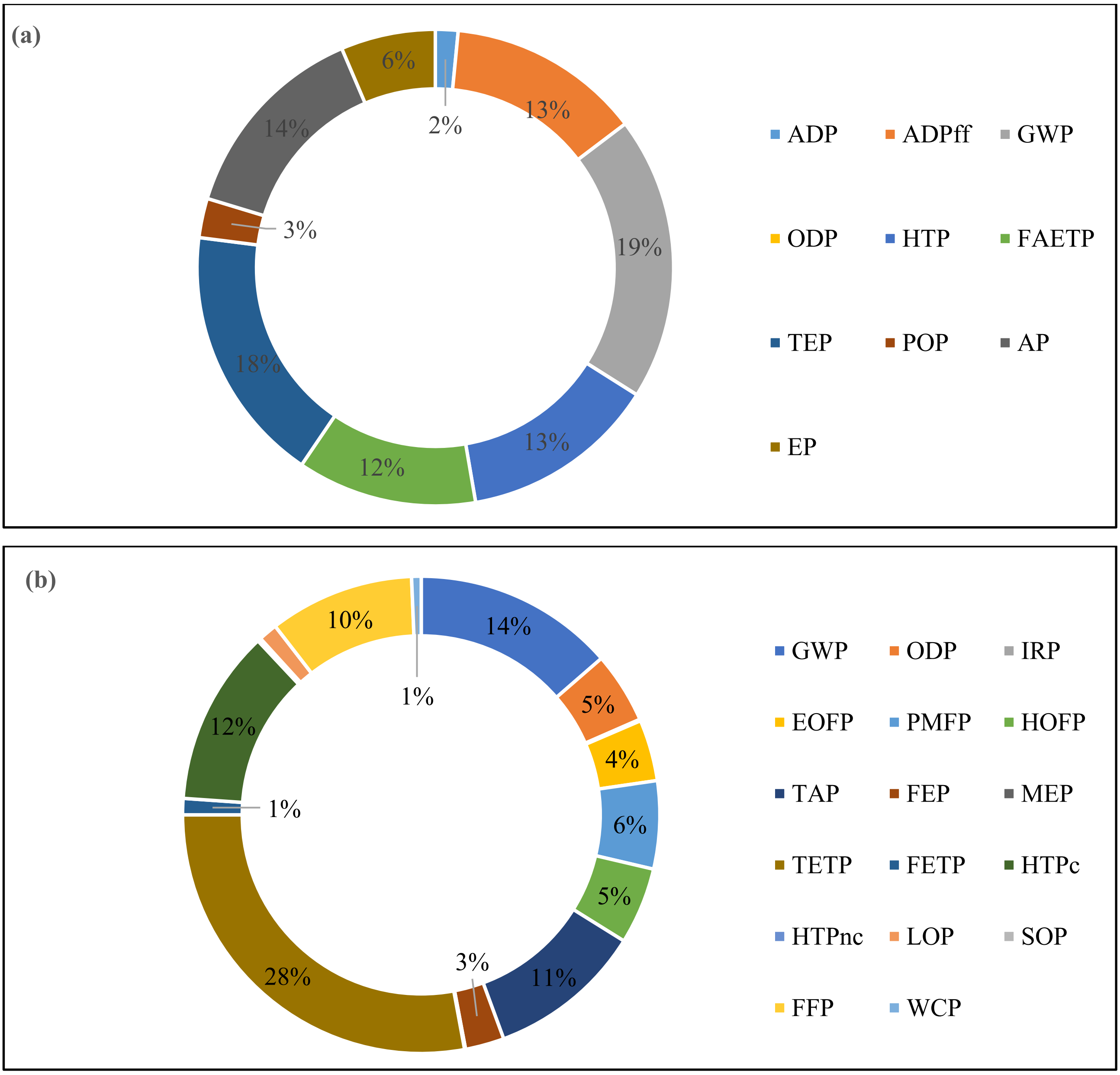

Figure 2 (a-b). Impact percentages based on the normalization results in (a) CML-IA method, (b) ReCiPe method.

The impacts of processes in biogas production have detailed analysed and the process contribution of this production illustrated in Figure 3 (a) and Figure 3(b) for CML-IA and ReCiPe methods, respectively. The effects on the ADP_{ff} impact category occurred due to electricity and heat energy production, as well as the transportation of manure, which involved the use of fossil fuel sources such as oil, gas, and coal. The biogas production in CML-IA impact assessment method, there are important impacts from the operation of ADP on GWP_{100}, AP, and EP impact categories due to its emissions. In the GWP, CH_4 (biogenic) and N_2O are primarily occurring from operation of the ADP, CO_2 fossil derives from the energy production for electricity and heat in both methods. For AP category, NH_3 substance is the main contributor pollutant due to operation of the ADP, whereas SO_2 and NOx are chiefly occurred from electricity production based on fossil fuels in particularly coals. Like AP category, EP impact is resulted from NH_3 and N_2O pollutants from operation of the ADP and nitrogen oxides to air due to electricity. The construction of the anaerobic digester, energy (heat and electricity) production, and transportation processes have similarly contributed to ecotoxicity impact categories, including HTP, FAETP, and TEP. It was found that these impacts primarily result from indirect processes, particularly related to the consumption of coke coal for produce pig iron in the background. Additionally, the substances of cobalt (II), anthracene and chromium (III) were significant impact to these three categories, respectively.

Figure 3(b) also shows the process details analysed for seven different impact categories. As seen previously in the CML-IA method, the operation of the ADP has a remarkable direct effect on impact categories such as GWP, TAP, and PMFP. The responsible pollutants in these categories, as identified in the ReCiPe method, were found to be similar to those in the CML-IA method. It has been observed that in PMFP impact category, $PM_{2.5}$ and SO_2 pollutants primarily result from the electrical and heat energy production process, while NH_3 emissions derived from the operation of the ADP. Besides, NOx emissions were considered to play important role in the HOFP impact category from both energy production processes. In particular, the main gas emissions of NH_3 and NOx were found to be responsible for this impact, because their presence in the environment might be led to change in pH levels and nutrient balance. The construction of the ADP process has high impact on TETP and HTPnc impact categories. Other process such as manure transportation has remarkable impact on TETP due to brake wear emissions mainly from cobalt (II) and copper. Additionally, antimony and zinc ions contribute to the TETP impact category. The background data for the HTPnc impact category showed that chromium (IV) and nickel emissions are the main contributors to the HTPnc impact, resulting from the construction of the ADP plant (pig iron production process) and electricity generation (based on lignite coal). For the last investigated impact category, FFP, the consumption of oil, gas, and hard coal during energy production and transportation processes demonstrated a significant impact. This finding was also observed in ADP_{ff} impact category in the CML-IA method.

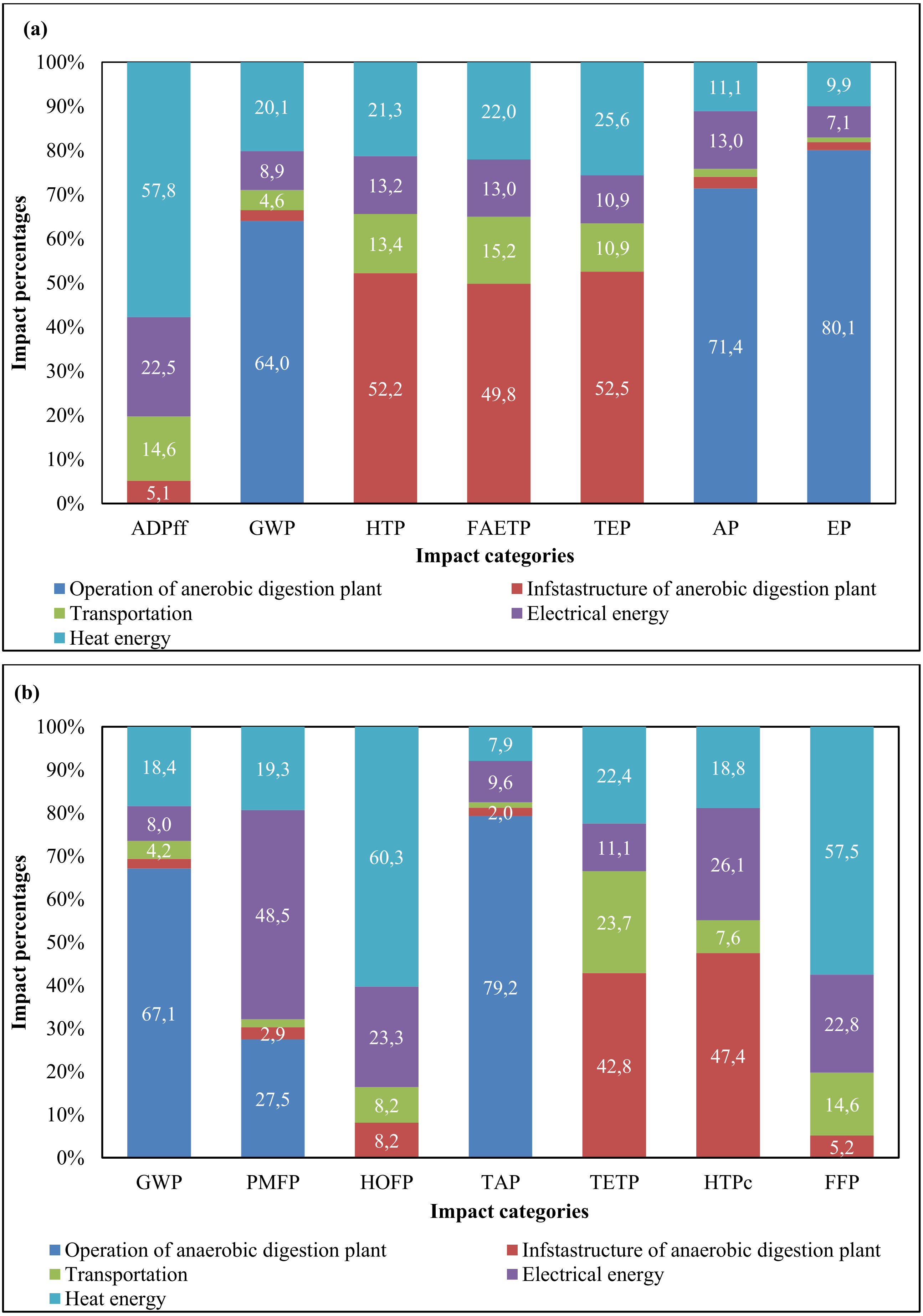

Figure 3 (a-b). Process contribution of biogas production (a) in CML-IA method (b) in ReCiPe method.

The characterization results for 1 m^3 of biogas production, obtained using the CML-IA and ReCiPe methods in this study, were compared with those from existing literature. The comparison exhibits notable variations due to high specify of the LCA results, which are influenced by factors such as local conditions, plant scale, annual gas production volume, energy sources, study motivations, scope, and system boundaries. For instance, Elizabeth Sinsuw et al. (2023) reported a GWP of 0.018 kg CO_2 eq per m^3 of produced biogas under specific conditions. On the other hand, Garfi al. (2019) observed significantly higher GWP values ranging from 4.83 to 5.93 kg CO_2 eq. for small scale digesters. These differences can be linked to variations in the system boundaries and operational scales. When the results of each related study are compared to one another, each case provides a clearer understanding of the contextual factors influencing biogas LCA outcomes.

On the other hand, decreasing dependency on fossil fuels is crucial for transitioning to a low-carbon application. Therefore, understanding the environmental impacts of biogas compared to natural gas production is essential. Marconi and Rosa (2023) reported that substituting fossil natural gas with biomethane can reduce emissions from natural gas systems by 11%, corresponding to an annual decrease of 1.1 Gt CO_2-eq. worldwide.

In the sensitivity analysis, the obtained results of the analysis are illustrated in Table 3. As the share of renewable energy sources increases in the electricity generation mix, there is a noticeable decline in ADPff, GWP, TAP, EP, PMFP, HOFP and FFP are resulting from the environmental benefits of transitioning from fossil fuels to cleaner energy sources. The sensitivity analysis results reveal that the reduction of coal and natural gas in the electricity mix contributes significantly to lowering the environmental footprint across multiple impact categories, demonstrating the importance of decarbonizing electricity production in biogas systems.

Table 3. The characterization results of sensitivity analysis of 1 m^3 biogas production

Impact category	Unit	CML-IA			ReCiPe		
		I	II	III	I	II	III
ADP_{ff}	MJ	5.1E+00	4.2E+00	3.2E+00	n.a	n.a	n.a
GWP_{100}	kg CO_2 eq.	4.8E-01	4.0E-01	3.0E-01	n.a	n.a	n.a
HTP	kg 1,4-DB eq.	8.3E-01	8.1E-01	7.9E-01	n.a	n.a	n.a
FAETP	kg 1,4-DB eq.	5.0E-02	4.9E-02	4.8E-02	n.a	n.a	n.a
TEP	kg 1,4-DB eq.	5.7E-03	5.5E-03	5.4E-03	n.a	n.a	n.a
AP	kg SO_2 eq.	2.9E-03	2.4E-03	1.9E-03	n.a	n.a	n.a
EP	kg PO_4^{3-} eq.	3.4E-04	2.9E-04	2.2E-04	n.a	n.a	n.a
GWP	kg CO_2 eq.	n.a	n.a	n.a	4.9E-01	4.0E-01	3.1E-01
PMFP	kg $PM_{2.5}$ eq.	n.a	n.a	n.a	4.2E-03	3.6E-03	2.8E-03
HOFP	kg NOx eq.	n.a	n.a	n.a	1.2E-03	1.0E-03	7.7E-04
TAP	kg SO_2 eq.	n.a	n.a	n.a	2.3E-03	2.0E-03	1.5E-03
TETP	kg 1,4-DB eq.	n.a	n.a	n.a	2.9E+00	2.9E+00	2.8E+00
HTPc	kg 1,4-DB eq.	n.a	n.a	n.a	1.9E-03	1.6E-03	1.4E-03
FFP	kg oil eq.	n.a	n.a	n.a	1.2E-01	9.9E-02	7.6E-02

n.a means that this impact category is not applicable to the applied impact assessment method.
Abbreviation terms of I, II, and III represents electricity generation mix profile I, II and III, respectively.

4. Conclusions and Recommendations

There is significant importance in evaluating, monitoring, and reporting the environmental impacts of biogas production, to improve biogas plants' sustainability performance. From this motivation, this study aimed to evaluate the environmental impacts of biogas production in ADP within cradle-to-grave system boundaries using the CML-IA and the ReCiPe impact assessment methods. The important findings of LCA analysis in this study are summarized:

- The operation of the ADP process has significant impacts on the GWP, AP, and EP, representing almost 64%, 71% and 81% of the total impacts, respectively, due to direct release of emissions such as methane, carbon dioxide, and dinitrogen monoxide.
- Electrical and heat energy production account for approximately 41% and 37% of the impacts on ADP_{ff} and TEP, respectively.
- The construction of the ADP process has significant impact on ecotoxicity categories such as HTP, FAETP and TEP.
- The transportation of manure significantly has a significant impact on the TETP and FFP impact categories compared to other impact categories with having about %24 and 15%, respectively.
- The characterization results for impact categories such as GWP_{100}-GWP; AP-TAP HTP-HTPc plus HTPnc; AP-TAP in both methods indicated that these categories have compatibility. However, the results of the ecotoxicity categories in both impact assessment methods showed less compatibility, as these methods cover different time horizons and geographical scope.

While the findings clearly demonstrate that the operation of the ADP contributes dominantly to GWP, AP, and EP deeper analysis of how these impacts scale at the national and global levels is crucial. For instance, CH_4 and N_2O emissions from ADP operations not only affect local air quality but also contribute to climate change on a global scale, emphasizing the need for policies that address these emissions in both developing and developed countries. The study's identification of energy production as a significant contributor to several impact categories underscores the importance of transitioning to renewable energy sources, which would have far-reaching benefits globally in reducing carbon footprints. Additionally, the global implications of transporting manure, particularly its contribution to the toxicity categories, suggest that international logistics must be reevaluated. Finally, while the construction and operation of ADPs have substantial local impacts, these findings could be expanded to highlight the need for sustainable practices in infrastructure development and energy production, both nationally and globally, to minimize environmental harm and promote a circular economy. Regarding with these benefits, to achieves a more sustainable method of biogas production utilizing manure, it is important to evaluate the considering comprehensive different environmental impact categories contributed by each stage of the biogas production process and this study is trying to fill the gap. Additionally, the LCA analysis outcomes emphasize the importance of stakeholders primarily focusing on reducing greenhouse gas emissions and toxicities to improve environmental sustainability performance. In the next application in macro/micro levels of ADPs, improving the efficiency of anaerobic digestion processes might be prioritized to increase biogas yield and process stability. Utilizing biogas for energy production rather than releasing it into the atmosphere can enhance the environmental performance of this system and serve as a useful energy source, offering a sustainable alternative to conventional fossil fuel power generation.

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