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Research article

The implications of management practices on life cycle greenhouse gas emissions in biogas production

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ABSTRACT

Biogas production is seen as one of the key measures in circular economy providing several benefits for the environment. In practice, however, these benefits may not be achieved if the production is not implemented and managed in ways that reduce gaseous emissions. Thus, this study aimed at highlighting how different management practices impact the climate during the life cycle of biogas production in comparison to management without biogas production (reference). Advanced, more emission-reducing practices resulted in 97–107% and conventional practices in 57–75% less emissions when biogas was utilized as transport fuel. If biogas was utilized in CHP (combined heat and power production), the emission reductions were 67–74% and 13–30%, respectively. This reflects the fact that inefficient practices can lead to minimal emission reduction without achieving the desired climate benefit in comparison to the reference. On the European level, this may also mean that the emission reduction demands of RED II (Renewable Energy Directive) regulation are not met. Therefore, when supporting biogas production with public funds, assurance of using emission-reducing practices should be made a prerequisite.

1. Introduction

In Europe, biogas and biomethane production in 2021 was about 196 TWh, contributing about 4.5% of the European Union's gas consumption (EBA, 2022). The aim is to increase biogas production due to the numerous advantages it offers from security of supply to climate change mitigation. Moreover, the production and use of biogas is seen as one of the central aspects of circular economy contributing simultaneously to renewable energy, climate change mitigation, sustainability of the food system and nutrient recycling (Fagerström et al., 2018; European Commission, 2019, 2020a). Overall, biogas production is seen to promote a transition where the utilization of various organic wastes and side streams reduces both harmful environmental effects and dependence on fossil energy and mineral fertilizer products. However, the fact that biogas production needs to be implemented and managed with emission-reducing practices is rarely recognized. When reading the strategy papers, little if any attention is paid to the fact that minimizing the emissions related to biogas production chain is a key to ensure achieving the listed benefits.

The sustainability of biogas production should be considered in each phase of the production chain. The feed material(s), technology and management practices chosen affect the biogas yield, the quality of the end products and the emissions produced, both in terms of economy and the environment. As biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2) and CH_4 is a potent but relatively short-lived greenhouse gas (GHG), even small emissions and leakages of CH_4 within the life cycle decrease the climate benefits pursued. Reducing CH_4 emissions is one of the most immediate and effective climate change mitigation strategies, and their reduction is supported by the Global Methane Pledge and EU methane strategy (European Commission, 2020b; 2021). In addition to CH_4 emissions, nitrous oxide (N_2O) emissions can occur due to the transformation of the nitrogen (N) -containing compounds during different phases of the biogas production chain, especially during digestate handling.

Recent studies report a great variation in measured CH_4 losses from biogas plants. According to Fredenslund et al. (2023), the CH_4 losses in 69 Danish biogas plants varied between 0.3 and 40.6% of the produced CH_4. In relation to the structure and maintenance of the biogas process, the most significant CH_4 emission sources have been identified as digestate storage without gas collection, fastening of membrane domes

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used as roofs, holes in concrete walls/structures, pressure control valves, gas pipes, gas compressors and mixers (Reinelt et al., 2017, 2022; Fredenslund et al., 2018, 2023; Tauber et al., 2019). However, also the design parameters and management practices chosen for the whole production chain have an impact on overall emissions.

A significant design parameter and practice affecting gaseous emissions from biogas production is the retention time (RT) of the feed material in the biogas reactor. The RT affects the efficiency of decomposition achieved and thus, the longer the RT is, the better the organic matter decomposes into biogas (Bi et al., 2020). The RT of the biogas reactor is also a critical parameter for the quality of the digestate (Vergote et al., 2019). A short RT and high organic loading rate may result in digestate still containing a lot of easily degradable organic matter, which, during favorable storage conditions, further degrades and forms CH_4 emissions. The biodegradability of digestate under storage conditions is usually lower than that of, for example, raw manure (Maldaner et al., 2018; Vergote et al., 2019). Contradictory results have also been reported. For example, Rodhe et al. (2015) measured higher CH_4 emissions from digested slurry than from raw slurry in summer conditions (outdoor temperature between 5 and 35 °C during April–August).

Typically, the climate sustainability of biogas plants is evaluated by life cycle assessment (LCA), but the possible CH_4 leaks and emissions from the process might be ignored (e.g., Wang et al., 2016; Aziz and Hanafiah, 2020; Morsink-Georgali et al., 2022; Ugwu et al., 2022). Moreover, the climate impacts of alternative management practices are even less recognized in LCA studies and other sustainability assessments regarding biogas production. However, the refinement of IPCC guidelines (IPCC et al., 2019) includes categories for both high- and low-quality digesters and three levels for the storage gas tightness, but the actual practices are not defined. The Renewable Energy Directive (EU 2018/2001, RED II) also gives four separate default emission values for biogas plant emissions. The default values take into account, if the digestate storage is open or closed as well as if the off-gas from biogas upgrading is treated or not. On top of that, the emission reduction credit for wet manure is included.

So far, many sustainability assessments of biogas production have inadequately considered the CH_4 emissions leaks and the impacts of the different management practices. The objective of this study was to highlight and thus increase awareness of the significance of emission-reducing practices on the climate sustainability in the implementation and management of biogas production. This was done by assessing the life cycle climate impact of a theoretical case study biogas plant with i) advanced, emission reducing practices, ii) conventional practices with little special regard to emission reduction, and iii) a reference situation (biomass treatment without biogas process). To assess the potential impact of the different practices on the realization of the RED II sustainability criteria, the manure credits were calculated based on the RED II principles to quantify the applicable emissions credits within the manure management chain. The emission factors used were based on scientific literature on measured CH_4 emissions on biogas plants, and the data was applied to a theoretical case study situated in the Northern Europe.

2. Material and methods

2.1. Case study biogas plant

This study is based on a theoretical example of a biogas plant including continuously stirred tank reactor, gas utilization, and digestate processing, storage, and utilization. The feed mixture, operation and digestate treatment mimicked a typical Finnish biogas plant, though the capacity is larger than yet executed for manure-based biogas production (Table 1).

Two scenarios, referred as "Conventional" and "Advanced", were developed to study the role of different management practices on the emissions. Alternative emission management practices were determined as conventional and advanced (emission-reducing) (Table 1), including differences in RT, emissions from feed processing, leaks, maintenance and digestate storage. The advanced practices also included drying and pelletizing of separated digestate solid fraction and evaporation of respective liquid fraction to achieve concentrated, transportable fertilizer products. For both practices, two alternatives for gas utilization were studied: transport fuel (A) and combined heat and power generation (CHP) (B).

Table 1
The case study biogas plant with conventional and advanced management practices.

Parameter	Conventional practices	Advanced practices
Feed capacity (t/year)	200,000	200,000
Total reactor volume (m^3)	25,000	54,300
Organic loading rate (kgVS/m^3d)	2.1	5.1
Feed mixture	Pig slurry (40%) Poultry manure (15%) Separated solid fraction of pig and cattle slurry (15%) Grass from fallows (10%) Side stream from food industry (20%)	Pig slurry (40%) Poultry manure (15%) Separated solid fraction of pig and cattle slurry (15%) Grass from fallows (10%) Side stream from food industry (20%)
Process water (t/year)	180,000	130,000
Retention time (RT, days)	20	50
Gas utilization	a) transport fuel b) combined heat and power (CHP)	a) transport fuel b) combined heat and power (CHP)
Digestate processing	Separation with a centrifuge	• Separation with a centrifuge • Liquid fraction: evaporation combined with ammonia scrubbing • Solid fraction: thermal drying and pelletizing
Storage of digestate-based fertilizer products	Liquid fraction: open Solid fraction: open	Concentrated liquid fraction and ammonium sulfate: closed Thermally dried and pelletized solid fraction: covered

2.2. Life cycle assessment

2.2.1. Methodology and system boundaries

The life-cycle climate impacts were examined by applying a standardized methodology based on the Life Cycle Assessment (LCA) (ISO 2006: 14040; 14044). The most typical GHGs, i.e. fossil CO_2, CH_4 and N_2O were considered. In addition to direct N_2O emissions, the study considered the indirect N_2O emissions caused by ammonia (NH_3) and nitrogen oxides (NO_x). Climate impacts were measured using the Global Warming Potential (GWP) method which converts the heating effect of the unit emissions of different GHGs into its CO_2-equivalent (CO_2-eq.), considering the heating effect of the selected time frame. Typically, a 100-year period (GWP100) is considered due to being consistent with the UN Climate Convention and the Kyoto Protocol. In this study, GWP coefficients in the 100-year timespan were used. Emission characterization was made in accordance with the Finnish Greenhouse Gas Inventory Reporting and Methodological Guidelines (Suomen virallinen tilasto SVT, 2020) and the IPCC Fourth Assessment Report (IPCC, 2007).

The climate impacts were calculated for the case study for one year of operation using data from mass, nutrient and energy balance calculations as the basis (See: 2.2.2). Emission factors for the two studied management practices (conventional and advanced) were applied based on a literature (See: 2.2.3 and Supplementary Material B). Due to uncertainties in the background data, the calculation was made with minimum and maximum emission factors for both conventional and advanced practices. No separate sensitivity analysis was therefore conducted. In addition, emission reduction potential of advanced practices by each life cycle phase was examined.

The feeds of the biogas plant were assumed to be side streams and waste from agriculture and food industry. Consequently, the emissions resulting from their production were not included. However, feed transportation to the biogas plant and digestate-based product transportation to the fields were included. Emissions from machine work during field spreading were not included. Emissions from construction of facilities and production of materials used in construction were also not included (Fig. 1).

To evaluate the effects of different practices considering the consequences, emission credits (substitutions) for products formed in the process were studied. These include the energy produced and nutrients (N and phosphorus, P) contained in the digestate and digestate-based products. The final products were assumed to fully replace the existing production and use of electricity and heat or transport fuels and inorganic fertilizers.

In addition, as the climate impact of biogas production is realized as the difference between biogas production and traditional processing, the traditional means of processing and utilization of the same biomasses (without biogas production) was examined as the reference situation (Fig. 1).

2.2.2. Mass, nutrient and energy balance calculations

Simplified mass, nutrient and energy balances were modeled to highlight the effects of management practices on the emission risks of the theoretical biogas plant for both conventional and advanced practices. The calculations were used as the basis for LCA. The balances

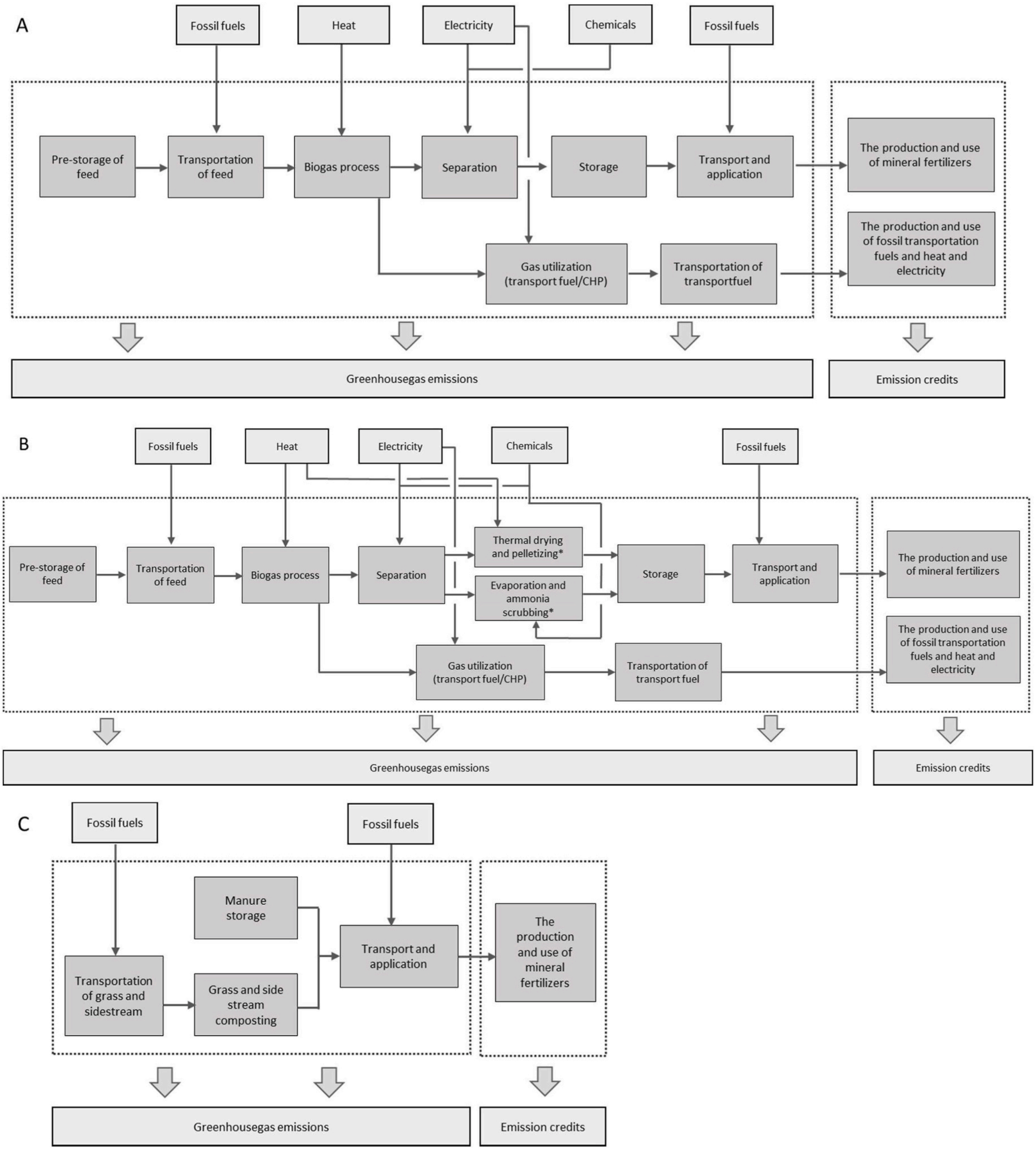

Fig. 1. The system boundaries of alternative management practices for biogas production and the reference without biogas production. A: conventional practices, B: advanced practices, C: reference (traditional treatment without biogas process).

describe the transformation of the feed mass, organic matter (degradation into biogas) and nutrients (mineralization of N) during the biogas process and the digestate processing.

The feed consisted of agricultural biomasses and a side-stream from food industry (Table 2). In addition, process water from the digestate processing was added to the feed mixture to acquire suitable total solids (TS) content for wet digestion (TS approx. 13%). In advanced practices, the almost solid-free process water from evaporation was used (130,000 t/y), while with conventional practices, the liquid fraction from digestate separation was used (180,000 t/y). Both biogas plant processes were assumed to be operated similarly, and only changes in RT, process water circulation and digestate treatment were evaluated.

The CH_4 production realized was modeled with a formula originally applied to materials of animal origin, such as manure (Chen and Hashimoto, 1978; Hill, 1983). Also, N mineralization is dependent on the degree of organic matter decomposition (Angelidaki and Sanders, 2004) and thus, a longer RT also affects the amount of soluble N in the digestate. When calculating the nutrient balances, it was assumed that N mineralization follows the decomposition of organic matter using factor 0.63 as the ratio of organic-N to organic matter decomposition (Marcato et al., 2008). The total N and total P were assumed to remain unchanged.

The digestate processing differed between conventional and advanced practices. In conventional practices, digestate was centrifuged into solid and liquid fractions, while in advanced practices the solid fraction was also dried to 90% TS content with subsequent scrubbing of the NH_3-containing air with sulfuric acid (H_2SO_4) to produce ammonium sulfate $(NH_4)_2SO_4$. The dried digestate was further pelletized. The respective liquid fraction of advanced practices was evaporated to a nutrient concentrate and the soluble N was scrubbed to $(NH_4)_2SO_4$ (see Supplementary Material A). H_2SO_4 (93%) consumption in scrubbing was calculated in accordance with the molar masses of H_2SO_4 and $(NH_4)_2SO_4$. Polymer use in centrifuging was based on literature (Paavola et al., 2019; Lehtoranta et al., 2020). Residual NH_3 emissions from digestate processing were assumed to consist of the NH_4^+-N that was not recovered in scrubbing process.

When calculating the energy balance and amount of energy produced, CH_4 losses were assumed to occur during plant operation (leaks, safety valves) or due to maintenance procedures and equipment malfunctions (See: 2.2.3, Table 3). It was assumed that the CH_4 volume realized was used to produce transport fuel, while the plant's own electricity and heat needs were covered with purchased energy (scenario A). The energy consumption at the case study plant consisted of the electricity and heat requirement of different equipment based on literature (see Supplementary Material A).

Table 3
CH_4 emission factors used in the study (% of CH_4 produced).

	Conventional	Advanced	Reference
BIOGAS PROCESS			
Emissions from mixing and feeding unit	0.1–0.2%	0.01–0.03%	Estimated based on Liebetrau et al. (2013), (2010)
Emissions leakages from plant structures	0.15–0.28%	0.017–0.1%	Estimated based on Liebetrau et al. (2013), (2010); Reinelt et al. (2022); Wechselberger et al. (2023)
Pressure release valves	1.1–3.6%	0.04–0.73%	Estimated based on Reinelt et al. (2016), (2017); Reinelt and Liebetrau (2020)
Maintenance	1.0–2.0%	0.1–0.5%	Estimated based on expert estimates
Flaring	5%	2%	Estimated based on expert estimates
DIGESTATE			
Digestate separation	0.1%	0.001%	Liebetrau et al. (2013), (2010)
Digestate storage	8%	2%	Calculated estimate based on mass balance calculations
BIOGAS USE			
Upgrading to transport fuel (A)	1.7%–1.97% (water scrubber)	0.04–0.07% (amine scrubber)	Avfall Sverige (2016)
CHP (B)	1.74–3.72%	0.17–0.4%	Liebetrau et al. (2010), (2013), Fredenslund et al., (2023)

2.2.3. *Life cycle inventory*

The primary data for Life Cycle Inventory (LCI) including assumptions of CH_4 leaks and emissions in conventional and advanced practices were collected mainly from scientific literature. Based on the deviation in emission data found in literature, the data was divided between impacts of advanced and conventional practices. Outliers, such as very high measurement results, were excluded. Data that were not available from the literature were supplemented by estimates. The parameters used for CH_4 leaks and emissions in the calculations for the different life cycle stages are presented in Table 3 and described in Supplementary Material B. The assumptions and parameters used for transportation, substitutions and reference are described in detail in the Supplementary Material B.

In the LCI, the results of mass, nutrient and energy balance calculations (chapter 3.1 and Supplementary Material A) were utilized. Emission factors from ecoinvent database (v3) was utilized for individual

Table 2
Characteristics of the feed, biochemical methane potential (BMP) and the process water used for feed dilution in the case study plant (capacity 200,000 t/y). Details for the calculation of separated slurry characteristics and process water are presented in the Supplementary Material A.

	TS (%)	VS (%)	Ntot (g/kg)	NH_4–N (g/kg)	Ptot (g/kg)	BMP (m^3/t_{VS})	Ref.
Pig slurry	8.2	6.9	4.6	2.9	1.0	320	Characteristics: Luostarinen et al., (2017) BMP: Luostarinen et al., (2019a)
Poultry manure	54.7	44.9	23.8	7.8	9.6	201	Characteristics: Luostarinen et al., (2017) BMP: Luostarinen et al., (2019a)
Separated solid fraction of pig slurry	22.2	18.5	3.7	1.2	1.4	305	Characteristics calculated from pig slurry with screw-press BMP: Pyykkönen (2019), Luostarinen (2013)
Separated solid fraction of cattle slurry	22.4	11.5	4.5	1.4	1.0	190	Characteristics calculated from cattle slurry with screw-press BMP: Pyykkönen (2019), Luostarinen (2013)
Grass from fallows	40.0	27.0	5.2	0.4	0.8	280	Mavi Maaseutuvirasto (2008) BMP: Niemeläinen et al., (2014)
Side stream from food industry	20.0	17.0	6.0	0.3	1.0	350	Luostarinen et al. (2019a)
Process water, advanced practices	0.07	0.07	0.03	0.03	0.00	0	Calculated
Process water, conventional practices	4.38	3.09	7.32	4.39	0.17	0	Calculated

inputs. In addition, when external energy was needed to supplement the energy need in the case study plant, average emission data on Finnish electricity and heat was used (Soimakallio, 2020).

2.3. Emissions and manure credits according to RED II regulation

The emission reduction calculation according to the Renewable Energy Directive (EU, 2018) was done for transport fuel production (scenario A). The calculation principles followed the rules of RED II directive and Finnish guidelines for sustainability criteria (Energy Authority, 2022). System boundaries differed slightly compared to the LCA done as digestate separation and field spread were excluded for not being included in the REDII calculation guidelines.

Emissions from the different biogas production phases (cultivation, processing (including digestate storage), gas upgrading, transportation, and compression at filling station) obtained from the LCA calculation were divided by the amount of biomethane produced for sale. As the grass from fallows was considered as a side stream, the cultivation phase included only its transportation to the plant (and digestate transportation back to the fields). For other feeds, the emissions of transportation were included in transportation phase.

In addition to emissions, emission credits were included for manure due to improved manure management according to the RED II guidance. This credit is based on the idea that biogas production decreases the amount of volatile solids in storage and therefore mitigates emissions. As the default value for manure credits is given only to slurry (wet manure in the regulation), the credits in this case study were calculated using the manure's CH_4 production potential and TS content (Table 2, formulas 1 and 2).

$$e_{sca} = \frac{L_h}{P_n * \frac{BMP_{achieved}}{100}} \tag{1}$$

where e_{sca} [g CO_2-eq./MJ] is manure credit, L_h is a coefficient for good manure management practices defined in the Renewable Energy Directive (−54.06 kg CO_2.eq./t_{ww}), P_n is energy production [MJ/kg_{ww}] and $BMP_{achieved}$ is the realized share of the CH_4 production potential (90% with advanced and 78% with conventional practices).

$$P_n = BMP * VS * LHV_{biogas} \tag{2}$$

where BMP is CH_4 production potential of substrate n [m^3_{biogas}/kg_{VS}], VS is the amount of organic matter [kg_{VS}/kg_{WW}] and LHV_{biogas} is the lower heating value of biogas (18.30 MJ/m^3_{biogas}; Agostini et al., 2017).

The distribution of emissions and credits for different feed materials were calculated according to their energy content, in accordance with the Finnish Energy Authority's sustainability criteria guidelines (Energy Authority, 2022). The weight factor of the feed (W_n) for solid manures and grass was calculated by assuming that the annual average moisture content (AM_n) of the feed n (calculated from dry matter, Table 2) is the same as the standard moisture content (SM_n) of the feed n, because the standard moisture content is given in the guidelines of the Directive only for wet manure, maize and biowaste.

The results were finally compared to the fossil reference value (94 g CO_2-eq./MJ) to find out the emission reduction potential.

3. Results

3.1. The effect of conventional and advanced practices on the digestate and energy output

The advanced practices (long RT and other emission-reducing practices) of the case study plant gave significantly higher energy production (approx. 80 GWh/year) than the conventional practices (65–68 GWh/year) despite the energy consumption of digestate processing (Table 4). Due to the latter, the plant with advanced practices bought more electricity and heat for its own use, but the plant's total energy net balance was positive. The energy used in the digestate processing consisted of thermal energy for drying and electricity for evaporation and pelletizing.

Table 4
Energy balance of the case study biogas plant with conventional and advanced practices.[a]

ENERGY BALANCE (MWh/year)	Conventional	Advanced
Consumption		
Reactor (heat)	1,853	1,609
Reactor (electricity)	1,996–2,075	2,391–2,420
Hygienization (electricity)	7,471	6,389
Hygienization (heat)	13,933	13,933
Separation (electricity)	1,092	934
Drying (electricity)	–	1,357
Drying (heat)	–	28,950
Gas scrubber for drying	–	296
Pelletizing (electricity)	–	2
Evaporation	–	6,460
Gas upgrading to transport fuel (A) (electricity)	3,003–3,121	3,597–3,641
Production (out of the system)		
Transport fuel (A)	65,220–67,975	79,636–80,629
CHP (B) (electricity)	14,058–14,949	11,987–12,592
CHP (B) (heat)	6,313–7,596	14,088–14,563

[a] Note that when producing transport fuel (scenario A), the plant needed to buy external heat and electricity, while with CHP (scenario B), the plant produced all energy for its own use.

The plant with advanced practices also produced more concentrated fertilizer products. Due to their lower volume (80,000 tonnes vs. 180,000 tonnes in the conventional practices) and higher nutrient concentrations they were more efficiently transported and utilized as fertilizers. While most of the removed water was recirculated, some water fractions were also directed outside the plant (as evaporated water from digestate drying and processed water from evaporation) (Fig. 2).

3.2. The effect of practices on life-cycle climate impacts

The total net GHG emissions of the reference system varied between 36,660 … 40,557 tonnes CO_2-eq./year, when the emission credits of substitutions were considered. Without them, the corresponding GHG emissions varied between 39,233 … 43,131 tonnes CO_2-eq./year.

When the biogas was fully upgraded into transport fuel and the energy used for digestate processing is purchased from outside the plant (scenario A) and emission credits from substitutions were considered, the total net GHG emissions of the case study plant varied between −2,951 … 1,165 tonnes CO_2-eq/year for advanced practices and 9,060 … 17,628 tonnes CO_2-eq./year for conventional practices. Without emission credits, the corresponding GHG emissions were higher, between 22,747 … 26,598 tonnes CO_2-eq./year for advanced practices and 30,671 … 38,497 tonnes CO_2-eq./year for conventional practices. The highest impact on emissions occurred from process operation, digestate processing and the storage and field use of the fertilizer products (Table 5).

Advanced practices resulted in lower emissions from the biogas production chain than those of conventional practices. Compared to the reference system, advanced practices reduced emissions by approximately 97–107% in total when including substitutions (Table 5, Fig. 3). Without substitutions, advanced practices reduced emissions by approximately 32–47%. With the same comparison, conventional practices reduced emissions by 57–75% in total when considering substitutions. Without substitutions, the reduction was approximately 11–22%.

When the biogas was used for in CHP and the heat produced for digestate processing (B), the total net GHG emissions varied greatly between 9,691 … 35,469 tonnes CO_2-eq./year), when considering substitutions. Without substitutions, the corresponding GHG emissions were higher and varied between 15,640 … 41,960 tonnes CO_2-eq./year.

Also with the CHP, advanced practices produced less emissions from

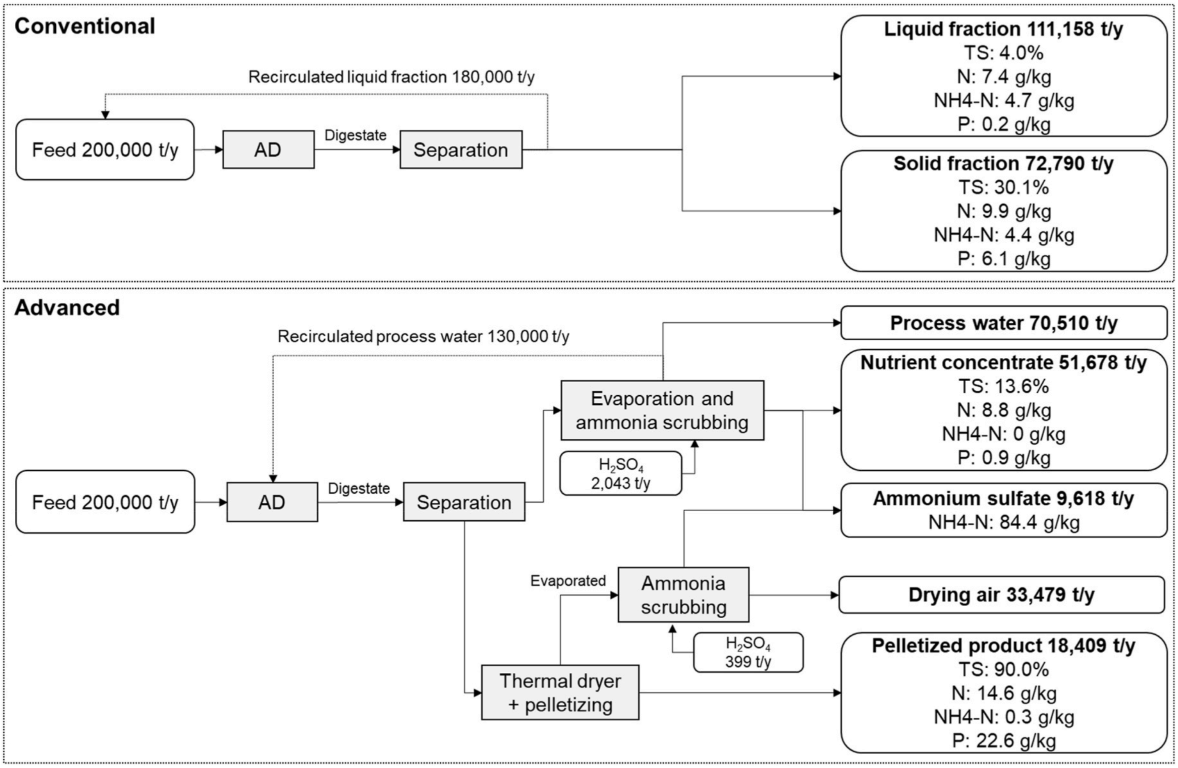

Fig. 2. Flow scheme and mass balance with end-products from digestate processing of the case study biogas plant with conventional and advanced practices.

Table 5
GHG emissions (tonnes CO_2-eq./year) of the reference system and the impact of conventional and advanced practices on life cycle emissions of the two energy production alternatives in comparison to the reference system. Negative values represent the decreased emissions and positive values represent increased emissions. The difference in the emissions between the energy alternatives is presented in tonnes CO_2-eq./year and in percentages.

	Reference (total emission in tonnes CO_2- eq./year)	A: Transport fuel	B: CHP		
	Minimum-maximum	Conventional	Advanced	Conventional	Advanced
Feed pre-storage	–	2,450 (100%)	1,225 (100%)	2,450 (100%)	1,225 (100%)
Biogas process	–	6,823–11,593 (100%)	3,660–5,436 (100%)	3,013–7,794 (100%)	250-2,030 (100%)
Gas purification and pressurization/CHP-unit	–	2,605–2831 (100%)	617-653 (100%)	8,292–10,359 (100%)	377-711 (100%)
Transport fuel use	–	23-24 (100%)	29 (100%)	–	–
Digestate separation	–	613 (100%)	442 (100%)	613 (100%)	442 (100%)
Digestate processing	–	–	5,782 (100%)	–	2,357 (100%)
Digestate storage	15,097	−4,695 (−31%)	−12,085 (−80%)	−4,695 (−31%)	−12,085 (−80%)
Composting	17,097–18,817	−18,817 … −17,097 (−100%)	−18,817 … −17,097 (−100%)	−18,817 … −17,097 (−100%)	−18,817 … −17,097 (−100%)
Transportations	47-2,225	418-1,073 (48–881%)	−1,399–2,817 (-63-5,933%)	418-831 (37–881%)	776-420 (19–1,635%)
Field use (soil emissions)	6,991	296 (4%)	161 (2%)	296 (4%)	161 (2%)
Substitutions (fertilizer)	−2,573	−841 (33%)	−1,542 (60%)	−841 (33%)	−1,542 (60%)
Substitutions (energy)	–	−18,197 … -17,453 (100%)	−21,582 … -21,318 (100%)	−3,404 - … - 3,076 (100%)	−1,927 … - 1,834 (100%)
Total (excl. substitutions)	39,233–43,131	−8,563 … - 4,634 (−11% … -22%)	−20,384 … - 12,636 (−32% … -47%)	−6,710 … -1,170 (−3% … -17%)	−23,593 … -23,555 (−55% … -60%)
Total (incl. substitutions)	36,660–40,557	−27,600 … - 22,929 (−57% … -75%)	−43,508 … −35,496 (−97% … -107%)	−10,955 … -5,088 (−13% … -30%)	−27,024 … - 26,969 (−67% … -74%)

the biogas production chain than conventional practices, but they were higher than with transport fuel (A). Compared to the reference system, advanced practices reduced emissions by approximately 67–74% in total when considering substitutions (Table 5, Fig. 4). Without them, advanced practices reduced emissions by approximately 55–60%. With the same comparison, conventional practices reduced emissions by 13–30% in total when considering substitutions and by 3–17% without them.

3.3. Emissions and manure credits according to RED II regulation

When the RED II emission calculation was carried out using the emission data from the LCA, the transport fuel production had significant emission reductions compared to the fossil reference value with advanced practices (with both minimum and maximum values, 127 and 117 %, respectively, Fig. 5). However, with conventional practices, the emission reduction target required (65% reduction compared to the fossil reference value) was only met with minimum emission values

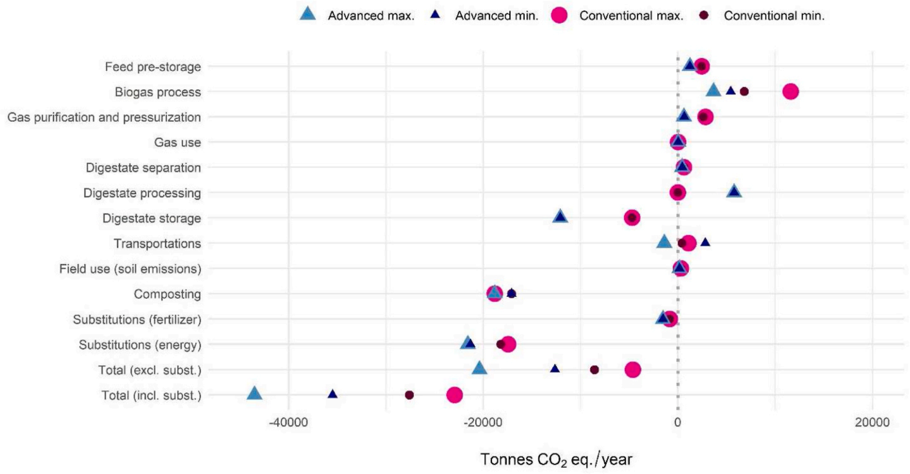

Fig. 3. Impact of conventional and advanced practices on life cycle GHG emissions (tonnes CO_2-eq./year) in comparison to the reference system when biogas is utilized as transport fuel (A).

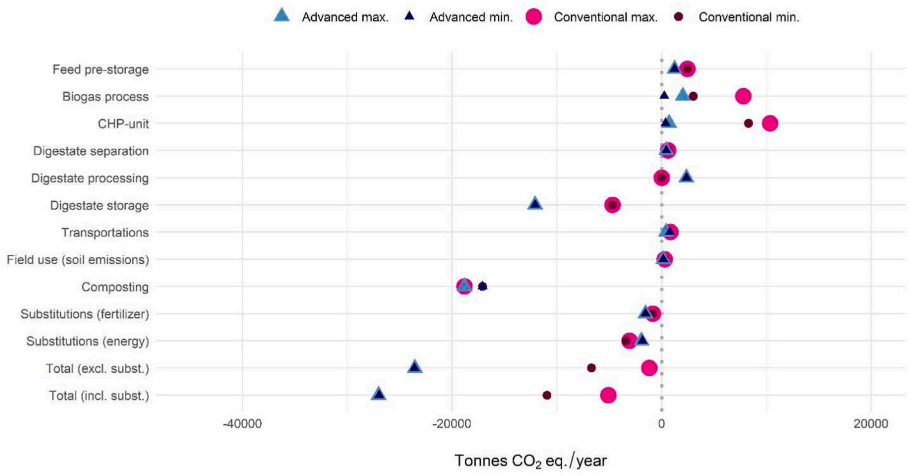

Fig. 4. Impact of conventional and advanced practices on life cycle GHG emissions (tonnes CO_2-eq./year) in relation to the reference system when biogas is utilized in CHP production (B).

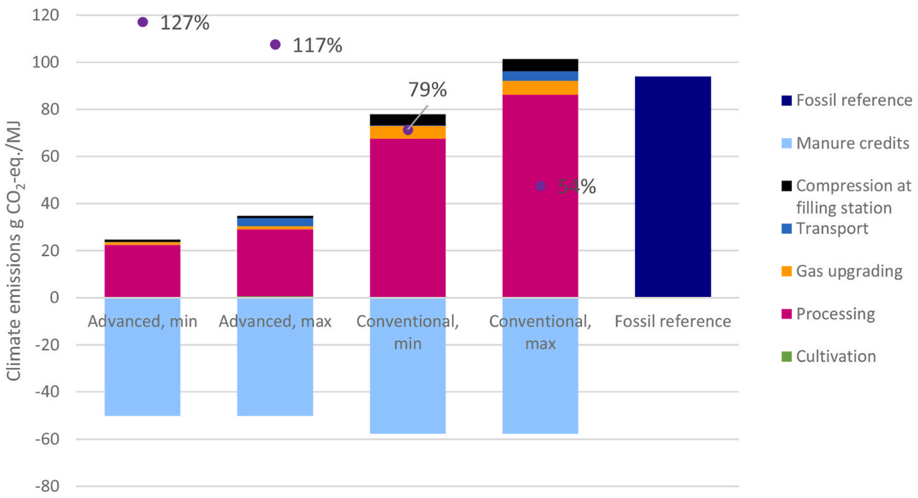

Fig. 5. Range of emissions, manure credits and emission reductions for transport fuel production with advanced and conventional practices, compared to fossil reference.

(79% reduction). Although with the conventional practices with maximum emission, the emissions were reduced (54% reduction), the results highlight the need of careful emission management.

Manure credits play an important role in emission reduction calculations. The manure credits were calculated for each manure feed separately (Table 6), as the default value from Directive was given only to wet (cattle) manure (−119.9 g CO_2-eq./MJ with closed digestate storage and off-gas combustion vs. −124.4 g CO_2-eq./MJ with open digestate storage and no off-gas combustion). Also, in this study, the manure was mainly pig slurry, rest being poultry manure and separated solid fractions of pig and cattle slurry, all having different quality (CH_4 potential and TS) than cattle slurry.

4. Discussion

4.1. The life cycle climate impact of biogas production

The results of the LCA performed show the significance of the management practices of the biogas production chain on GHG emissions and the subsequent climate benefit, compared to the reference and between the practices chosen. Climate benefits are the greatest when using advanced practices, replacing fossil energy sources and efficiently recycling nutrients to replace fertilizers. According to the LCA, practices that do not pay attention to minimizing emissions can hamper the emission reduction compared to the reference minimal and lose the desired climate benefit.

The practices that do not actively aim at reducing emissions in the biogas production chain also affect potential substitutions by losing part of the energy and nutrients. However, it should be noted that the substitution benefit is always formed in relation to the reference and the substitution is modeled with certain assumptions. If the substitutions assumed do not materialize as they are assumed or the end-products replace products with lower emissions, the benefit achieved by the biogas process will decrease compared to the reference. Thus, if the emission factor for electricity and heat decreases in the future, the climate benefit of the CHP unit plant will decrease compared to the reference system. Instead, when biogas replaces fossil fuels in transportation, the climate benefit increases compared to the reference, if the emission factor for electricity decreases.

This LCA study did not include the analysis of temporal impacts on soil carbon decomposition in conjunction to fertilizer use due to incomplete methods and knowledge available. In the biogas process, the amount and composition of the carbon originally contained in the feed materials change, reducing the carbon input to the soil compared to reference. However, the overall effects of soil processes on the carbon cycle are still incompletely known (Liang et al., 2017; Chenu et al., 2019). In the future, it is important that these points are also considered when evaluating the climate impacts of biogas production.

GHG emissions from the field use of digestate may be underestimated in the LCA calculation, as northern climatic conditions (winter frost, high precipitation) have been shown to increase soil N_2O emissions compared to the global IPCC (2019) default of 1% of total applied fertilizer N (e.g. Regina et al., 2013; Häfner et al., 2021). The effect of field application of untreated slurry manure and digested slurry manure on soil emissions is not significantly different, as both can enhance denitrification by increasing soil moisture and providing an additional carbon source (Wulf et al., 2002; Rodhe et al., 2015; Severin et al., 2016). However, it should be noted that some of the characteristics of the digestates, such as higher pH, lower viscosity and higher soluble N content, may increase the risk of emissions from the soil compared to untreated slurry manure (Clemens et al., 2006).

Table 6

The manure credit of each manure feed and distribution of emissions according to their energy content (g CO_2-eq./MJ) calculated according to the RED II regulation.

	Advanced practice		Conventional practice	
	Manure credit	Manure credit distributed by energy content	Manure credit	Manure credit distributed by energy content
Pig slurry	−149.6	−27.6	−172.6	−31.9
Separated solid fraction of cattle slurry	−150.8	−3.7	−174.0	−4.3
Separated solid fraction of pig slurry	−58.1	−7.5	−67.1	−8.6
Poultry manure	−36.5	−11.2	−42.1	−12.9

The current results indicate the importance of including management practices in LCA studies of biogas production. The chosen emission factors play a critical role in the climate impact modeling with significant influence on the results. Here, a range between minimum and maximum emissions was chosen to highlight the variation dependent of multiple factors. Evidently, more research on the effects of different practices is needed to support policies and actions to lower emissions. According to Fredenslund et al. (2023), emission mitigating actions at biogas plants resulted in 46% reduction of CH_4 emissions. Also, Wechelberger et al. (2023) present emission factors for different biogas technologies and biogas upgrading. They recognize, however, the uncertainty of the determined emission factors related to changing management practices and climate conditions. Moreover, the emission factors they determined were based on relatively short measurements periods and the authors call for more measurements to strengthen the reliability of the results.

The emissions from biogas plants have lately been measured to an increasing extent. The studies indicate that CH_4 emissions may be much higher than previously estimated (Scheutz and Fredenslund, 2019; Bakkaloglu et al., 2021; Reinelt et al., 2022; Fredenslund et al., 2023). According to literature, the measured total CH_4 emissions in biogas plant area vary between 0.02 and 40.6% of the CH_4 produced (Flesch et al., 2011; Holmgren, 2012; Liebetrau et al., 2013; Hrad et al., 2015; Groth et al., 2015; Avfall Sverige, 2016; Jensen et al., 2017; Reinelt et al., 2017, 2022; Fredenslund et al., 2018, 2023; Scheutz and Fredenslund, 2019; Bakkaloglu et al., 2021; Wechselberger et al., 2023). The largest sources of CH_4 emissions have been reported to be uncovered digestate storages and the gas losses in the CHP unit and pressure release valves (Liebetrau et al., 2013; Reinelt et al., 2017, 2022; Fredenslund et al., 2018, 2023; Vergote et al., 2020). The results of these studies arouse growing concern about the climate sustainability of biogas production and indicate that special attention should be paid to the management practices of biogas plants and the promotion of emission-reducing practices.

Considerable differences in the measurement results have been found between the sum of the individual CH_4 emission sources of the different production phases and the emissions of the entire plant area (Jensen et al., 2017; Fredenslund et al., 2018). Emissions measured from the entire plant area have been significantly higher than the sum of the emissions measured individually at different emission sources (Jensen et al., 2017). This has been speculated to be due to unspecified leaks and unidentified emission sources. In addition, Fredenslund et al. (2023) observed that smaller plants emit a larger fraction of the gas produced compared to the larger ones. The lower CH_4 emissions of larger plants have been estimated to be due to more precise management practices, such as dedicated workforce and maintenance (Scheutz and Fredenslund, 2019). On the other hand, the resulting CH_4 emissions and their magnitude are not necessarily proportional to the amount of biogas produced or the plant size, especially if the emissions are caused by plant structures, such as ruptured roof or cracks in the reactor (Flesch et al., 2011). Overall, in the scientific literature, the emission measurements typically focus on a specific source in the biogas plant, which leads to difficulties in getting an overall picture of the total amount of the emissions.

In the coming years, biogas production is expected to reduce GHG emissions from energy use, ensure a domestic and reliable source of energy and increase circularity in nutrient use. However, excessively striving for cost efficiency can result in investments and/or management practices that do not pay attention to emission reduction, reduce the amount of biogas produced, and produce fertilizer products that are difficult to utilize in terms of quality and/or quantity. To realize the desired benefits of biogas production, the entire biogas production chain, from raw materials to the use of end products, must optimize emission reduction as an integral part of the production life cycle.

4.2. *Emissions and manure credits according to RED II regulation*

According to the results, the achievement of emission reduction target set in RED II regulation is sensitive for the assumptions used. In conventional practices, this may mean that these emission reduction demands are not met for transport fuel (biomethane) production.

In this study, the main difference between advanced and conventional practices was the RT of the reactor. In advanced practices, the long RT was assumed to be result in effective degradation and thus little CH_4 production in digestate storage. In this case, the storage did not have to include gas collection to achieve the needed emission reductions. With conventional practices, short RT and open digestate storage increased the emissions to three times higher compared to advanced practices (Fig. 5). Considering the current results, a long RT is an effective emission-reducing practice for biogas plants and a solid alternative to the practice included in the Directive (no requirement for RT, but always a gas tight cover for digestate storage with gas collection).

The requirements for biogas plant operators varies in different countries. As an example, Germany requires a minimum RT of 150 days from agricultural plants and new digestate storages have to be built with gas tight cover. Also, there are maximum emission values given to both CHP plants and gas upgrading off-gas (EEG, 2017). In addition, in Sweden a voluntary emission monitoring has been running since 2007 (Avfall Sverige, 2016). The increasing number of initiatives in different countries also indicate that more attention is being paid to biogas plant emissions.

5. Conclusions

The results of this study stress the importance of including the impacts of management practices in the overall sustainability evaluation of biogas production. Also, awareness should be raised among the actors regulating, supporting, and implementing biogas production so that emission-reducing practices are demanded and executed already from the first planning steps of new biogas plants.

There is a clear risk of losing the desired climate benefits if emission-reduction techniques and practices are overlooked. Special attention should be paid to the RT in the reactor (ultimately the ratio between reactor size and feed quantity), proper maintenance of all structures and equipment, digestate storage methods and advanced methods for utilizing biogas. Also, digestate processing affects the efficiency of its end-use in fertilization and thus its sustainability.

At the time of writing, no comprehensive international calculation guidelines have been issued on emission formation and the individual factors affecting them in biogas production. To promote the use of advanced practices, an emission calculation protocol should be developed, and emission measurement practices standardized, and regular measurements and emission monitoring required. Also, knowledge and support for plant operators and policy makers on climate sustainable biogas production should be strengthened.

Since biogas production is expected to increase in the coming years it is important to ensure that funding is directed to biogas plants executing emission-reducing practices.

CRediT authorship contribution statement

S. Lehtoranta: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **E. Tampio:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation. **S. Rasi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **J. Laakso:** Writing – original draft, Investigation, Data curation. **K. Vikki:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **S. Luostarinen:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121884.

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