The biogas yield, climate impact, energy balance, nutrient recovery, and resource cost of biogas production from household food waste—A comparison of multiple cases from Sweden

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ABSTRACT

The depletion of natural resources, climate change and energy security are some of today's societal challenges. One way to address these is through anaerobic digestion of food waste, which provides multiple benefits such as waste treatment, nutrient recycling and renewable energy, such as biogas. Biogas solutions tend to vary, so to gain a holistic understanding of their pros and cons there is a need to use a common analytical approach and simultaneously consider several issues. This study has analysed the climate impact, primary energy use, nutrient recycling potential, and resource cost of producing biogas from food waste in three Swedish biogas plants with different setups. In addition, several scenarios representing changes in the existing systems were analysed. The study aims to provide insights into factors that affect the performance of biogas production from food waste. The method applied is based on life cycle analysis and key performance indicators (KPIs), which were used to compare and analyse the performance of the biogas systems. The analysis synthesises a large amount of information about the performance of these systems and their sub-systems. Despite significant differences between the studied cases, all led to the production of biomethane with a low climate impact (62–80% less climate impact in grCO2eq/MJ compared with the fossil reference), low non-renewable primary energy use (16–31% MJ per MJ delivered biomethane), and significant nutrient recovery (e.g., 52–86% of phosphorus content of food waste was delivered as biofertilizer). In addition to the collection system, the efficiency of pretreatment, the choice of energy system (e.g., for heating the biogas plant), and a suitable digestate treatment were found to be among the main factors that influence the overall performance of these systems.

1. Introduction

Estimations show that around 50% of the world's overall municipal waste is considered food waste (FW) (Xue et al., 2017). There are different solutions to handling FW, including landfilling, incineration, and biological treatment such as composting or anaerobic digestion (AD). AD of FW has been shown to have multiple benefits in comparison with other FW treatment methods (Evangelisti et al., 2014; Gao et al., 2017). For example, it has been shown that AD of FW can be an efficient technology for climate mitigation in future circular and low-carbon economies (Styles et al., 2022; Xu et al., 2015). This is mainly because through AD, both the energy and nutrient content of the organic material is recovered; in contrast to most other treatment methods that can recover only one of them—e.g., composting can recover nutrients but not energy, and incineration can recover energy but the ashes lack a carbon source and the nitrogen and microorganisms that are present in the digestate of the AD process (Garcia Sánchez et al., 2015). The biogas produced from AD can be upgraded and used as transportation fuel or other industrial applications (Lindfors et al., 2022). In a broader sense, Obaideen et al. (2022) have argued that biogas contributes to 12 of the

17 United Nations sustainability goals (SDGs).

In the last two decades, a series of regulations in Sweden have progressively prompted the development of the recycling of organic waste. Most notable is the Law on Landfill Tax, introduced in 2000, which requires taxes to be paid—in addition to gate fees—for each tonne of landfilled waste. Later, this law was fortified by banning the landfilling of combustible wastes from 2002 and organic wastes from 2005. Furthermore, in 2006, an incineration tax was introduced to favour other resource recovery methods (Miliūtė and Plepys, 2009). Swedish national goals mandate increased nutrient recycling and energy recovery from FW. The 2020 goal was to biologically treat at least 50% of the FW from households, kitchens, shops and restaurants to recover the plant nutrients, and ensure that at least 40% of FW is treated with both nutrient and energy recovery (Avfall Sverige, 2019; Swedish EPA, 2021). The renewed and more ambitious goal is to ensure that by 2023 a minimum of 75% of FW should be sorted and biologically treated so that both nutrients and biogas are utilised (Swedish EPA, 2021). Consequently, source separation of FW is increasing in Sweden. In 2018, 82% of Swedish municipalities collected source-separated FW in different amounts (Swedish EPA, 2020), and biogas production is the main biological treatment method of FW in Sweden. In 2018, 90% of all biologically treated FW was used as feedstock in co-digestion biogas plants (Swedish EPA, 2020). In 2019, about 2 TWh of biogas were produced in Sweden, and in terms of the biogas produced, FW was the third largest feedstock contributing to 11% of total production—after sludge from wastewater treatment plants at 35% and manure at 20% (Westlund et al., 2019). Notwithstanding these figures, there still exist significant potential for expanding biogas and biofertilizer production from FW and improving the existing biogas solutions. According to a recent estimate, the Swedish realisable potential for producing biogas from AD by 2030 is 7 TWh, after manure with a 1.5–2.6 TWh potential; FW is the largest contributor by 1.2 TWh (Westlund et al., 2019).

Table 1
Selected publications that include life cycle assessment of biogas production from food waste.

(year)	Type of study	Country	Studied case	Alternatives	Impacts or indicators
Styles et al. (2022)	LCA (future oriented)	UK	Generic data	AD of different feedstock (FW, industrial waste, crops, manure)	GWP, EP, AP, etc.
Xiao et al. (2022)	LCA, LCC	China	Generic data	Wet vs dry AD (with alternatives such as landfilling, incineration, or composting of digestate)	GWP, EP, AP, etc. Cost
Mayer et al. (2021)	LCA	Germany	Generic data	Different FW treatment (AD, incineration, HTC)	GWP, EP, AP, etc. Cost
Slorach et al. (2020)	LCA, LCC (future oriented)	UK	Generic data	Different FW management options (business as usual, incineration, AD, composting, landfill)	GWP, EP, AP, etc. Cost
Feiz et al. (2020)	LCA (KPIs)	Sweden	Generic data	Different setups for AD of FW	GWP Energy balance Mass balance (effective yield, nutrients flow) Cost
Ascher et al. (2020)	LCA, LCC	UK	Generic data	Analysing a regional food waste treatment scheme	GWP, AP, and PMF Cost
Yu et al. (2020)	LCA, LCC	China	Two full scale plants	Two different AD process technologies (single vs. double phase)	GWP, AP Energy balance Mass balance (carbon flow) Cost
Bartocci et al. (2020)	Potential study, LCA, LCC	Italy	Food waste collection and treatment in a region	Two main food waste collection scenarios	Food waste potential; Optimized collection route GWP Cost
Gao et al. (2017)	LCA	China	Shandong University	Different FW treatment (landfill, incineration, composting, AD, heat-moisture reaction)	GWP, EP, AP, etc.
Edwards et al. (2017)	LCI	Australia	Generic data	Different FW treatment options (Landfilling, AD, composting)	Air/water/soil emissions (inventory) Energy balance Mass balance (water flow)
Oldfield et al. (2016)	LCA	Ireland	Generic data	Different FW management options (business-as-usual, minimization, composting, AD and incineration)	GWP, EP, AP
Eriksson et al. (2016)	LCA, LCC	Sweden	Two biogas plants (an existing, and a planned)	Different setups for AD of FW and sewage sludge	GWP Cost
Eriksson et al. (2015)	LCA	Sweden	A biogas plant	Different FW treatment (landfill, incineration, composting, anaerobic digestion, animal feed and donation)	GWP
Xu et al. (2015)	LCA	China	Two biogas plants	Different FW treatment (landfill, AD with sewage sludge, and AD)	GWP, EP, AP, etc. Energy balance
Jin et al. (2015)	LCA	China	A biogas plant	Factors that can improve the performance	GWP, EP, AP, etc. Energy balance
Evangelisti et al. (2014)	LCA	UK	Generic data	Different FW treatment (AD, incineration, and landfill)	GWP, EP, AP, etc.
Poeschl et al. (2012a, 2012b)	LCA	Germany	Generic data	AD of different feedstocks (FW, manure, straw, corn silage, etc.), and different AD setups and utilisation pathways (small/large scale, CHP, upgrading, fuel cell, etc.)	GWP, EP, AP, etc.
Bernstad and la Cour Jansen (2011)	LCA	Sweden	Residential area (Augustenborg)	Different FW treatment (AD, incineration, and composting)	GWP, EP, AP, etc. Energy balance
Levis and Barlaz (2011)	LCA	USA	Generic data	Different FW treatment (AD, Landfill, composting)	GWP, EP, AP Energy balance

In the process of reaching this potential, it is important to be able to evaluate different configurations and solutions to achieve resource efficient biogas systems with good sustainability performance. However, based on a review of 58 articles, Mancini and Raggi (2021) concluded that there is no shared framework for sustainability assessment and circularity metrics for AD processes. While there are life cycle assessments (LCA) that focus on environmental or economic performance of biogas production from FW, they typically have different goals, use different terminologies, models and assumptions and rarely have a holistic view on issues such as climate impact, energy balance, nutrient recycling, and resource costs, as can be seen in Table 1. For example, energy analysis is not included in the studies by Xiao et al. (2022), Bartocci et al. (2020) and Eriksson et al. (2016), while nutrients recovery potential is missing in the study by Xu et a. (2015). Furthermore, Xu et al. (2015) included several environmental impact categories, as well as an energy analysis, but did not include cost analysis. Furthermore, many studies rely on generic data and do not provide insight based on real production facilities (Table 1). For example, Xiao et al. (2022) investigates biogas production from food waste using wet or dry system, but relies mainly on generic data. Finally, there are studies such as the one performed by Al-Wahaibi et al. (2020) that do not adopt a life cycle perspective and focus on techno economic evaluation of biogas production from different types of food waste.

However, to gain a holistic understanding of the pros and cons associated with different biogas systems, there is a need for a more comprehensive analysis and the inclusion of e.g., resource costs, climate impact and nutrient recycling potential. Paying attention to several issues (e.g., energy, nutrients, and costs) at the same time and using the same analytical approach will provide valuable insights into biogas systems and help avoid suboptimal solutions. Comparing different technological choices and systems solutions would provide a basis for future decisions when designing the best practice for biogas solutions in various settings. Even though there are several LCA studies analysing the treatment of FW by AD, Feiz et al. (2020) point out the difficulties in directly comparing the results due to different system boundaries, functional units, assumptions, and LCA methods. Therefore, more studies are needed using empirical data from real production systems with a consistent and comparable method (Feiz et al., 2020).

In this study, the performance of three large-scale Swedish biogas production systems that receive FW as their main feedstock are studied from a life cycle perspective. The main novelty of this paper is the combination of the following aspects: (1) empirical basis (based on commercially active large-scale biogas plants in the Nordic region), (2) life cycle analysis based on mass and energy balance across the system, (3) and providing a comparable and integrative systems analysis that includes key aspects of AD of FW including conversion efficiency, resource recovery potential, economic performance, and environmental impacts. In addition to this methodological novelty, the study has practical implications for the development of sustainable biogas systems based on FW.

2. Methods

The cases are based on actual large-scale co-digestion biogas plants, all of which receive food waste as their main feedstock. For the sake of comparability, several unifying assumptions were made, e.g., it was assumed that the composition of FW is similar in all cases, that all plants are using only FW as feedstock, and that the collection system in all cases relies on a common fuel mix. Since all cases are in Sweden, the unifying assumption regarding the composition of food waste is reasonable. However, this matter has not been independently investigated. With regard to source separation and collection, the differences between the studied systems in terms of the kind of system used (paper bags in separate bins, or plastic tinted bags in mixed bins which are optically/mechanically sorted out later) were considered. However, the specific characteristics of the collection systems in terms of the distances covered or the fuels used (average and common values were assumed) were not investigated. In reality, the collection distances (the ratio between urban/rural households) were different for each case.

The encompassing method of analysis is life cycle assessment (LCA) according to the general guidelines of the International Organization for Standardization (ISO, 2006) and the European Union (EC-JRC, 2010). However, a tailored approach to LCA was used to better accommodate the objectives of this paper. While this paper has a life-cycle perspective, the methodological approach, the selected Key Performance Indicators (KPI), and the presentation of the results across different sub-systems, are not exactly similar to most (mainly orthodox) LCA studies. For example, LCA results are commonly expressed in relation to a single functional unit, while this paper uses seven KPIs, some of which are expressed in terms of different units (e.g., KPI_3 as defined in Table 2). Further, the approach is process-based, which means the studied systems are analysed on the level of main processes and then aggregated under different system (and sub-system) levels (Tables 2 and 3). This approach is explained in more details in Feiz et al. (2020).

The selected functional unit is the full treatment of 1 tonne of FW using AD (from source-separation and collection to biogas and digestate processing and utilisation). The system boundary includes the main value chain of biogas production including food waste from the source-separation of food waste in households, collection and pre-treatment, management of rejects, AD, and the processing of biogas and digestate, and their distribution and use. For each process, the necessary life cycle impacts associated with the use of resources (such as electricity, fuel, chemicals) are included (Fig. 1). Impacts related to the construction of the plants and vehicles, as well as the infrastructure used, are not included.

Following the ISO recommendation, the environmental impact of the by-products is shown via system expansion: the produced biogas and digestate (or biofertilizer produced from it) substitute fossil diesel and mineral fertilizers under the assumption of an expanded system. An attributional approach is adopted and focuses on the studied biogas production systems and their relevant physical flows (in/out).

Data collection from the studied cases were iterative, and input data to the model was collected through dialogue with representatives from the biogas plants (in the form of questionnaires, interviews, and follow up email correspondence), environmental reports, measurement data provided by the biogas plants, and white and grey literature. The questionnaire was designed to cover the main aspects of the biogas production, e.g., a general process diagram of the biogas system, amounts of substrates, energy use, transportation types and distances,

Table 2

The breakdown of the biogas production system into main levels and sub-levels based on the taxonomy of biogas production systems developed in Feiz et al. (2020).

Code	System level	Description
L_1	Biogas plant	Core activities in the biogas plant
L_{1a}	Pretreatment, anaerobic digestion (AD), biogas processing[a]	
L_{1b}	Digestate processing	
L_2	Extended biogas plant	L_1 + main transportation activities
L_{2a}	Transportation of collected food waste	
L_{2b}	Transportation of digestate/biofertilizers	
L_{2c}	Transportation of delivered biogas	
L_3	Biogas production system	L_2 + systems of provision and utilisation
L_{3a}	Provision of food waste (collection)	
L_{3b}	Reject management	
L_{3c}	Digestate/biofertilizers utilisation	
L_{3d}	Biogas utilisation	
L_4	Expanded biogas production system	L_3 + system expansion
L_{4a}	Substitution of mineral biofertilizers	
L_{4b}	Substitution of fossil fuels	

[a] Processes such as upgrading or liquification.

Table 3

Description of the key performance indicators (KPIs) expressing the performance of biogas production from food waste (adapted from Feiz et al., 2020).

No.	Key Performance Indicator (KPI)	Unit	System level and sub-levels
KPI_1	Delivered biomethane[a]	$Nm^3\ CH_{4(delivered)}\ /\ t_{VS(FW\ at\ source)}$[b]	Biogas production system excluding biogas use ($L_3 - L_{3d} = L_{3a} + L_{3b} + L_{3c}$)
KPI_2	Climate impact[c]	$kg\ CO_2\text{-eq}\ /\ t_{(FW\ at\ source)}$	Expanded biogas production system (L_4)
KPI_3	Energy use[d]	$MJ_{(primary\ energy\ used)}\ /\ MJ\ CH_{4(delivered)}$	Expanded biogas production system excluding biogas use ($L_3 - L_{3d} = L_{3a} + L_{3b} + L_{3c}$)
$KPI_{4,6}$	Nitrogen recycling potential[a]	$kg\ TAN$[e]$_{(delivered)}\ /\ t_{(FW\ at\ source)}$	Biogas production system (L_3)
KPI_5	Phosphorus recycling potential[a]	$kg\ P_{(delivered)}\ /\ t_{(FW\ at\ source)}$	Biogas production system (L_3)
KPI_7	Cost[f]	€ $/\ t_{(FW\ at\ source)}$	Biogas production system (L_3)

[a] Higher values mean better performance.

[b] It is assumed that the generated food waste at source (e.g., households) enters the FW sorting and collection system.

[c] Lower values mean better performance. Climate impact is expressed in Global Warming Potential, using GWP_{100} impact characterisation factors (IPCC, 2013).

[d] Lower values mean better performance; expected to be ≤ 1.

[e] TAN: total ammonium nitrogen (mineralised nitrogen which is available for plants to grow and therefore comparable with mineral N fertilizers).

[f] Including operational costs, the cost of the used resources and services such as transportation and waste treatment, across the full value chain of biogas and biofertilizer production from food waste, and excluding investment, administration costs, context-specific fees, or revenues.

and the produced products. The interviews were semi-structured and, in most cases, involved a face-to-face meeting with different representatives from biogas plants at the respondents' workplace. The respondents were encouraged to reflect upon the uncertainties (when applicable) in the provided data, e.g., to provide intervals or mean values with deviations. During the interviews, notes were taken, and the notes were sent to the respondents to comment on. In these follow ups, additional questions about the processes diagram and corresponding data were asked to clarify the uncertainties. The research was performed in a participatory fashion as reflected in the close involvement of three experts from two of the studied cases in the co-authorship of the paper.

A wide range of sources were used to obtain the background data with regards to climate impact, energy use, and cost of resources used, such as district heating, wood chips, diesel, electricity, mineral fertilizers, and so on (see supplementary materials Table S1). Sources applicable to the Swedish context have been used as much as possible.

A generic biogas production system was considered based on the taxonomy of biogas production systems developed in Feiz et al. (2020). All studied cases and scenarios are specific instances of this generic

system (Fig. 1). The generated FW is separated at source (source-separated FW). It is collected and, if required, goes through extra sorting facility to sort out the plastic bags from the rest (sorted and collected FW). The collected FW is pre-treated, where most of the impurities are separated as rejects and sent to incineration, and the FW is then converted into a meal by milling. If needed it is diluted by adding fresh water, recycled water, or other thin substrates to create the slurry (meal) for the biogas plant. The meal is fed into the AD system where biogas and digestate are produced. Part of the produced biogas is lost due to slippage and flaring. Depending on the heating system, part of the useable biogas may be used for internal heating, and the rest (delivered biogas) can be used to produce heat and/or power, or, as is common in Sweden, can be upgraded to about 97% methane (Swedish Gas Association, 2019). The upgraded biogas can be delivered to users via a local distribution network but can also be compressed or liquefied before distribution. The produced digestate is either sent directly to farms where it is used as biofertilizer, or it is further processed by phase separation (solid/liquid separation), and if needed, additional processing such as ammonia stripping or evaporation. The accepted fractions may be used
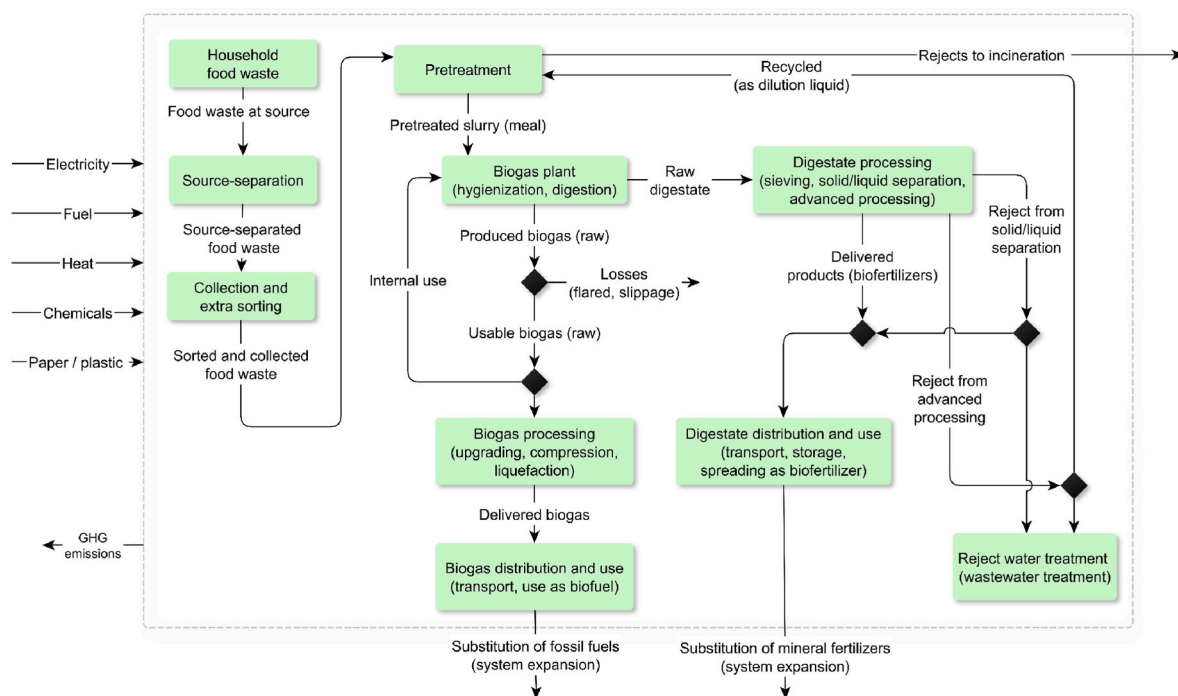

Fig. 1. Overview of the generic biogas production system based on the taxonomy of biogas production systems developed in Feiz et al. (2020). Individual transportation activities, energy and material inputs, and emissions are not shown. The transportation of rejects from pretreatment to the incineration plant is included in the analysis.

Table 4

Overview of the studied biogas plants.

	Biogas plant A	Biogas plant B	Biogas plant C
Running since	1997	2015	2014
Reference period for data collection[a]	2015-01-01 to 2016-12-31	2017-01-01 to 2017-12-31	2016-01-01 to 2016-09-01
Production:			
– food waste input	44,000 t	40,000 t	10,000 t
– biogas produced	100 GWh	67 GWh	25 GWh
Main feedstock	Food waste, liquid waste from slaughterhouse and food industry	Food waste, organic oils and glycerine	Food waste, manure
Type of biogas plant	Wet process, Mesophilic	Wet process, Mesophilic	Wet process, Thermophilic
Sorting of food waste	Mixed systems. Both paper bags and plastic bags from optical sorting	Paper bags (household) + waste from restaurants and grocery stores	Plastic bags and optical sorting
Pretreatment	Milling, grating, dilution	Milling, grating, dilution	Milling, grating, dilution
Upgrading	Chemical absorption (amine)	Pressure swing absorption	Chemical absorption (amine)
Heat supply	District heating	Own biogas	Wood chips
Digestate treatment	Raw digestate used as biofertilizer	Solid-liquid separation (centrifuge) and partially operational advance liquid processing. Fractions used as biofertilizer.	Raw digestate used as biofertilizer

[a] In cases where the period is less or more than a year, values are (later) adjusted to one year.

as biofertilizers (or other applications), while the rejected fractions can either be recycled (e.g., as dilution liquid in pretreatment), used as liquid biofertilizer, or discharged to wastewater treatment for safe disposal.

A process-based life cycle assessment (LCA) model was developed in Microsoft Excel, following the taxonomy and system levels described in Feiz et al. (2020). Microsoft Excel was chosen (over commercially available software) to create a generic model of a biogas production system that is re-useable and extendable and allows programming for automation (e.g., uncertainty management). Whenever needed, values from commercial LCA datasets such as EcoInvent were used. The system levels were introduced to allow a modular analysis of the biogas production system (Table 2); placing the biogas production at the centre (AD) and adding layers of activities around it. System levels can show the relative importance of certain type of activities (e.g., transport) regardless of the order in which they occur within the biogas production system or the actor who in practice may be responsible for them.

As an alternative way of presenting the biogas production system from a supply chain perspective, the source separation of FW can be implemented from the start all the way to the use of biogas and biofertilizer. This alternative view of the system can be complementary to the system-level perspective, as the activities are presented in terms of the actors who control them. The steps are as follows:

(1) *SOURCE*: generation of waste at households;
(2) *COLLECT*: collection of the waste and extra sorting (if needed);
(3) *PRETREAT*: pretreatment of the waste;
(4) PROD: biogas production through anaerobic digestion;
(5) *DISTR*: cleaning and/or upgrading of the gas together with the distribution of biogas, and digestate processing and distribution;
(6) *USE(BIOFERT)*: storage and spreading of digestate, including soil carbon change;
(7) SUB(FERT): substitution of artificial fertilizers by digestate or digestate-based products;

Table 5

Distinctive features of each production system; the reference and scenarios for each case.

Scenario	Biogas processing and use	Digestate processing and use	Key distances
A_0	Amine scrubber is used for upgrading, where 70% of the upgraded biogas is compressed and distributed in CBG cylinders. The rest is distributed locally.	No digestate processing	- 33 (22–44) km for raw digestate - 30 km for CBG carrying trucks
A_1	Same as A_0: 70% is upgraded, liquefied, and distributed as LBG. The rest is distributed locally.	Same as A_0	- 33 (22–44) km for raw digestate - 60 km for LBG carrying trucks
B_0	Some biogas is used for internal heating. All deliverable biogas is upgraded (PSA), compressed, and distributed in CBG cylinders.	No digestate processing	- 30 km for CBG carrying trucks - 100 km for raw digestate
B_1	Same as B_0	Digestate is passed through solid-liquid separation. The solid fraction is sent to farms as biofertilizer. The liquid fraction is treated in a municipal wastewater treatment plant.	- 40 km for solid biofertilizer
B_2	Same as B_0	Digestate is passed through solid-liquid separation. The solid fraction is sent to farms as biofertilizer. The liquid fraction is sent to an evaporation unit for advanced processing. The concentrate from evaporation is sent to farm as biofertilizer. The condensate (clean reject) is used as a dilution liquid in a pretreatment plant.	- 40 km for solid biofertilizer - 40 km for concentrated liquid biofertilizer
C_0	All deliverable biogas is upgraded, compressed, and distributed in CBG cylinders. Biogas production is limited by the demand; the excess biogas is flared (4–5% flaring due unstable market)	No digestate processing	- 30 (20–40) km for raw digestate - 100 km for produced biogas (partly shipped outside the region)
C_1	- All deliverable biogas is upgraded, compressed, and distributed in CBG cylinders.- The local market for biogas is expanded and has become more stable, with 1% flaring due to a stable market.	Same as C_0	- 10 km for produced biogas (used within the region).

Table 6
Main input data for the cases. Most of the data are case specific, but some are generic assumptions to enable meaningful comparisons.

Parameter	Case A	Case B	Case C
Collection			
Transportation of collected food waste to pretreatment plant	Collection trucks run on an average fuel mix for waste collection of 39% biogas, 39% HVO/other renewables, and the rest diesel[a]		
Distance (km)	30	30	22
Pretreatment			
Rejection rate (% of incoming fresh weight)	10 (5–15)%	10 (6–12)%	10 (8–12)%[b]
Dry matter content of the reject (%)	28% for all cases		
Rejection rate of organic material (% of input VS)	5 (2.5–7.5)%	5 (3–6)%	5 (4–6)%
Electricity use (MJ/t)	21.1	58.5	39.6
Dilution rate	Approximately 1:1 for all cases		
Dilution liquid	50% of dilution by thin substrate from food industry; for the rest fresh water is used	Recycled water from digestate treatment (condensate from evaporator); otherwise, fresh water	Fresh water
Reject handling	Incineration for district heating/electricity production; distance to incineration plant: 10 km	Incineration for district heating/electricity production; distance to incineration plant: 20 km	Incineration for district heating/electricity production; distance to incineration plant: 20 km
Digestion system (integrated hygienisation and AD)			
Electricity use (MJ/t)	42.2	84.3	47.8
Heat use (MJ/t)	174 (district heating)	121 (boiler with own biogas)	108[c] (boiler with wood chips)
$FeCl_2$ use (kg/t)	5 for all cases.		
Methane slip (AD) (%vol. of produced biogas)	<1% for all cases		
Biogas flared (%vol. of produced biogas)	1%	1.7 (0.7–2.8)%	4–5%
Biogas processing			
Electricity use (upgrading) (MJ/Nm³ input)	0.76 vehicle fuel quality 1.2 liquefaction quality	1.1 vehicle fuel quality	0.49 vehicle fuel quality
Heat use (upgrading) (MJ/Nm³ input)	0.6 MJ/Nm³ (0.17 kWh/Nm³)	0	0.4 MJ/Nm³ (0.11 kWh/Nm³)
Methane slip (upgrading) (% of input)	0.1%	0.7%	0.1%
Off-gas heat recovery	No	Yes	Yes
Electricity use (compression to 250 bar) (MJ/Nm3 input):	0.77 MJ/Nm³ (0.21 kWh/Nm³: 1–250 bar)	0.58 MJ/Nm³ input (0.16 kWh/Nm³ input)	0.77 MJ/Nm³ (0.21 kWh/Nm³)
Digestate processing			
Digestate management	Raw digestate is used as biofertilizer	Solid-liquid separation; solid fraction used as biofertilizer; liquid fraction is sent to evaporation; concentrate used as biofertilizer	Raw digestate is used as biofertilizer

[a] (Avfall Sverige, 2019).

[b] The measured rejection rate after dilution with water is 10–15%. This includes some of the dilution water. To compensate for this issue, the rejection rate was reduced by 20%.

[c] The specific heat demand for plant C is lower than other plants, despite being thermophilic. The reason for this is not investigated, as this requires an in-depth energy audit/exergy analysis within each plant, but a hypothesis can be that this is due to different temperatures being used (Plant A uses more heat at a lower temperature, but plant C uses less heat at higher temperature), and also due to differences in the designs of the plants in terms of their heat integration/recovery system.

(8) SUB(FUEL): Substitution of fossil fuels by biogas.

Several methodological recommendations were provided for a life-cycle-based analysis of biogas production from FW, and these showed the benefits of expressing the performance of such systems in the form of a few integrative Key Performance Indicators (KPI). These cover aspects such as climate impact, primary energy use, nutrient recycling potential, and cost (Table 3). The KPI for the enhancement of plant available nitrogen (KPI_6) was chosen since this is one of the positive implications of AD. KPI_7 is based on the cost of resources and transportation to complement the environmental impact of resources that are used within the system. In this study, the investment costs are not included, but they could be added as a new KPI (e.g., KPI_8). It should be noted that only 2 out of 7 KPIs are common LCA indicators. KPI_2 (Climate impact) is characterised by using the corresponding IPCC impact characterisation model (GWP_{100} as in IPCC, 2013), and the energy balance is characterised by "primary energy factors" (PEF) obtained from different sources (see supplementary materials Table S1) and analytically modelled based on energy and mass balance within the system. Other KPIs are calculated based on a modelling of the mass and energy flows through the system, considering the potential losses (mass and energy balancing).

3. Description of cases

The studied plants run on different scales and treat different portfolios of substrates with varying shares of FW. For the sake of anonymisation they are referred to as plant A, B, and C (Table 4).

For each case, a *reference* was defined, describing the production system as it was in the recent past and prior to certain real or perceived development. In addition to this reference, one or more *scenarios* were defined for each case in cooperation with representatives from the studied biogas plants. These scenarios introduced meaningful variations within these cases by altering specified parameters. Along with the *reference,* these *scenarios* represent possible developments of each biogas production system. Following the anonymous designation of the cases by letters A–C, the references are referred to as A_0–C_0 and the scenarios as A_1, $B_{1–2}$, and so on. Each scenario stands for an interesting and

justified variation within the corresponding reference (Table 5). More detailed information about each system is available in the supplementary materials (Table S2).

3.1. Assumptions and inventory

To maintain comparability between different cases, some unifying assumptions were made. The plants use a different feedstock mix (they treat other types of biomass in addition to FW). Taken as they are, it would not be possible to perform a meaningful comparative analysis and draw insightful conclusions about the characteristics of biogas from FW systems. Therefore, a common basis was constructed, on which all these systems were re-defined to become comparable. In this way, the focus is on their structural and systemic differences—rather than differences that arise from the higher or lower quality of substrates (Tables 5 and 6).

It was assumed that the composition of FW that is received at all plants is the same (see supplementary materials Table S3), and that the cases use a source-separation and sorting method that is either based on (1) a system of source sorting of FW into paper bags and collected in individual bins or (2) or system of source separation of FW in tinted plastic bags collected in mixed bins and later sorted out through optical sorting. In warmer periods of the year, FW collected in paper bags can result in noticeable loss of organic matter and water compared to the waste collected in plastic bags (Nilsson Påledal et al., 2017). Assumptions were made that on average 5% of the organic content of the FW in paper bags is aerobically degraded, and 10% of its water content is evaporated during collection.

The collection of FW was based on the average Swedish assumption that 87% of the population live in urban areas and 13% in the countryside (Hela Sverige ska leva, 2018), which results in an 18 km average collection distance with fuel demand of about 150 MJ/t (based on distance estimates by Berglund and Börjesson, 2003). A fuel mix similar to the average Swedish fuel mix for waste collection was used, i.e. 39% biogas, 39% HVO/biodiesel, and 22% diesel and other fossil fuels (Avfall Sverige, 2018). When required, a separate transportation was added for sending the collected FW to the pretreatment facility. Assumptions regarding fuel use and the cost of transportation are presented in the supplementary materials Table S4.

All studied plants use a wet process that requires the FW to be diluted by adding fresh water or mixing with feedstocks with low TS content. This will lead to the production of a slurry with a TS content of about 12–15%. Also, the FW is crushed and most of its impurities, in the form of large impurities such as pieces of plastic and metal (large inert solids or LIS), are removed. After considering losses and internal use (in case the plant uses its own biogas for heating), the rest of the biogas is sent to upgrading, and the upgraded biogas is transported via pipeline, CBG trucks (after compression), or LBG trucks (after liquefaction). The digestate is either used directly as biofertilizer (including storage and spreading) or is first processed (solid-liquid separation or more), and different fractions are used as biofertilizers (e.g., solid fraction and concentrate), recycled (e.g., condensate), or discharged to waste treatment (e.g., liquid fraction).

Several of the parameters—including some of the data from production facilities, but also some of the assumptions regarding different aspects of the system—were available in the form of intervals (implying variability or uncertainty), e.g., the rejection rate of the incoming FW in the pretreatment facility was expressed in the form of an interval. The same goes for the emission factors for climate impact associated with the storage and spreading of digestate. To deal with such parameters, they were preserved in their available (uncertain) form and their impact was propagated using stochastic modelling (Monte-Carlo simulation). For simplicity's sake, only the mean values of the results were shown and propagated uncertainties were shown as error bars. Uncertainty propagation was performed with regard to those parameters that were deemed either very uncertain or as having great variability—as mentioned before. This is clearly visible with regard to emission factors from

digestate storage and spreading (see supplementary materials in Table S5). Since these factors are quite variable/uncertain, several of them are characterised in terms of simple intervals, which are then propagated by Monte-Carlo simulation. For example, a factor called "carbon sequestration in soil", as a result of the application of digestate as biofertilizer, is an important parameter with high variability/uncertainty. Therefore, an interval was kept, i.e., 2–29%. Also, this study focused on parametric uncertainties, but other types of uncertainties could also be present, for example, due to differences in the LCA modelling approach (Brandão et al., 2022). This means that more in-depth uncertainty analysis can be performed in follow up studies. Also, it may be useful to perform sensitivity analyses to investigate the impact of individual parameters on the results (i.e., KPIs).

4. Results

The inventory of the main inputs to the system (i.e., energy and materials used, and other processes), direct emissions, and outputs from the system (products and byproducts and avoided products) are presented in Table S2 in the supplementary materials.

All scenarios have the same theoretical biomethane potential (due to the unifying assumption about the characteristics of the FW and digestion efficiency), but the delivered biomethane differs between the scenarios (Fig. 2). In case B, biogas is used internally for providing heat to the biogas plant and digestate processing. This explains the lower amounts of delivered biomethane for B_{0-2} compared with other cases. The reference for case C (C_0) has a lower useable biomethane yield than the C_1 scenario. This is due to the assumption that the local demand is limited and unstable, and hence, they are forced to have more frequent flaring of the excess biogas. Other factors affecting the amount of delivered biomethane are losses of organic material during pretreatment and slippage of biomethane.

The climate impact of the production of biogas from FW or KPI_2 (Fig. 3, and Figs. S1 and S2 in the supplementary materials) can also be considered. The contribution of different system levels shows that the benefit associated with substitution of fossil fuels by the produced biomethane is a dominant part of the KPI_2. In all cases and scenarios, the substitution effect for using biomethane as a vehicle fuel instead of a fossil diesel results in a negative climate impact.

The uncertainties in relation to the use of biofertilizers (storage and spreading) are high due to the use of relatively large ranges for various emission factors (e.g., what fraction of the carbon content in digestate is stored long-term in the soil? This factor is assumed to vary between 2 and 29% of the total carbon content of the digestate—see Table S5). For case A, no significant difference between A_0 and A_1 is observed. This is due to the offsetting of the savings from transport by the fact that the produced biogas is shipped a farther distance and the liquefaction process is also added. B_1 has a much worse climate performance than B_0, due to the high impact of treatment of the liquid fraction in the municipal wastewater treatment plant. This issue is resolved by fully processing the digestate in B_2. C_1 has a slightly better climate performance than C_0, which is mainly due to less biogas flaring.

In the biofuel literature, it is common to express the climate impact of the delivered biofuel in terms of $grCO_2eq/MJ$. The performance indicator based on the main process steps in the supply chain of biogas production is shown (Fig. 4). The values can be compared with a reference value for fossil fuel emissions defined by the renewable energy directive in Europe, which is 94.1 $grCO_2eq/MJ$ (European Parliament, 2018; f3, 2021), and which would indicate about an 62–80% reduction (without system expansion). As mentioned before, the scenario standing out from the others is B_1. In this scenario, case B has introduced a solid-liquid separation of the digestate, and only the solid fraction is sent to farms as biofertilizer, while the liquid fraction is treated in WWTP and not used. That explains why the activity "distribution", which includes digestate distribution, digestate processing and reject water management, has a higher climate impact for B_1.
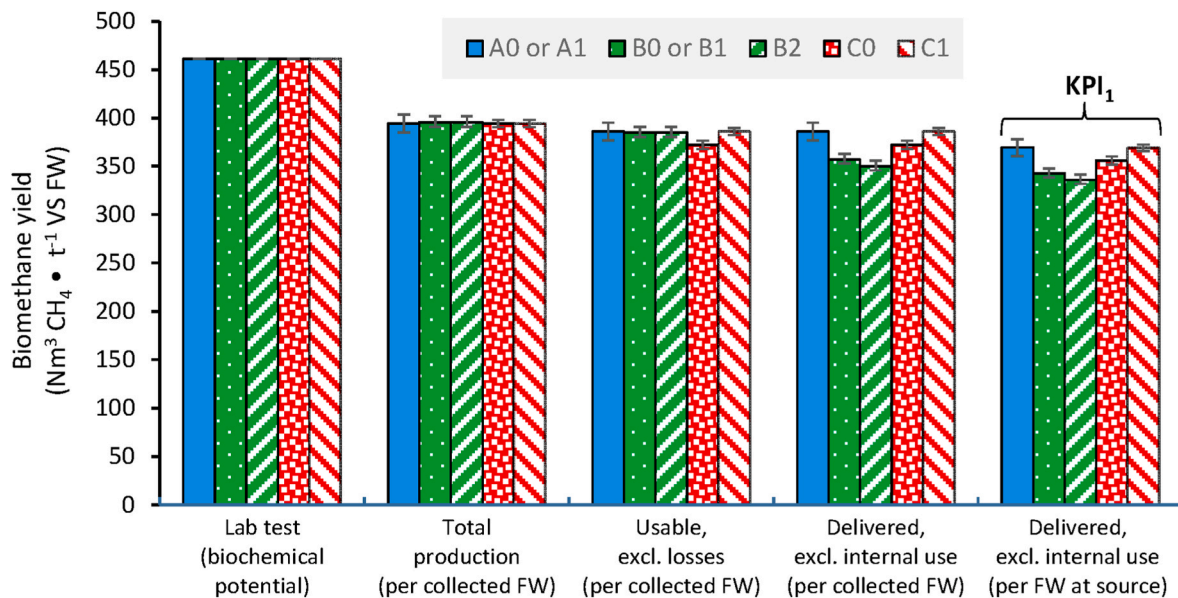
Fig. 2. Different ways of expressing biomethane yield for the studied biogas plants and scenarios (A0–1, B0–2, C0–1 as defined in Table 5) per tonne VS depending on the system level that is considered (horizontal axis). Total production represents the gross amount of biomethane that is produced from the received food waste, but after considering the losses we have the total useable biomethane; and after considering the internal use of biogas we arrive at the amount of biomethane that is delivered to the market. If we consider the amount of delivered biomethane that is produced from 1 tonne VS of food waste generated at households (FW at source) after all internal usages and losses, KPI_1 is obtained.
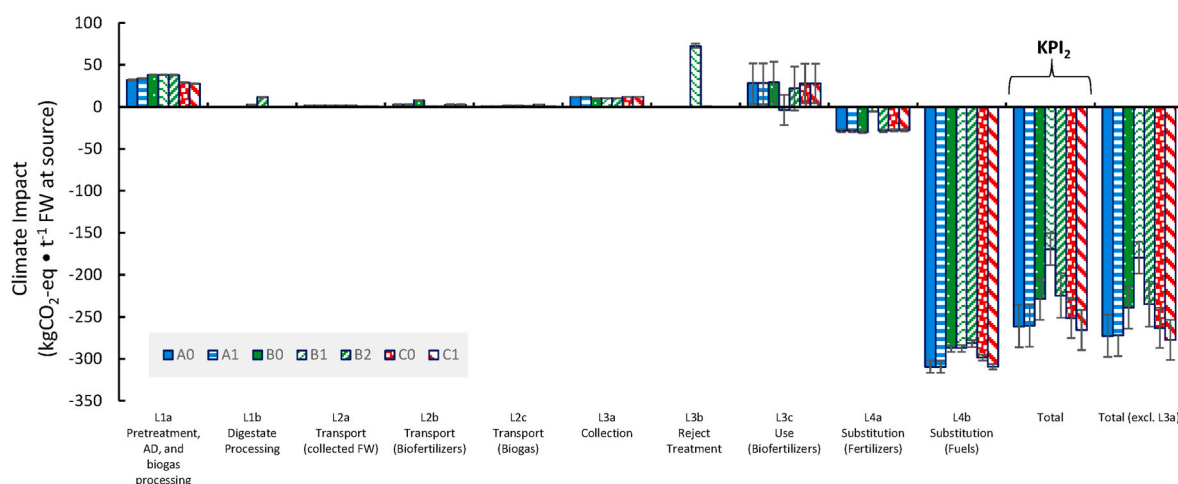
Fig. 3. Climate impact of producing biogas from food waste in different cases and scenarios. The total represents the KPI_2 (Table 3). Since the collection of food waste is sometimes considered as a necessary service that should be performed regardless of the eventual treatment option, we also show the total excluding the collection (Total, excluding L3a).

The next key performance indicator is energy performance (KPI_3), which can be expressed as the amount of non-renewable primary energy that needs to be expended to deliver an MJ of energy in the form of biomethane (Fig. 5). The main contributors that affect total non-renewable primary energy use in the system are the collection (L_{3a}), pretreatment, AD, biogas processing (upgrading, liquification—if done) (L_{1a}), digestate processing (L_{1b})—if done—and substitution of fossil fuels. As can be seen, the A and C cases have better energy performance (lower KPI_3) compared to B. This is mainly because the B system uses some of its own biogas for internal use and therefore delivers less biomethane to the market; it also needs some energy to perform digestate processing. Non-renewable primary energy use for all cases and scenarios were about 16–31% MJ per MJ delivered biomethane.

The key performance indicators associated with nutrients recovery, KPI_{4-6}, can be nicely illustrated using a kind of diagram that we refer to

as a *budget curve*. The idea behind these diagrams is that there are certain amounts of nutrients—nitrogen (N), phosphorus (P), and total ammonium nitrogen (TAN)—in the received FW, and the biomass management system (in this case biogas production system) must deal with this budget. If there are losses of organic materials or emissions along with different processes, some of this budget is consumed. If there is an enhancement of nutrients (e.g., due to the mineralisation of nitrogen and the increase of TAN), it will gain some budget (Fig. 6).

In all cases and scenarios there are some losses of organic matter in the pretreatment of FW and digestate management—which explains the decrease in nutrient amounts—but at the same time all scenarios except B_1 deliver almost 90% of the P content of the FW and lead to a several fold increase of the plant-available nitrogen (represented by TAN). The increase of TAN as a result of AD is assumed to be similar for all cases, but the amount of TAN delivered to agriculture depends on the digestate
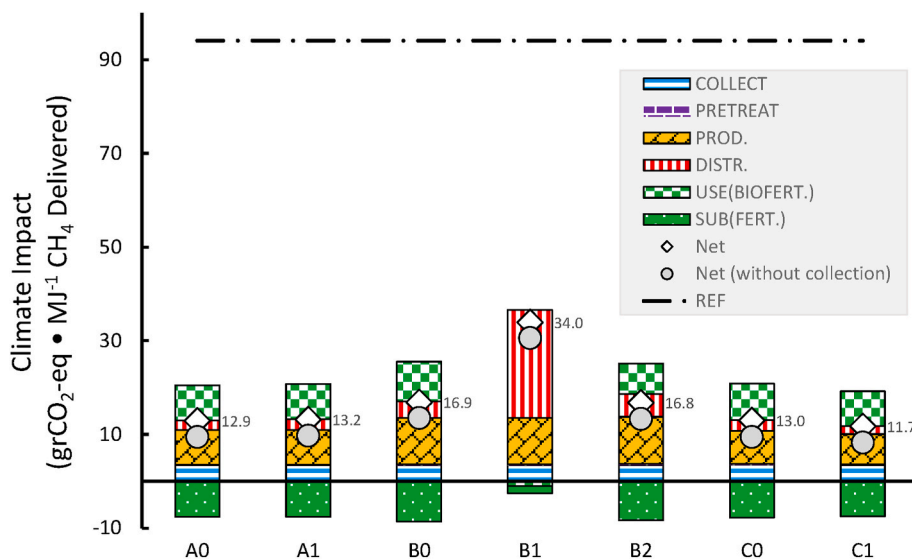
Fig. 4. Climate performance of the delivered biomethane produced from food waste in different cases and scenarios (the white diamonds) using the system expansion method, i.e., if the digestate-based products replace artificial fertilizers. The contribution of the main steps in the supply chain of biogas are shown. Since the collection of food waste is sometimes considered as a necessary service that should be performed regardless of the eventual treatment option, we also show the total excluding the collection (the grey circles).
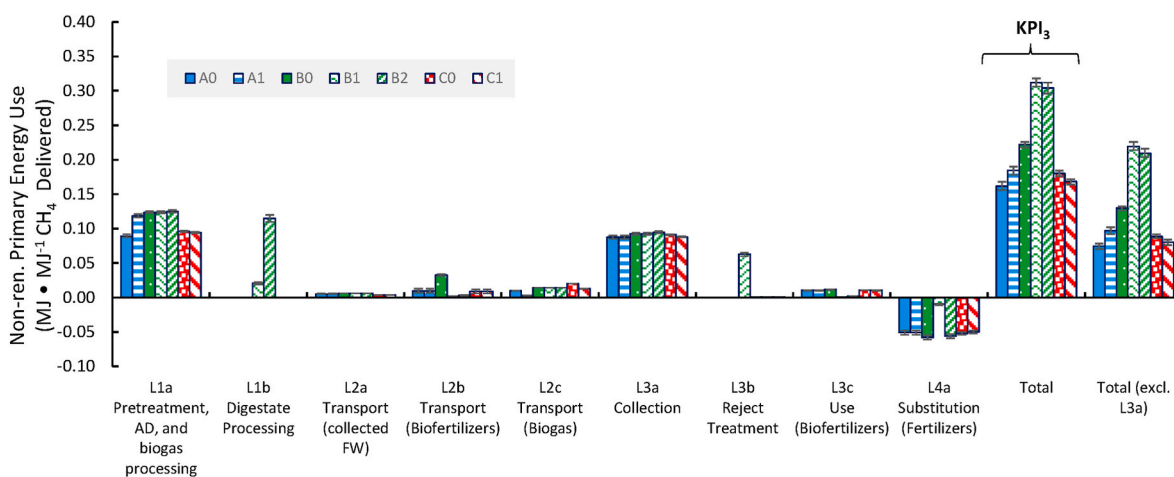

Fig. 5. The non-renewable primary energy use per MJ biomethane delivered for the scenarios in relation to the system levels (Table 2). The total value represents KPI_3 (Table 2).
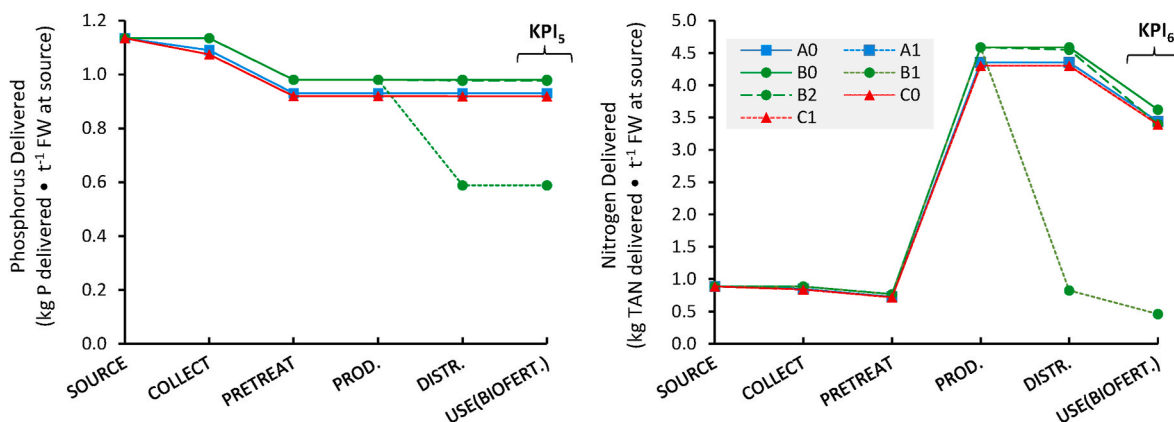

Fig. 6. Budget curves showing the amount of nutrients that are passed through the biogas production system and eventually to agriculture as biofertilizers in the studied biogas cases and scenarios. The left panel shows the amount of phosphorus (P) in the food waste (at source) that after some losses is delivered as biofertilizer. The right panel shows the amount of total ammonium nitrogen (TAN) that due to anaerobic digestion of food waste is increased compared to undigested food waste. The eventual amount of P and TAN delivered (the value corresponding to the right-end of each curve in each figure, i.e., the use as biofertilizer) represents KPI_5 and KPI_6 (Table 3). To save space, we have not shown the amount of nitrogen delivered expressed in Total N, which was defined as KPI_4 in ibid.
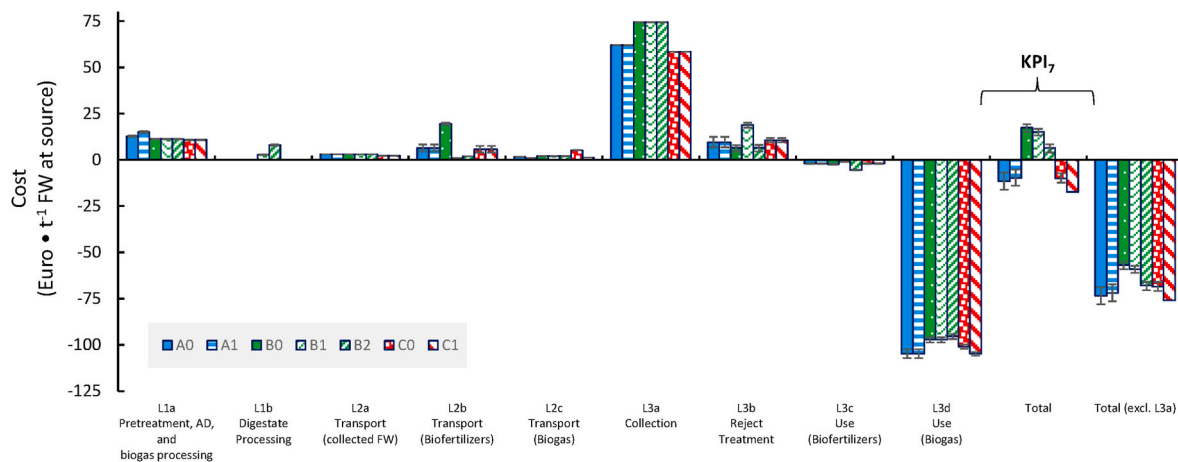
Fig. 7. The cost of the used resources and the transportation of treating food waste through biogas production in the studied scenarios and connected to different system levels (Table 2). Negative values indicate the sale of products or by-products. The total value represents KPI_7 as defined in ibid.

processing choices. The scenario that stands out is B_1. This scenario includes a partial processing of the digestate with no utilisation of the liquid fraction from the solid/liquid separation, which explains the lower amounts of nutrients delivered to the farms. On the other hand, scenario B_2 has a full processing of the digestate where both the solid and the liquid fractions are used as biofertilizer.

The last key performance indicator is associated with the cost of producing biogas from FW—focusing on transportation, physical resources used, and delivered products—and excluding investment, maintenance, and personnel (Fig. 7). The largest cost component is for the collection of FW, which is noticeably higher for case B since it uses the source-separation and collection based on paper bags in individual bins, and the main revenue (negative cost) is from the sale of the upgraded biogas. All cases and scenarios have comparable costs along the supply chain, and the total cost of biogas production is somewhat higher for case B (KPI_7). This has several causes (e.g., mainly using paper bags in sorting collection, use of own biogas, etc.), but is also because this biogas plant is located far from agricultural areas and therefore its digestate management options are more costly.

If the cost of spare parts and consumer goods for biogas plant (including pretreatment) is included, about 9 (3–25) €/t should be added to the cost for all cases based on the estimates by Yngvesson et al. (2013). The same study estimated that an additional 11 (1–24) €/t can be added for personnel costs, and the total cost of the biogas plant and pretreatment is about 29 (14–63) €/t; a result that matches the findings of this paper, if maintenance and personnel costs are added to them (see the L_{1a} costs in Fig. 7).

If the collection costs are excluded, the biogas systems have a net positive income (shown as negative cost), but it should also be noted that in this analysis the cost of the biogas plant is under-estimated due to the exclusion of investment and personnel from the cost analysis. The collection cost is based on similar assumptions for all cases—with some variations due to their separation and sorting methods. KPI_7 includes costs that are typically not managed by the biogas producer (e.g., collection costs), therefore it should not be viewed as an indicator of their financial performance. A biogas producer may not incur the collection cost or indeed normally obtain revenues (receive gate fees) for treating the FW. These aspects are not included in this analysis as the focus is on the system-wide cost of producing biogas from FW—as well as on its life cycle climate impact or primary energy use.

In general, biogas systems A and C have a lower total climate impact and non-renewable primary energy use than biogas system B. Plant B has a higher cost than A and C due to several factors, but this is partly due to the higher cost of digestate management in B compared to A and C. In terms of nutrients' recycling potential, all scenarios have comparable

performance except for B_1 in which, due to the partial processing of the digestate, a significant part of the nutrients were not recovered as biofertilizer.

5. Discussion

In this paper, three large-scale biogas production systems in Sweden receiving FW from households were studied, and in addition, several scenarios that altered the configuration of the systems were introduced and analysed. The results from the cases differed, but variations in the economic and environmental performances were not always considerable.

Processes related to pretreatment, AD and biogas processing (L_{1a}); collection (L_{3a}); and digestate utilisation (L_{3c}) were the most impactful parts of the production system, e.g., looking at all cases, about 40% and 27% of the climate impact of "biogas production from FW (excluding the substitution effects in L_{4a} and L_{4b}) was from pretreatment, AD and biogas processing (L_{1a}), while digestate utilisation (L_{3c})—i.e., L_{1a}'s share was 40% and L_{3c}'s 27%. The most contributing processes were slightly different with regard to primary energy use: about 41% and 34% of the energy use (excluding the substitution effects in L_{4a} and L_{4b}) came from pretreatment, AD and biogas processing (L_{1a}), and collection (L_{3a})—i.e., L_{1a}'s share was 41% and L_{3a}'s 34%. Finally, the collection of FW (L_{3a}) was the major contributor to the cost by being responsible for about 65% of the cost of biogas production from FW (excluding the sale, i.e., utilisation of digestate and biogas, i.e., L_{3c} and L_{3d}). Poeschl et al. (2012a) also came to a similar conclusion in their environmental study of several different feedstocks in Germany and emphasized on the importance of feedstock supply logistics (i.e., collection) in the total life cycle impact of biogas production (their study did not include cost analysis, but they estimated that about 50% of the primary energy input into the biogas production system from food waste was from collection). It should be noted that collection (L_{3a}) is a municipal service in Sweden and typically out of the direct control of the biogas producers. However, regardless of the controlling, and considering the life cycle perspective, optimising the logistics and use of more renewable fuels in transports can have a significant effect on the life cycle impact of biogas production from FW. Nevertheless, the collection and transportation of feedstocks used for biogas production is often neglected in systems studies, e.g., Herbes et al. (2020) includes transportation of digestate in their study, but not the transportation and collection of feedstocks. In a systems analysis of biogas production systems performed by Lindkvist et al. (2019), all transportations were excluded. The climate impact of the delivered biomethane in the studied cases was 12–34 $grCO_2$/MJ delivered (12–17 $grCO_2$/MJ excluding B_1) (Fig. 4), which can be compared with the

default value for the climate impact of biomethane produced from biowaste in EU RED II, which is set to 19 grCO$_2$eq/MJ (f3, 2021). Considering the climate impact per tonne FW, the impact of the studied cases was between −266 and −170 kg CO$_2$eq/t which can be contrasted with results from other studies; e.g., −195 kg CO$_2$eq/t (Xiao et al., 2022), −127 and −159 kg CO$_2$eq/t (Yu et al., 2020), and −90 kg CO$_2$eq/t (Ascher et al., 2020). The differences can be due to differences in systems definitions, but also differences in the climate impact of the used energy system.

The primary energy use of biogas production from FW under Swedish conditions was previously estimated to be about 0.18–0.59 MJ PE/MJ biogas produced (Berglund and Börjesson, 2006). This can be contrasted with our studied cases concerning the primary energy use of 0.16–0.31 MJ PE/MJ biomethane delivered. In addition to electricity type, which in all studied cases were common, the source of heating energy for biogas plants had significant implications on the economic and environmental performances of the studied systems (Feiz et al., 2020). In the studied cases, the biogas plant that used its own biogas for heating—plant B, which used about 7–9% of its produced biogas for internal use in different scenarios, comparable to the figure of 7.9% reported by Bernstad and la Cour Jansen (2011)—could deliver less biogas to the market, which resulted in a higher life cycle climate impact compared to the other biogas plants. It should be noted that in Sweden the alternative energy sources for heating are often low-carbon sources (e.g., wood chips, district heating or electricity with a low carbon footprint). In countries and regions with energy supply based on high carbon sources (e.g., coal and oil), the better option could be to use biogas as an energy source in the biogas plant (Poeschl et al., 2012a). This shows the importance of considering the energy system in analysing the performance of biogas solutions. Another alternative for heating could be to use excess heat through symbiotic relations with other industries (Broberg Viklund and Lindkvist, 2015). Additionally, solar-aided heating could be an option, e.g., hot water from solar thermal collectors in combination with chemical heat storages, and cooling water from photovoltaic cells (Kalaiselvan et al., 2022).

Suitable market conditions and the presence of stable demand for the produced biogas can reduce the loss of biogas due to flaring during low-demand periods. This was analysed in the biogas plant C in which a more stable local market was assumed in one of the scenarios (C$_1$). Having less flaring (wasted biogas) directly increases the resource utilisation rate and consequently lowers the climate impact, primary energy use, and resource cost. The expansion of a local market also led to savings in the distribution of compressed biogas (CBG) due to shorter distances (from 100 km to 10 km). Furthermore, the market for bio-methane is rapidly developing in Sweden with more actors seeking opportunities to substitute fossil fuels with bio-methane (Klackenberg, 2021). This development has partly been driven by the introduction of upgrading technologies that liquify the biogas to LBG, which is a more energy-dense fuel compared to CBG. Hence, transports of bio-methane become more cost-efficient with LBG, compared with CBG (Gustafsson et al., 2020), and also it can be used in many different (and new) applications. This aspect was reflected in biogas plant A by comparing the production and distribution of CBG (A$_0$) with LBG (A$_1$). The results showed a higher resource cost and non-renewable energy use for producing LBG compared to CBG, but lower resource cost and climate impact for transporting LBG, even though the distance for transportation of LBG was doubled (60 km for LBG and 30 km for CBG).

Digestate management includes digestate processing (L$_{1b}$) and digestate utilisation (L$_{3c}$) but can also affect reject management (L$_{3b}$) if some fractions need to be disposed of. The decision to choose the digestate processing methods is affected by the location of the market for nutrients (farmland) and the possibility of applying the digestate on land (Feiz et al., 2022). Based on a survey, the average distance that agricultural biogas plants in Sweden transport their digestate to farms is about 10 km (up to 35 km), and only a few transport their digestate farther than 20 km (Bergh, 2013). Berglund and Börjesson (2006)

concluded that the solid-liquid separation of digestate would be beneficial if the transport distance to arable land exceeds 60 km, which would imply that such distances can be considered "far" for digestate transport in the Swedish context. However, certain nutrient compositions of soils can motivate solid-liquid separation even at shorter distances to farmland (e.g., up to 35 km). Most of the phosphorous ends up in the solid phase, while the liquid phase contains more nitrogen. Hence, solid-liquid separation can be a solution when there are limitations to applying phosphorous on nearby farmland and the solid phase can be transported to regions with a phosphorous deficit.

In relatively nearby markets under Swedish conditions, no processing of digestate is required, and as it was observed in the A and C plants, digestate was sent an average distance of about 30 km. However, at longer distances (as shown in case B, which had about a 100 km average distance to farms), processing becomes an important way of reducing the cost of digestate management. Plant B was the only one that used solid-liquid separation (decanter centrifuge with the use of conditioners for better separation). In a partial processing scenario (B$_1$), the liquid fraction was discharged to a wastewater treatment plant, increasing the impact of reject management (L$_{3b}$). Partial processing (using solid-liquid separation, but not full processing) can be attractive if there is nearby demand for the liquid fraction as biofertilizer so that the discharging of the liquid fraction to wastewater treatment is avoided. In the full processing scenario (B$_2$), the liquid fraction was processed using evaporation techniques, which can be improved if excess or residual heat is available. In general, the additional environmental impact and costs related to digestate processing should be justified with the savings from transport, flexibility in using different fractions in different applications (e.g., solid fraction from solid-liquid separation, or concentrated fraction from evaporation as advanced liquid processing), and the potentially better valuation of the digestate-based products (Feiz et al., 2022). As was observed in the studied cases, the substitution of mineral fertilizers with the produced digestate (or its derivatives) (L$_{4a}$) significantly reduces the environmental impact of the production system. This depends on the fraction of nutrients that are recovered and used as biofertilizer, but also the environmental (and cost) impact of the mineral fertilizers (Pierie et al., 2017).

Several studies have demonstrated that AD can be a preferred technique for the treatment of municipal FW compared to alternative solutions such as composting or incineration. Bernstad and la Cour Jansen (2011) compared different waste management options for municipal FW and found that AD is a preferred option in terms of GHG-emissions and nutrient enrichment, especially compared to incineration. Cherubini et al. (2009) performed a life cycle assessment of four different waste management options and concluded that AD is likely the preferred option among those studied. However, the study did not include the utilisation of the digestate, which could have improved the results further. Evangelisti et al. (2014) compared the AD of FW with incineration and landfilling. The results showed that AD was the best treatment option in terms of GHG emissions and acidification. The same results for GHG emissions and AD were found by Eriksson et al. (2015) in their environmental analysis, as well as in a study by Levis and Barlaz (2011). Mayer et al. (2021) concluded in their life cycle assessment, that AD was the preferred technique for the treatment of municipal and Oldfield et al. (2016) concluded that AD of FW is a preferred option from both an environmental and economic perspective, compared to composting and incineration. All the studies mentioned above have performed environmental assessments, and many have also included an energy analysis. However, few have included an economic assessment in their study, and only one includes the nutrient circulation. This indicates that even though many studies show the benefits of the AD of municipal food waste, a holistic view is missing in the study to capture all aspects of biogas production. The inclusion of these aspects in the same analysis, as done in this study, can better illustrate the benefits of AD as a method for the treatment of FW.

If AD is not possible, feeding FW to livestock can also be an option, a

practice that is not allowed in Europe but is common in many parts of the world (Salemdeeb et al., 2016). Although the aim in this paper was not to compare different FW treatment pathways with each other, the KPIs that are used in this study can be used to compare different FW treatment pathways with each other, e.g., KPI$_3$ (energy use), KPI$_{4-6}$ (nutrient recycling potential), and KPI$_7$ can be used to compare other FW management systems such as composting or incineration using a consistent methodology. However, it is important to bear in mind that the primary goal, before applying any waste treatment method, should be waste reduction through waste prevention strategies (Slorach et al., 2020).

The results from the present study have implications for decision makers—e.g., in municipalities, biogas producers, and agriculture. Combining KPIs for different system levels and analysing different perspectives in one study show the multiple functions of biogas solutions where trade-offs and synergies can be identified. The combination of all KPIs gives the broad view, but at the same time allows for looking at the contribution and combination of each constituent sub-process. The method can be used to analyse how a change in one part of the system affects other parts, as well as the entire system. This can serve as a decision basis for new investments or structural reorganisations, reducing the risk of sub-optimisations, e.g., increased energy demand in pretreatment can result in lower energy demand in digestate management. This was also highlighted by Edwards et al. (2017) who stated that when comparing waste management systems net-energy demand should be considered.

The studied plants have different contextual conditions and designs; hence, a definitive conclusion with regard to observed differences between their environmental or cost performance cannot be drawn (i.e., one cannot say which plant is "best"), because they do not operate under the same challenges. For example, plant B is far from agriculture, so it has a more challenging digestate management issues compared to plant A and C, which are relatively near to farms. Also, plant B uses its own biogas for heating, which means it can deliver less biogas to the market but, on the other hand, it has a somewhat higher energy autonomy. Nevertheless, biogas solutions were shown to be a sustainable way of treating FW in general. This means that there is a flexibility in designing sustainable biogas solutions that fit different local preconditions and surrounding systems. In a literature review by Hagman and Eklund (2016), it was stated that biogas solutions could contribute to all 17 UN Sustainable Development Goals. The results of this study confirm previous studies that biogas solutions can contribute to sustainable development and a biobased economy (Hagman et al., 2018). Although this study is more focused on environmental sustainability, it includes some aspects of economics, in the sense that resource costs and delivered biomethane were two of the KPIs analysed.

Finally, the incorporation of variabilities and uncertainties into the analysis increased the robustness of the assessment, e.g., it could be seen that digestate utilisation (L$_{3c}$) is among the processes whose climate impact has a particularly high uncertainty—mainly due to variabilities in the assumptions related to emission factors in storage and spreading. This study strived to preserve parametric variabilities and uncertainties and propagate them to the results; however, a more extensive approach to identifying the variabilities in the biogas production from FW can be adopted.

6. Conclusions

This study has analysed the climate impact, primary energy use, nutrient recycling potential, and cost of producing biogas from FW in three Swedish biogas plants. The biogas production systems come with great varieties and configurations, and to be able to represent their performance and to make them comparable with each other, a method based on life cycle analysis (LCA) and key performance indicators (KPIs) has been used. The analysis synthesises large amount of information about the performance of these systems and their sub-systems, including

variabilities and uncertainties. Despite significant differences between the cases, all led to the production of biomethane with a low climate impact (62–80% less climate impact in grCO$_2$eq/MJ compared with the fossil reference), low non-renewable primary energy use (16–31% MJ per MJ delivered biomethane), and significant nutrient recovery potential (e.g., 52–86% of phosphorus content of food waste was delivered as biofertilizer). In addition to the collection system, the efficiency of pretreatment, the choice of energy system (e.g., for heating the biogas plant), and the choice of digestate management (which is mainly affected by the location of the biogas plant and its nearby environment in terms of the possibilities to use digestate or the separated fractions as biofertilizers) are among the main factors that influence the overall performance of these systems.

In Sweden, electricity is obtained from low carbon sources, and district heating is often based on biomass and waste. However, other options such as directly using biomass or one's own biogas to provide the required heating is possible, as was seen in two of the studied cases. The results show that in the case of long distances, the solid-liquid separation of digestate along with evaporation could be one interesting alternative for digestate management to reduce the transported volume. The performance of biogas production from FW depends to some extent on local conditions. This study has included a variety of production configurations and system prerequisites, which provides transparent information to stakeholders in the biogas sector so that they can develop efficient and sustainable biogas production systems. It is therefore recommended to evaluate each biogas solution in light of the specific local prerequisites.

This study is a step toward performing more integrative analyses of biogas production from food waste, their environmental and economic performance, and the factors that influence them. In future works, a more in-depth and thorough investigation of the variabilities and uncertainties in these types of production systems can be explored. In addition, other aspects such as a complete financial analysis, or other environmental impact categories, can be included in the analysis. The studied cases were based on a wet digestion process, which have been the most common type in Sweden. However, the interest in using dry AD for the treatment of FW is growing so it will be interesting in the future to perform similar integrative studies on such systems.

CRediT authorship contribution statement

Roozbeh Feiz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Maria Johansson:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Emma Lindkvist:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jan Moestedt:** Validation, Writing – review & editing. **Sören Nilsson Påledal:** Validation, Writing – review & editing. **Francesco Ometto:** Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Three of the co-authors are employed at biogas producing organizations that are included in the studied cases. These organizations are part of the Biogas Research Center (Biogas Solutions Research Center since 2022). The contribution of these co-authors has been made in the spirit of transdisciplinary research and to ensure that the studied cases are represented in a realistic manner. We believe this collaboration has enriched the quality and validity of this paper, and we do not believe it has been affected by any potentially conflicting interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134536.

Abbreviations

AD	Anaerobic digestion
CBG	Compressed (upgraded) biogas
COLLECT	Collection of the waste and extra sorting (if needed)
DISTR	Cleaning and/or upgrading of the gas together with the distribution of biogas, and digestate processing and distribution
FW	Food waste
HVO	Hydrotreated vegetable oil
KPI	Key Performance Indicator
LBG	Liquefied (upgraded) biogas
LCA	Life cycle assessment
LIS	Large inert solids
N	Nitrogen
P	Phosphorus
PE	Primary energy
PRETREAT	Pretreatment of the waste
PROD	Biogas production through anaerobic digestion
PSA	Pressure Swing Adsorption
SOURCE	Generation of waste at households
SUB(FERT)	Substitution of artificial fertilizers by digestate or digestate-based products
SUB(FUEL)	Substitution of fossil fuels by biogas
TAN	Total ammonium nitrogen
TS	Total solids (dry matter)
TWh	Terawatt hour (3.6 x 10^{15} jouls)
USE(BIOFERT)	Storage and spreading of digestate, including soil carbon change

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