Key performance indicators for biogas production-methodological insights on the life-cycle analysis of biogas production from source-separated food waste

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Abstract

The anaerobic digestion of food waste can not only enhance the treatment of organic wastes, but also contributes to renewable energy production and the recirculation of nutrients. These multiple benefits are among the main reasons for the expansion of biogas production from food waste in many countries. We present methodological insights and recommendations on assessing the environmental and economic performance of these systems from a life-cycle perspective. We provide a taxonomy of the value chain of biogas from food waste which describes major activities, flows, and parameters across the value chain with a relatively high detail. By considering the multiple functions of biogas production from food waste, we propose a few key performance indicators (KPI) to allow comparison of different biogas production systems from the perspectives of climate impact, primary energy use, nutrients recycling, and cost. We demonstrate the operational use of our method through an example, where alternatives regarding the heat supply of the biogas plant are investigated. We demonstrate how global and local sensitivity analyses can be combined with the suggested taxonomy and KPIs for uncertainty management and additional analyses. The KPIs provide useful input into decision-making processes regarding the future development of biogas solutions from food waste.

Keywords: biogas, anaerobic digestion, food waste, systems analysis, key performance indicators, life-cycle assessment

Highlights:

- Multi-level and life-cycle-based taxonomy of biogas production from food waste
- Methodological recommendations to improve and complement life-cycle analysis
- Integrating three different functions of biogas production
- Seven key performance indicators to capture multiple functions of biogas production
- A hypothetical example demonstrating the use of our suggested method

1 Introduction

Landfilling is the most common method worldwide for disposal of municipal organic waste [1–3]. The EU's Landfill Directive obliges Member States to reduce the amount of organic municipal waste that is landfilled [4]. Since 2002, the landfilling of organic waste has been forbidden in Sweden, and national targets have been set for increasing the share of biological treatment of food waste. By 2020, at least 50% of food waste (FW) shall be treated biologically with the utilization of nutrients, and at least 40% should be treated to recover both nutrients and energy [5–7]. These goals have led to a significant development of sorting and collection systems for household FW with subsequent biogas production through anaerobic digestion [8]. Biogas production from municipal organic waste allows for both energy and nutrient recovery, and therefore contributes to the development of a biobased economy and moving toward national targets for resource-efficient waste management and reduced environmental impacts [9–11].

Results from studies on the performance of biogas systems can vary significantly depending on the way that the studies are structured, the assumptions, and the employed methods. Hijazi et al. [12] reviewed 15 studies of the life-cycle performance of biogas systems in Europe. Although these studies followed the standards for life-cycle assessment, the authors pointed out the diversity among the studies and concluded that due to varying functional units, the choice of allocation methods and system boundaries, the results from the studies were hard to compare. With the focus on food waste, several studies have assessed the benefits of anaerobic digestion as a technique for treating municipal organic waste [13–17]. Here again, the methods and the results are diverse. Furthermore, Eriksson et al. [18] observed that while there are many system studies on biogas production from municipal organic waste, it is difficult to compare them with each other due to differences in the technological steps, geographical areas, and feedstock (substrate) mixes.

Consequently, it appears that there are three main shortcomings in the existing literature of the life-cycle performance of biogas production. First, system studies of biogas production from FW are based on different terminologies, models, and assumptions. Second, most studies do not consider uncertainties that are typical in biobased processes [19,20], and consequently, their results provide limited insight into the range of variations, uncertainties, and possible improvement potentials. Finally, a common trait in existing systems studies of biogas solutions from FW is that they rarely have an integrative view on environmental and economic performance [21]; e.g., they rarely assess climate impact, energy balance, nutrient balances, and costs using the same terminology and modelling approach. This can lead to compartmentalized, incomparable, and limited conclusions about the performance of the studied systems. These shortcomings are often due to methodological challenges, which invites (over)simplification and reduces the comparability and usability of the results. Some of these challenges are as follows:

- Different cases have distinctive characteristics, configurations, and technologies.
- Different terminologies exist for similar parts of the system, flows and processes. Conversely, sometimes the same terminology is used to name different things.
- Data is gathered from various sources, and if parts of the systems are modelled separately, there is a risk that mass balances are not fully kept across the whole product system. In addition, data gaps, variabilities, and uncertainties that exist in various parts of the system entail a challenge to consider systematically.
- Results of systems analysis can be based on different choices about system boundaries, assumptions, and modelling approaches. If these definitions, choices, and approaches are not clearly expressed, no justified comparisons among different cases can be made.

The aim of our study, considering these issues, is to offer methodological recommendations and an approach for how to improve modeling and simulations with existing LCA methods for analyzing the environmental and economic performance of biogas production from food waste. The novelty of our approach is that we suggest a detailed taxonomy for the main elements, activities and flows in a biogas system, which provides a basis for more comprehensive, transparent, and comparable studies. The suggested taxonomy covers the value chain of biogas production from FW from a life-cycle perspective. In contrast to previous approaches, we structure the production system into several system levels, instead of only categorizing the processes according to their origin or type (energy, transport, material, etc.). Structuring the system in this way makes the approach modular so that it can be easily applied on the whole expanded production system or separate parts of the production. Moreover, we emphasize the importance of maintaining mass flows, including nutrient flows; a practice that is not common in most LCA studies, but is an important aspect of sustainable treatment of organic wastes. Additionally, we suggest and describe specific key performance indicators (KPIs) and performance indicators (PIs) that are connected to actual activities and not only overall aggregated results. Our method and the suggested KPIs take into account the multiple functions of biogas production from FW (waste management, production of a renewable energy carrier, and contribution to nutrient recycling) in order to provide a more encompassing understanding of the performance of such systems. Finally, we show the use of our suggested methodological approach in an example in which we offer recommendations on the use of uncertainty management, sensitivity analysis, and scenario analysis for evaluating the performance of biogas production systems.

Our method is based on typical Swedish biogas production system based on source-separated food waste. A typical Swedish biogas system for source-separated FW is characterized by hygienisation of the waste, a high degree of biogas upgrading to vehicle fuel and digestate treatment to biofertilizer [22]. However, we believe that most of its key elements are relevant to many other types of biogas production systems in the world as we have included a range of process options to choose from, e.g. different configurations of the biogas treatment, different usage options for the biogas, and different treatment methods for the digestate.

2 Methods

Our understanding of biogas production from FW is based on our general knowledge about Swedish co-digestion biogas plants [22], and close collaboration with actors from several Swedish biogas plants. This is reflected not only by the fact that two of the co-authors are experts working in the biogas sector, but also due to our network of collaboration within the Biogas Research Center, which is a Swedish-based center of excellence for developing resource-efficient biogas solutions and includes several biogas and biofertilizer producing companies and many other relevant organizations [23]. The prioritized approach is participatory research which is sometimes referred to as “mode 2 science” [24], in the sense that the domain experts and stakeholders participate in the design and execution of research, and play an active role in the development of the method. Experts from several biogas production plants in Sweden have contributed to the development of our method. We believe that the developed approach is applicable to most industrial-scale biogas plants.

2.1 LCA and mass balance approach

Our approach follows common guidelines and recommendations, as mentioned in the standards for life-cycle assessment (LCA) [25,26]. Activities related to the value chain of biogas and biofertilizer were in the foreground and indirect activities related to the provision of energy and raw materials and their life-cycle impacts in the background.

Our LCA modelling approach is process-based and maintains mass balance across different processes, keeping track of fresh matter, dry matter (in total solids or TS), organic matter (in volatile solids or VS), nitrogen (in total nitrogen or TN, as well as ammonium nitrogen or NH_4-N), phosphorus (in total phosphorus or TP), potassium (in total potassium or TK), sulphur (in total sulphur or TSulf), and carbon (in total carbon or TC). This allows us to have a mass-balanced, integrated, and consistent approach to assessing the performance of biogas production systems.

2.2 The common taxonomy

Unlike traditional LCAs that focus on a functional unit, we decided to keep the approach more flexible and cross-functional. Therefore, we consider a generic "system purpose" as "managing FW and producing renewable fuels and biofertilizers (or related products) through anaerobic digestion." This purpose is more flexible than any particular "functional unit" but encompasses most commonly used functional units such as "treatment of 1 t food waste" or "production and use of 1 MJ biogas as fuel". This does not mean that the studies that follow our taxonomy will lack a functional unit, but that our approach is flexible in the sense that it allows different functional units.

We defined a generic product system to match the above-mentioned purpose of the system. The product system was divided into four levels, each level enclosing the former, and including more processes. We considered the overall value chain of biogas from food waste, referring to all necessary operations that should be performed for the delivery of the produced biogas or biofertilizers to the market. These activities include all inbound and outbound transportation; separation, sorting and collection of food waste; pretreatment and anaerobic digestion; treatment of raw biogas and digestate; and distribution and use of biogas and biofertilizer products.

2.3 Key performance indicators

The performance of biogas production from FW can be viewed from various aspects, so finding performance indicators (PI) is easy. In addition to efficiency of individual processes within the biogas value chain (e.g., the efficiency of pretreatment of food waste), in principle, any of the conventional impact categories of life-cycle impact assessment (LCIA) models such as global warming potential (GWP) or eutrophication potential (EP) can be used as a performance indicator of these systems. However, while these impact categories can be informative and widely used, they tend to be too narrow (in case of the efficiency of a single or a few related processes) or too aggregated (in case of LCIA impact categories) and need to be expressed in terms of a single functional unit. Hence, they are less practical and mask the multiple functions of biogas production. These impact categories can be complemented by a few performance indicators that not only reflect the life-cycle performance of these systems but also are more directly linked to their multiple functions and therefore are more practical with regard to their performance. We refer to such selected indicators as "key performance indicators" (KPIs). The choice of KPIs is partly subjective and depends on the context and purpose of the assessment. In Section 4, we provide a line of reasoning and suggest seven generic KPIs that represent the environmental and economic performance of the biogas production from food waste. These KPIs strongly relate to the purpose of the system, including any of its three main functions, that is, treatment of FW (organic waste treatment), production of biomethane (energy conversion), and production of biofertilizers (nutrient recirculation).

The chosen KPIs represent important aspects related to the performance of the studied biogas production system which can be used for in-depth study of a production system or comparisons among different production systems. In general, they can contribute to improved reporting, benchmarking, and decision making for continuous improvement in relation to an existing production system, a new production system, or forthcoming changes in an existing production system. These KPIs have overlaps with the conventional PIs (e.g. KPI_2 is based on GWP) and, they should be viewed as complementary to the conventional PIs in LCA or other methodologies. For simplicity, we strived to limit the number of KPIs to seven, but by using the same approach, one can use many more performance indicators (PI), depending on their relevance to a specific case.

2.4 Uncertainty management

Uncertainties can occur due to lack of knowledge, inherent variations, or deliberate choices regarding different technological options or pathways. Assuming that we have made a model that has established a deterministic link between the input parameters and the outputs, the uncertainties that can be parametrically expressed can be propagated by global sensitivity analysis, namely by using stochastic methods such as Monte Carlo simulations [27]. These methods can be useful in situations where there are many uncertain parameters and we want to propagate their collective effect on the results.

Uncertainties due to deliberate choices that can alter the structure of the system, e.g., choice related to certain technologies or treatment pathways, can be demonstrated by defining qualitatively different scenarios and comparing the performance of these scenarios against each other. If the differences among the scenarios can be parametrically expressed by a single or a few parameters, scenario analysis can be facilitated by using local sensitivity analysis methods, e.g., by progressively varying a defining input parameter and observing the changes in the results.

In this paper we, via an example, show how these approaches to uncertainty management can be incorporated for evaluating the performance of biogas production systems.

3 The common taxonomy and system models

A conceptual overview of the main activities and processes to produce biogas from source-separated municipal FW is depicted in the "foreground system" portion of Figure 1. Transportation activities and most of the products and elementary flows are not shown to simplify the diagram. Nevertheless, all processes that are relevant from a life-cycle perspective are bundled in the background system.

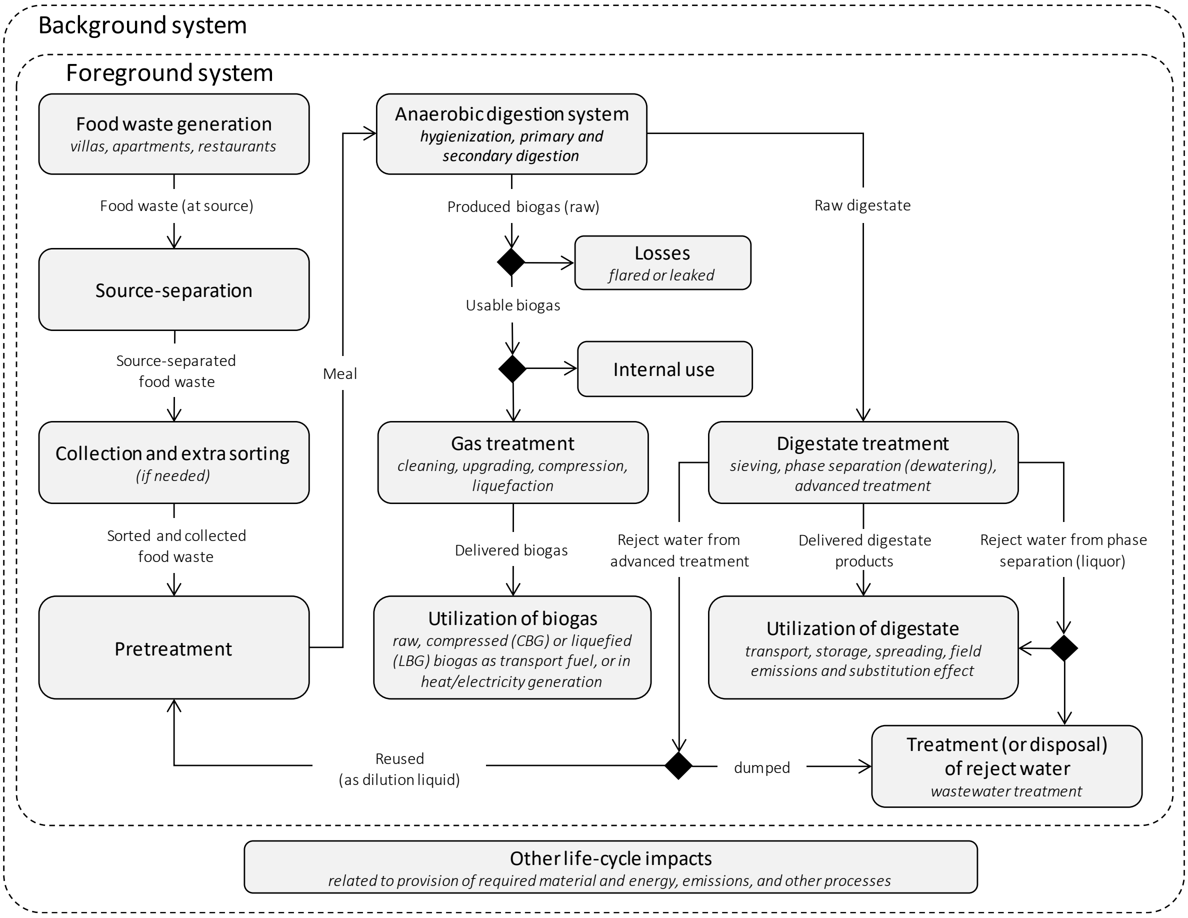

Figure 1. *Overview of the main activities and processes to produce biogas from source-separated municipal food waste (foreground system), and other relevant life-cycle impacts (background system)*

We have grouped the activities and processes required to produce and deliver biogas and biofertilizer from FW into four system levels ($L_{1–4}$) (Figure 2). The depicted processes cover a generic biogas production system, but not all processes are necessarily present in every biogas production system. In addition, in order to make it easier to define system boundaries of the study in a modular way, we have defined a few sub-levels for each of the levels. These levels are like matryoshka dolls, each wrapped within the upper level.

Level 1, "L_1: biogas plant", contains activities related to anaerobic digestion, gas treatment, and digestate treatment. Pretreatment, hygienisation, anaerobic digestion and post digestion, and biogas treatment (i.e. cleaning, upgrading, compression and liquefaction) are grouped under the sublevel L_{1a}; and digestate treatment, i.e. sieving, phase separation (such as dewatering), and advanced treatment (such as drying by evaporation) are grouped under the sublevel L_{1b}. Level 2, "L_2: extended biogas plant", contains activities mentioned in L_1, but also all transportation to and from the biogas plant: the transportation of feedstock, that is, the collected FW to the biogas plant (L_{2a}), the transportation of digestate (or various biofertilizer products) to farms (L_{2b}), as well as the distribution of biogas (L_{2c}). Collection of FW is placed in Level 3 because it is typically a municipal service and in the upstream of the biogas plant. We define the extended biogas plant (L_2) from the point that the FW is already collected.

Level 3, "L_3: Biogas production system", includes $L_{1–2}$, and the upstream processes that are required for the provision of feedstock (i.e. FW), and downstream processes related to the utilization of the products. Provision of FW including source separation, sorting and collection of FW is placed under (L_{3a}); wastewater and rejects management (L_{3b}); the utilization of digestate as biofertilizer or in other soil applications including storage, spreading, and field emissions (L_{3c}); and the utilization of biogas as fuel, heat and/or power generation, or other applications (L_{3d}). Finally, Level 4, "L_4: Biogas production system plus substitution effects", includes $L_{1–3}$ (or L_{1-2} and selected parts of L_3) and the effects associated with substitution of fossil fuels, mineral fertilizers, or other products by biogas and digestate. In the standard LCA method [25,26], this implies using a "system expansion" to consider the potential impact of the delivered products. Here also, sub-levels are used to allow different ways of considering the system expansion in the study: system expansion related to the substitution of mineral fertilizers and other products (L_{4a}), and system expansion related to the substitution of fossil fuels (L_{4b}).

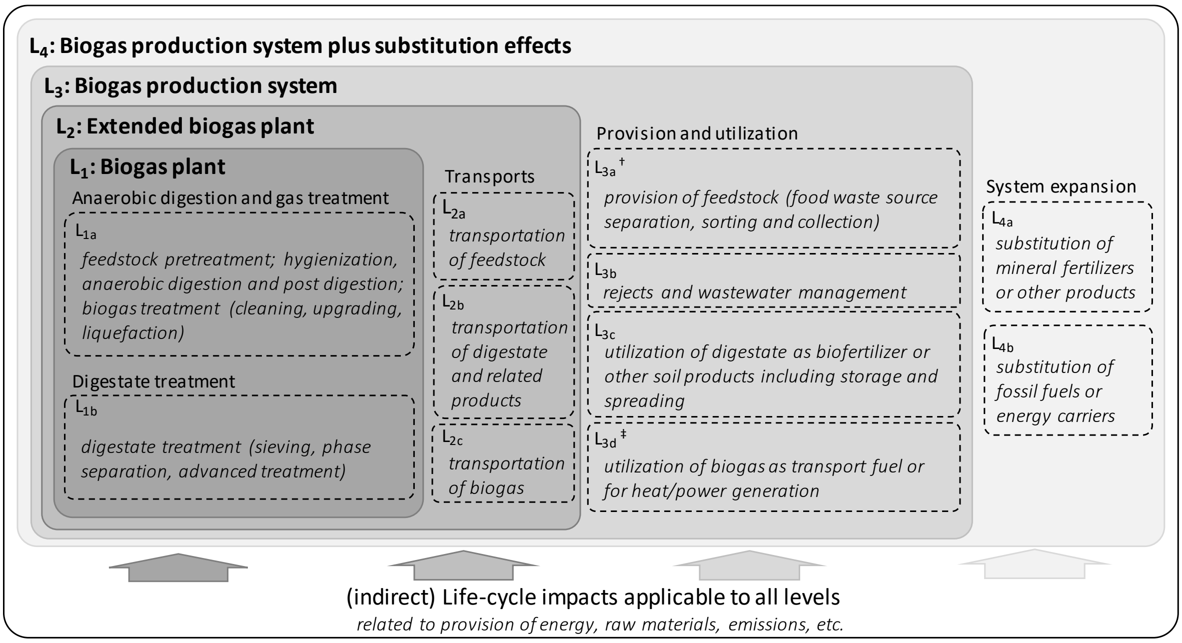

Figure 2. *Grouping of activities and processes for producing biogas from food waste into four system levels.*
† *In case of food waste, L_{3a} is often a municipal service that will occur regardless of biogas production. Only the activities that are specifically performed to make the collected food waste more suitable for biogas production could be included.*
‡ *If the functional unit of the study (or any specific KPI) is based on the methane delivered (e.g., in a well-to-tank study), the utilization of biogas (L_{3d}) could be excluded from the scope.*

Depending on the aim of the performance evaluation, systems analysis can focus on each of these levels. L_1 and L_2 are useful for plant operators to gain a better understanding of the impacts and costs associated with activities that are close to them. The difference between L_1 and L_2 reflects transportation activities, which is typically of importance in biogas systems due to the handling of large volumes of materials, both inbound and outbound. L_3 and L_4 are useful for considering the full scope of the system from a life-cycle perspective. The distinction between L_3 and L_4 allows for discussing the performance of the system with or without assumptions about system expansion. Sub-levels in $L_{1–4}$ allow system levels to be defined in different ways: e.g., if the purpose of the study is to compare the performance of the produced biogas with that of a fossil-based energy carrier, one may exclude L_{4b} (and possibly L_{3d}); or, as noted earlier regarding the FW, municipal services that occur regardless of biogas production could be excluded. For example, L_{3a} could be adapted to include only the activities that are specifically performed to make the collected FW more suitable for biogas production.

We emphasize that this grouping of activities is done on the value chain of biogas from FW, and the scope of the analysis decides which system level to study. However, regardless of the choice of the system level, one should consider the processes in the background system, e.g., the electricity used in the biogas plant (L_1) and its associated life-cycle impacts.

3.1 Characterizing the food waste

Source-separated food waste (FW) is the part of municipal organic waste that originates from households, restaurants, hotels, and catering services. It does not include the organic wastes that end up in wastewater treatment systems, nor does it include waste originating from gardens and food processing industries. FW is separated by the end consumer before it is collected. Depending on the collection system, source-separated FW may require sorting in specialized facilities.

The composition of source-separated FW can vary seasonally, and also from country to country depending on food culture [28–30]. Moreover, the collection system can significantly affect the composition of the collected FW. Therefore, it is important that the composition used as input to the model is representative of the region or country in which the biogas productions system is situated. Average annual figures can be used to overcome seasonal variations.

If measurement of the composition of FW is performed on the sorted and collected FW (see Figure 1), compositions of FW before collection and extra sorting (source-separated FW in Figure 1), and before source separation (FW at source in Figure 1) can be estimated by back calculation. The following information is relevant for the characteristics of the FW:

- dry matter content or TS (% of fresh weight);
- organic matter content or VS (wt% of TS);
- large inert solids or LIS, defined as visible impurities that should be removed in pretreatment (wt% of TS);
- biochemical methane potential or BMP (Nm^3 CH_4/t VS);
- share of methane in the produced biogas (vol%); and
- nutrient contents including total nitrogen content or TN (kg N/t), ammonium content (%NH4-N/TN or kg NH_4-N/t), total phosphorus content (kg P/t), total potassium content (kg K/t), total sulphur content (kg S/t), and total carbon content (kg C/t).

3.2 Source separation, sorting, and collection

We consider two main systems for the source separation and collection of FW from households in Sweden (Figure 3). In the first system, household members manually sort FW into biodegradable bags, typically made of paper, and place it inside a designated garbage bin, or a bin with a designated compartment for FW. The bins are collected, and since they only have sorted FW, they are directly sent to a pretreatment plant. In the second system, the household members manually sort FW into tinted bags, made of plastic or biodegradable materials, and place it inside a mixed bin along with other types of wastes. The bins are collected, but since they have mixed bags, they are first sent to an extra sorting facility where the tinted bags are separated from other bags via optical sorting, and the sorted bags are sent to a pretreatment plant.

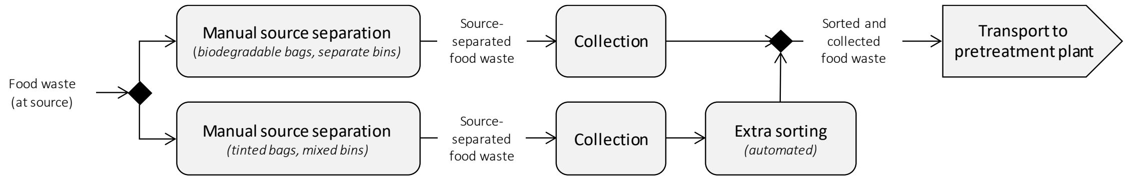

Figure 3. *Process flow of the source separation, sorting, and collection of food waste*

For modelling the collection of FW from restaurants, a system that resembles the first system can be used: FW is collected in separate bins and is sent to a pretreatment plant. Note that the composition of FW from restaurants can be different from that of households.

3.3 Pretreatment

The sorted and collected FW is transported to a pretreatment plant, which may or may not be in the same location as the biogas plant. Pretreatment involves the removal of impurities and unrequired fractions such as metals, glasses, plastics, or other materials unfit for anaerobic digestion, which are here referred to as large inert solids (LIS). The rejects, depending on their characteristics, can be sent to a landfill, an incineration plant, or another recycling facility (Figure 4). It is clear that if the purpose of study is to have a better picture on how these activities are performed, more detailed process flows, and sublevels can be defined.

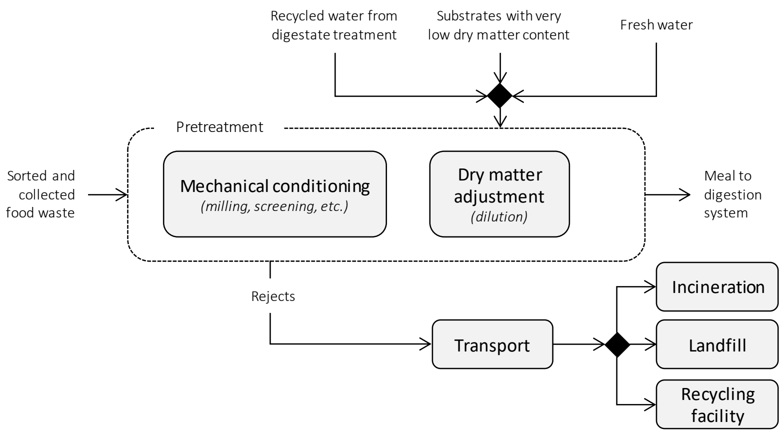

Figure 4. *Process flow of pretreatment of the sorted and collected food waste*

Pretreatment may involve dry matter adjustment by diluting the FW with fresh water, recycled water from the treatment of digestate, or other types of thin substrates. The result is the meal (in wet processes, the meal is in the form of a pumpable slurry) which is fed to the digestion system (Figure 4).

3.4 Digestion system

The meal is anaerobically digested (including secondary digestion if present), and biogas and digestate are produced. Depending on the national regulations, the meal may require passing through a hygienisation step. Due to real-world conditions, the biogas yield does not reach the yield from lab tests. This can be modelled by considering a parameter for the efficiency of degradation under real conditions and setting this parameter to, e.g., 70% or 90%. The heat demand of the digestion system depends on several factors, including the working temperature of the digesters, which is commonly around 35 °C for mesophilic systems and about 55 °C for thermophilic systems; the ambient temperature that can vary depending on the climate and season; the temperature of the received meal; and the thermal efficiency of the design so that more heat is reused and less heat is lost. After considering losses and flaring, the rest of the biogas (usable biogas) can be used for internal or external demand (Figure 5).

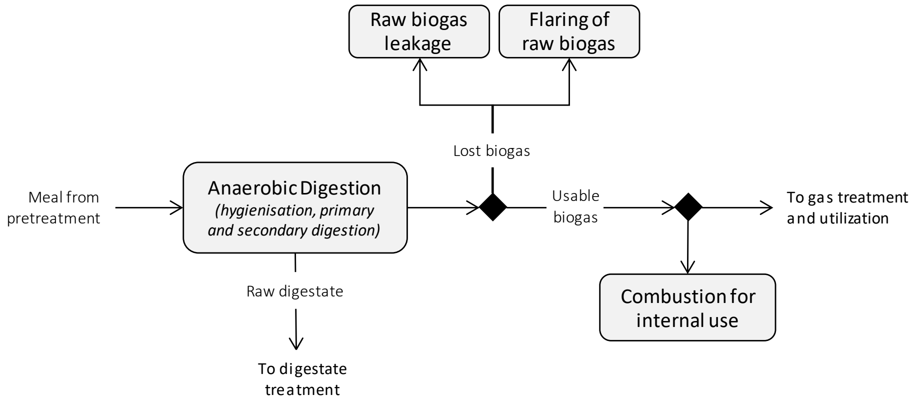

Figure 5. *Process flow of digestion system including hygienisation, and primary and secondary digestion*

A mass balance should be kept before and after the digestion system. The mass of the produced digestate can be estimated by removing the mass of the produced raw biogas and leakages from the meal input. For heating, the plant may use some of the biogas it has produced. Alternatively, it may rely on external sources such as fuels (fossil or biofuels) or district heating (Figure 6).

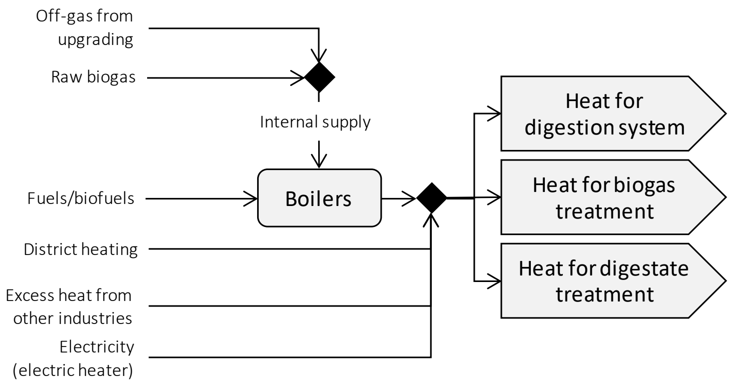

Figure 6. *Process flow of the heat system of a biogas plant, biogas treatment, and digestate treatment*

3.5 Biogas treatment and utilization

The produced raw biogas has substantial amounts of carbon dioxide and some impurities. Raw biogas can be used for heat and/or electricity production, but a customary practice in Swedish large-scale biogas plants is to upgrade it to about 97% methane content to allow it to be used for other applications as well. After upgrading, biogas can be distributed by low-pressure regional pipeline, or it can be compressed or liquefied to allow longer distance transportation. Upgraded biogas can be used in almost any applications as a substitute for natural gas. In Sweden, it is common to use the upgraded biogas as transportation fuel for buses or other vehicles (Figure 7). For modeling biogas utilization its performance can be compared to that of the alternative systems (often a fossil-based reference); e.g., use of biogas as vehicle fuel compared to diesel.

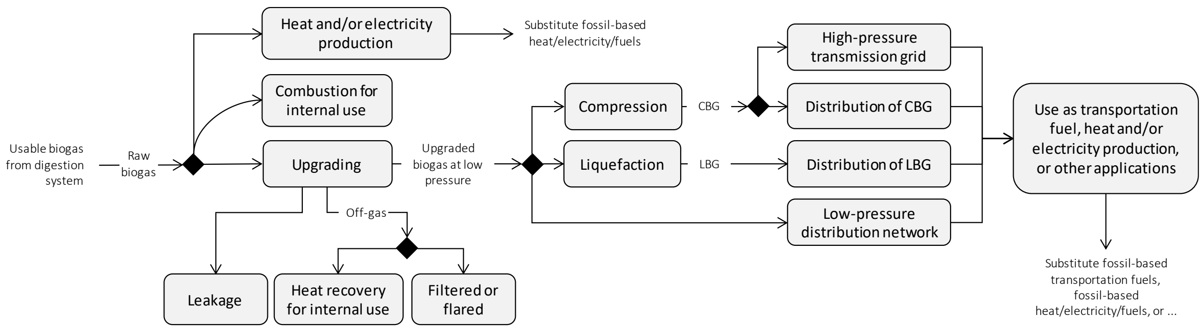

Figure 7. *Process flow of the biogas treatment, including upgrading, compression, and liquefaction. CBG: compressed biogas, LBG: liquefied biogas, off-gas: gaseous "rejected" stream from the upgrading unit, containing mainly carbon dioxide, but a bit of methane as well.*

3.6 Digestate treatment and utilization

The produced raw digestate contains most of the macronutrients received in the meal but is commonly very bulky due to high water content. Figure 8 shows a flowsheet of the digestate treatment and utilization. The impurities can be reduced by passing the raw digestate through a sieve. Digestate can then be transported to farms and used as biofertilizer as it is, or it can go through more treatments to produce less bulky products. Part (or all) of the digestate can go through phase separation (solid-liquid separation, solid removal, etc.) as the primary treatment step, where cake (solid fraction) and liquor (liquid fraction) are produced. The cake can be used as biofertilizer, can be treated by other means such as composting, drying, or incineration, or can be used as landfill cover. All or part of the liquor may be used as biofertilizer, further treated, or (in rare cases) disposed of or dumped in a municipal wastewater treatment system. Liquor can go through advanced treatment techniques such as evaporation, stripping, precipitation, and so on, where two or possibly three main fractions are produced: (1) the concentrated liquid which contains nutrients and can be used as biofertilizer; (2) the rejected water (condensate in case of evaporation), which is relatively clean and can be used as a substitute for fresh water in the pretreatment; and (3) possibly, some solids that can be used as biofertilizer or mixed with other products.

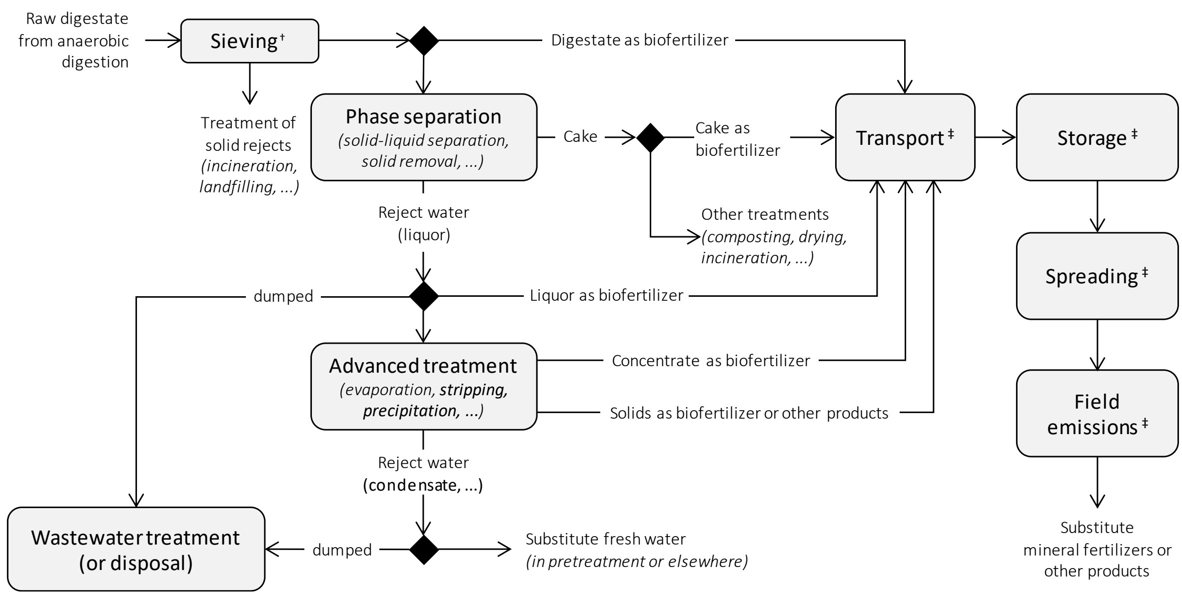

Figure 8. *Process flow of digestate treatment, including phase separation and secondary treatment*

† *Sometimes sieving is performed after phase separation.*

‡ *For simplicity, "transport, storage, spreading, and field emissions" are shown in common boxes regardless of the type of biofertilizer product. In effect, each of these activities should be modelled corresponding to the type of biofertilizer product.*

In addition to the above processes, the utilization of the biofertilizer products depends on their substitution rate with mineral fertilizers (or other conventional soil products). For example, it can be assumed that 100% of the total ammonium nitrogen in the biofertilizer product can substitute the equivalent amount of mineral nitrogen fertilizer.

3.7 Other processes and required parameters

Regardless of the type of transportation or distribution of the FW, digestate, and biogas, these activities can be modelled by considering the type and amount of fuel used (MJ/t-km), electricity use (MJ/t-km) if relevant, losses (%), and costs. With regard to other processes, depending on the type of the studied system, knowledge about the environmental impacts and cost of processes such as incineration, wastewater treatment, use of upgraded biogas as transportation fuel, use of biogas for heat and power generation, substitution of mineral fertilizers by different types of biofertilizers, and substitution of diesel or other fossil fuels by biogas may be required, or otherwise, their impacts should be modelled. In order to model the above-mentioned parts of the system, certain parameters and information are required. Some of these parameters for the main parts of the system are listed in the supplementary materials.

4 Key Performance Indicators

As mentioned before (see Section 2.2), biogas production from FW can be viewed as a system that can have any (or all) of the following functions: waste treatment, renewable energy conversion, and nutrient recirculation. Correspondingly, the performance of biogas production from FW can be linked to energy balance, nutrient recycling potential, and resource- and cost-efficiency of the FW degradation. Moreover, since biogas production is typically seen as a contributor to climate change mitigation, it is relevant to consider its performance from the perspective of life-cycle greenhouse gas emissions. Additionally, the life-cycle cost can be considered, as most biogas producers find it crucial to decrease the cost of their production system. Consequently, we consider the following performance areas as the basis for selecting and defining the KPIs: biomass utilization and degradation, climate change mitigation, energy balance, nutrient recirculation, and cost.

4.1 Biomass utilization and degradation

Biomethane is often the main products of biogas production systems, so methane yield is a relevant and important performance indicator (PI). However, depending on the adopted system level, the different PIs based on methane yield can be defined. If we focus on the meal, the lab-based estimation of the biochemical methane potential (BMP) is the upper limit, but in practice and under continuous production a fraction of this upper limit can be achieved, e.g. 70–90% of the BMP, which can be referred to as specific methane potential (SMP). If we consider a wider system perspective, e.g., instead of the methane yield of the meal, focus on the methane yield of the received FW at the pretreatment plant, we will have a lower estimate, because some organic materials are lost during pretreatment (Figure 9). Similarly, if we remove from the gross methane production the losses and biogas that is used for internal use, we will get a smaller yields, that is, net methane yield.

Here, we consider the whole biogas production system (delivered biomethane produced from FW at source) to define our first key performance indicator: *effective methane yield* of food waste (KPI_1) (see Figure 9 and Table 1).

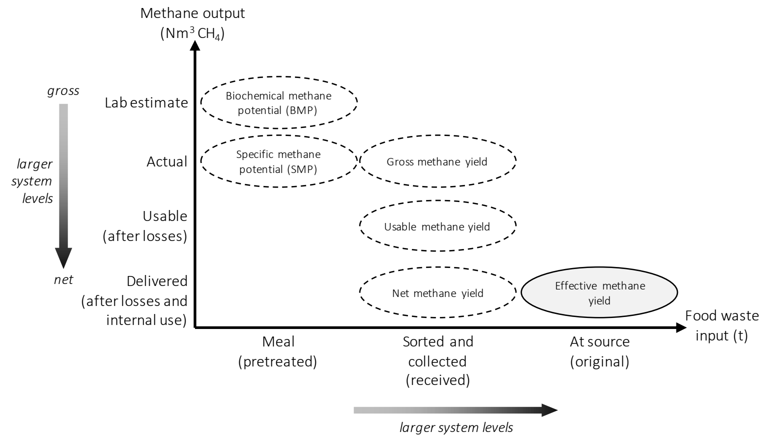

Figure 9. *Different ways of defining "methane yield" depending on the adopted system level*

In KPI_1 (and other relevant KPIs such as KPI_3), the "delivered biomethane" corresponds to any usable biomethane that is left, after losses and internal uses are excluded; so the physical form of the delivered biomethane is not pertinent and the biomethane can e.g. be in the form of raw or upgraded biogas, or in compressed or uncompressed form. KPI_1 includes degradation efficiency and other inefficiencies across the biogas production system. Degradation efficiency in itself can be viewed as a narrower performance indicator (PI).

4.2 Climate change mitigation

Climate change mitigation is closely related to life-cycle greenhouse gas emissions of the system and is sometimes referred to as global warming potential or carbon footprint. Depending on the aim of the system study and the adopted method, one can define different PIs for climate mitigation. For example, we can calculate the *climate impact of the delivered biomethane* in *g CO_2-eq/MJ* and the LCA method defined by EU RED which demands energy allocation instead of system expansion [31,32]. This would mean to include processes within system level L_3 but exclude processes related to digestate management (L_{3c}). If instead we adopt the standard LCA approach which recommends system expansion [25,26], we can consider L_4 system level excluding the substitution effect of using the biogas (L_{4b}), and define a PI as *climate impact of the delivered biomethane (ISO)*.

Here we consider the whole biogas production system including the substitution effects of utilizing the biogas and the digestate and define the second key performance indicator as *climate impact* of treating food waste through biogas production (KPI_2) (see Table 1).

4.3 Energy balance

To indicate the energy performance of biogas production from FW, we can contrast the amount of energy that is generated and delivered in the form of biomethane or biogas with the amount of primary energy that is used in order to generate and deliver that energy [9]. This notion is closely related to concepts such as *primary energy factor* or *PEF* [33] as well as *energy return on investment* or *EROI* [34,35]. We adopt a wide system perspective (L_4) that includes the substitution effect of utilizing the digestate (L_{4a}), but we do not include the use of biogas (L_{3d}) and its substitution effect (L_{4b}) since biogas is what we are considering here as the output of the bioenergy production system. One can of course define this KPI differently, e.g., to include the utilization step as well. Since the utilization of biogas/biomethane can be diverse (heat, cooling, electricity, fuel in different types of engines and in different application, etc.) we prefer to define this KPI based on the "delivered biomethane"; as define in Figure 1. Moreover, we do not include the original energy content of the FW itself, since here we consider it as an otherwise wasted resource. We define the third key performance indicator as *energy balance* of the delivered biogas from food waste (KPI_3) (see Table 1).

If required, other energy-related PIs can also be defined. For example, one can adopt a narrow system perspective (e.g. L_1 or L_2) and separately estimate the electricity, heat, or fuel use of the delivered biomethane.

4.4 Nutrient recycling potential

Digestate contains macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) required for plant growth, and the utilization of digestate and biofertilizer products in agriculture is one way of recycling (or reusing, or recirculating) them. Instead of using mineral fertilizers, crops can gain all or part of their nutrient demand from these products. Since we want to keep the number of KPIs low, we focus on two main macronutrients: total nitrogen (TN) and total phosphorus (TP). Theoretically, we would like to deliver all the nutrient content of the FW as biofertilizer in plant-available form and with minimum losses, considering a wide system perspective (L_3). Since the actual utilization rate of these nutrients by crops is region- and crop-specific, we focus on the potential recycling, defined as nutrients that are spread on land (excluding field emissions and crops uptake). Hence, the fourth and fifth KPIs are defined as *nitrogen recycling potential* (KPI_4) and *phosphorus recycling potential* (KPI_5) (see Figure 10 and Table 1).

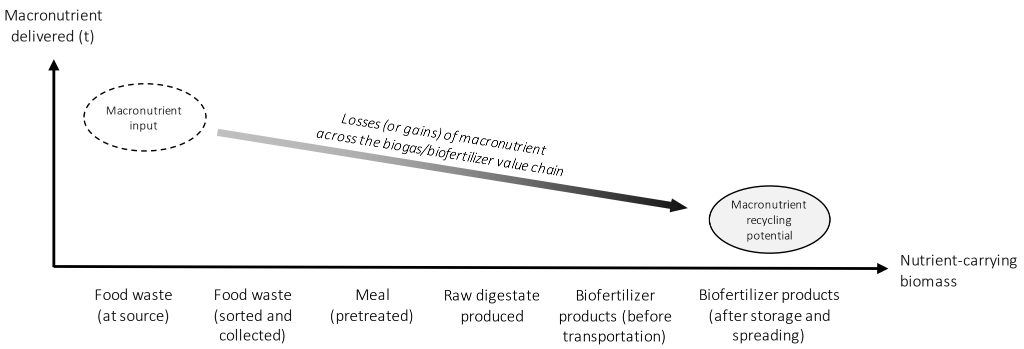

Figure 10. *Macronutrient input (in food waste) and its potential recycling through the treatment and utilization of digestate-based biofertilizers*

Anaerobic digestion increases the ammonium nitrogen content of biomass through mineralization of its organic nitrogen [36]. Ammonium nitrogen is plant-available form of nitrogen and can substitute mineral nitrogen fertilizers. Therefore, we define the sixth KPI as *enhancement of plant-available nitrogen* (KPI_6) (see Table 1).

Consequently, KPI_4 and KPI_5 are about resource preservation, while KPI_6 is about resource valorization (converting organic N to inorganic N). Both aspects are important features of the AD systems.

4.5 Cost

Our purpose for estimating the cost-performance of biogas production from FW is not to provide a full financial analysis that covers aspects such as investment, administration costs, context-specific fees, or revenues. Instead, we focus on the costs related to the used resources and services such as transportation and waste treatment, across the full value chain of biogas and biofertilizer production from FW. We consider a wide system perspective (L_3) and define the seventh (and last) KPI as *resource cost* of treating food waste through biogas production (KPI_7) (see Table 1).

When studying different parts of the system, one can add other PIs to include aspects such as investments and revenues in order to complement the KPI_7.

A list of the abovementioned KPIs is presented in Table 1.

Table 1. Summary of the selected KPIs for biogas and biofertilizer production from food waste (or treatment of food waste through anaerobic digestion)

No.	KPI Name	Unit	System level and sub-levels
KPI_1	Effective methane yield [a]	Nm^3 CH_4 (delivered) / t (food waste at source)	L_3 excluding L_{3d}
KPI_2	Climate impact [b]	kg CO_2-eq / t (food waste at source)	L_4
KPI_3	Energy balance [c]	MJ (primary energy used) / MJ CH_4 (delivered)	L_4 excluding L_{3d} and L_{4d}
KPI_4	Nitrogen recycling potential [d]	kg N (delivered) / kg N (food waste at source)	L_3 (after spreading on field)
KPI_5	Phosphorus recycling potential [d]	kg P (delivered) / kg P (food waste at source)	L_3 (after spreading on field)
KPI_6	Enhancement of plant-available nitrogen [e]	kg NH_4-N (delivered) / kg NH_4-N (food waste at source)	L_3 (after spreading on field)
KPI_7	Resource cost [b]	Euro / t (food waste at source)	L_3

[a] Higher values mean better performance.

[b] Lower values mean better performance.

[c] Lower values mean better performance; expected to be ≤ 1.
[d] Higher values (closer to 1) mean better performance.
[e] Higher values mean better performance. Value is expected to be higher than 1, because anaerobic digestion increases total ammonium nitrogen (TAN).

5 Example of a model biogas production system

We demonstrate the operational use of our suggested approach, taxonomy, and key performance indicators via applying them on a (hypothetical) model biogas production system. The purpose of this example is not to provide all detailed information about the modeling of biogas production systems, but to briefly sketch out the expected results from the presented approach. We show selected results based on the suggested KPIs and in different system levels, and also perform local and global sensitivity analysis (uncertainty analysis) to illustrate the versatility of our approach.

Most of the assumptions and operational conditions for this model biogas production system are drawn (with some adjustments) from Swedish studies, but we have also assumed a few of the parameters based on our own experience of biogas production systems. To demonstrate how the aforementioned approaches to uncertainty management can be incorporated for evaluating the performance of biogas production systems, we have introduced several uncertain parameters by providing simple min-max intervals. We use these intervals for stochastic analysis by Monte Carlo simulation. The parameters are expresses as either fixed, e.g. x=5; single interval, e.g. x=3–7 or x=5 (3–7) and assuming double triangle distribution; or double interval (the typical range, and the extreme range), e.g. x=5 (3–7; 2–10) assuming a trapezoidal distribution. Since the underlying information about these parameters are sparse, we have adopted a generally fuzzy approach to these uncertain parameters [27].The results are expressed in intervals covering 99% of the variations of the collected values from the output of Monte Carlo iterations.

Our model biogas production system receives 25000 of sorted and collected FW in biodegradable bags. Detailed information about the system and the assumptions can be found in the supplementary materials, mostly drawn from biogas literature [10,29,30,36–46,46–54]. The anaerobic digestion is assumed to be a wet mesophilic system, including a hygienization step. Approximately 4 million Nm^3 of biogas is produced. Some of the produced biogas is used for internal heating, but the main part is upgraded and compressed to 250 bars and then transported to costumers located at a 50 km distance. Around 46000 t of digestate is produced and transported to farms and used as biofertilizers. The average transportation distance is 20 km.

When system expansion is used, the NPK content of the digestate are assumed to replace mineral fertilizers in which N corresponds to the total ammonium nitrogen (TAN); and the biomethane is assumed to be a substitute for diesel (see Table 2).

Table 2. *Climate impact, primary energy factor, and cost of mineral fertilizers and diesel fuel in the system expansion*

Item	Climate impact (kg CO_2)	Primary energy use (MJ-eq)	Cost (Euro)
1 kg N fertilizer (substitutable by 1 kg TAN in digestate)	6.7 [a]	48 [a]	0.9 [b]
1 kg P fertilizer (substitutable by 1 kg P in digestate)	3.2 [a]	19 [a]	1.7 [b]
1 kg K fertilizer (substitutable by 1 kg K in digestate)	0.9 [c]	19 [c]	0.6 [b]
1 MJ diesel (substitutable by 1 MJ biomethane delivered)	0.091 [a]	1.2 [a]	0.03 [a]

[a] [10]
[b] [55]; calculated based on Yara N27, P20 and K50 products
[c] EcoInvent database version 3

The results of assessing the performance of the system represented by the seven KPIs and the propagated uncertainties (global sensitivity analysis) are shown in Table 3.

Table 3. *Performance of the model biogas plant expressed in selected KPIs, including the propagation of parametric uncertainties via Monte Carlo simulation*

KPI_1	KPI_2	KPI_3	KPI_4	KPI_5	KPI_6	KPI_7
Effective methane yield	Climate impact	Energy balance	Nitrogen recycling potential	Phosphorus recycling potential	Enhancement of plant-available nitrogen	Resource cost
(Nm^3/t)	(kg CO_2-eq/t)	(MJ/MJ CH_4)	(kg/kg)	(kg/kg)	(kg/kg)	(Euro/t)
210 (179 – 242)	-104 (-137 – -71)	0.75 (0.65 – 0.87)	0.75 (0.73 – 0.77)	0.82	4.7 (4.3 – 5.1)	6.4 (-4.6 – 15)

KPIs are very aggregated parameters, but they can also be presented in detail. For example, the contribution of various parts of the value chain of biogas to each KPI can be separately shown. Here, we exemplify this by presenting more details about KPI_2, KPI_3, and KPI_7 in Table 4.

Table 4. *Performance of the model biogas plant expressed in selected KPIs and breakdown of the impacts across the value chain*

Stage in value chain → KPI ↓	Food waste (at source)	Food waste (sorted and collected)	Meal	Biogas and digestate produced	Biogas and digestate delivered	Digestate use (Including substitution effects)	Biogas use (Including substitution effects)	Overall sum
KPI_2 (kg CO_2-eq/t)	0	19 (17 – 22)	1	25 (21 – 29)	5 (4–6)	20 (0 – 42)	-174 (-207 – -143)	-104 (-137 – -71)
KPI_3 (MJ/MJ CH_4)	0	0.26 (0.22 – 0.32)	0.11 (0.08 – 0.15)	0.20 (0.14 – 0.28)	0.25 (0.24 – 0.27)	-0.07 (-0.09 – -0.06)		0.75 (0.65 – 0.87)
KPI_7 (Euro/t)	0	35 (35–36)	6	13	17 (15–18)	-2 (-2 – -1)	-63 (-75–-51)	6 (-5 – 15)

Furthermore, whenever needed, these KPIs can be compared with other performance indicators (PIs). For example, consider KPI_1 or the "effective methane yield" with the mean value of 210 Nm^3 CH_4/t VS, and compare it with the PIs that are introduced in Figure 9: "net methane yield", "usable methane yield", "gross methane yield", "specific methane potential", and "biochemical methane potential" with estimated values of 311, 333, 350, 368, and 461 Nm^3 CH_4/t VS respectively.

The results of the KPIs—or any relevant performance indicator (PI)—can also be expressed in terms of the contribution of each system level, as defined in Figure 2. In Figure 11, we can see the contribution of different system levels for the KPI_2. These results are based on mean values collected from global sensitivity analysis.

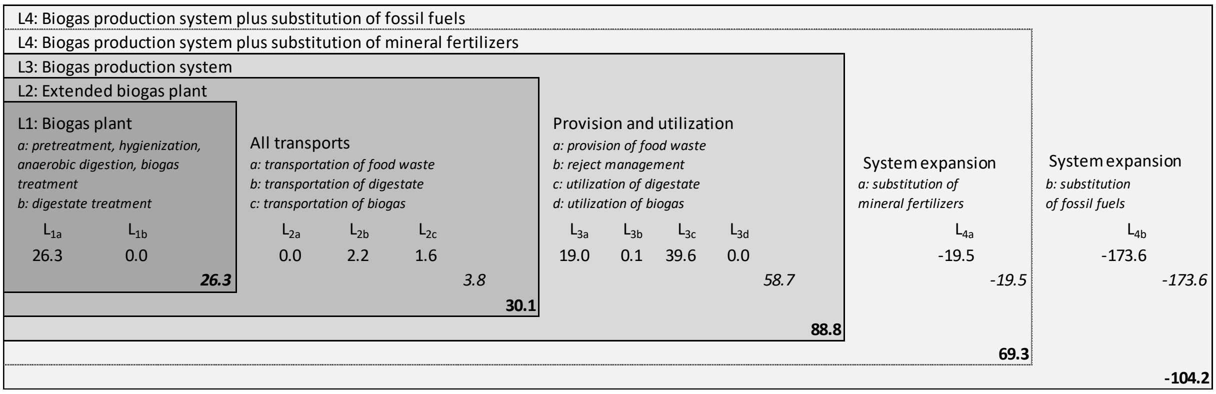

Figure 11. Contribution of different system levels to the climate impact of producing biogas from food waste (KPI_2 in kg CO2-eq/t food waste at source

Local sensitivity analysis can be used to learn more about the studied system and investigate other types of questions about it. Assume that we want to investigate the effect of the heat supply on the performance of this biogas production system, particularly on the climate performance (KPI_2), energy balance (KPI_3) and cost (KPI_7). In addition to the reference situation—described above—in which the biogas plant used its own biogas for heating (burner), we define a few alternative scenarios regarding the external sources of heat or heating fuel for the biogas plant. These scenarios include using natural gas (burner), biomass (burner), district heating (average in Sweden), district heating (waste-based), district heating (natural gas) and heat from residual heat from nearby industries assuming the possibility of industrial symbiosis [56]. We note that these scenarios can be parametrically modeled: we take the environmental impact or cost of the heat supply as a parameter and based on that calculate the key performance indicators. Since we are focusing on KPI_2, KPI_3, and KPI_7, we need to incorporate the climate impact (carbon footprint), primary energy (primary energy factor), and cost of obtaining each of these heat sources (Table 5).

Table 5. *Climate impact, primary energy factor, and cost of different heat sources in Sweden; and the corresponding KPIs calculated by performing a local sensitivity analysis of the heat supply of the biogas plant.*

Scenario, heat source	Impact or cost of heat supply			KPIs of biogas production system (based on local sensitivity analysis on the heat supply)		
	Climate impact (kg CO_2/GJ heat)	Primary energy factor (PEF)	Cost (Euro/GJ)	KPI_2 (kg CO_2-eq/t)	KPI_3 (MJ/MJ CH_4)	KPI_7 (Euro/t)
Heat from own biogas (gas burner)	0 (77) [a]	0 (0.57) [a]	0 (28.2) [a]	-111	0.73	5.7
Heat from biomass (pellet burner)	9 [b]	1.5 [b]	6.5 [c]	-121	0.79	2.5
Heat from district heating (natural gas)	83 [b]	1.3 [b]	32.7 [c]	-111	0.78	6.3
Heat from district heating (average)	17 [b]	0.9 [b]	8.3 [c, d]	-120	0.76	2.7
Heat from district heating (waste-based)	35 [b]	0.8 [b]	6.9 [c, d]	-117	0.75	2.5
Heat from industrial waste heat	13 [b]	0.1 [b]	1.4 [e]	-120	0.70	1.7

[a] There is no direct environmental impact or cost associated with the use of own biogas for heating. However, using own biogas also has some virtual environmental impacts and costs due to the opportunity cost or indirect impact (because it is not used to replace fossil alternatives). This virtual impact/cost of using own biogas can be viewed in brackets (based on results).
[b] [57]
[c] [10]; assuming 85% boiler efficiency, and 20% extra cost for delivering district heating from a fuel.
[d] [58]
[e] Based on the price of excess heat in Linköping at summer which can be as low as 0.005 Euro/kWh.

For each of the KPIs (KPI_2, KPI_3, and KPI_7), we perform a local sensitivity analysis, varying a parameter related to the heat supplies: “climate impact of the heat supply”, “primary energy factor of the heat supply”, and “cost of the heat supply”. The range of variation is selected wide enough to cover all the scenarios (types of heat supplies in Table 5); but since we assume a linear response from the model, other types of heat supplies—in addition to those scenarios—can also be matched against the results of the local sensitivity analysis. The results are shown in Table 5 (last three columns). We can also look at these results visually, e.g. by showing the variations in KPI_2 based on changes in the climate impact of the used heat supply (Figure 12).

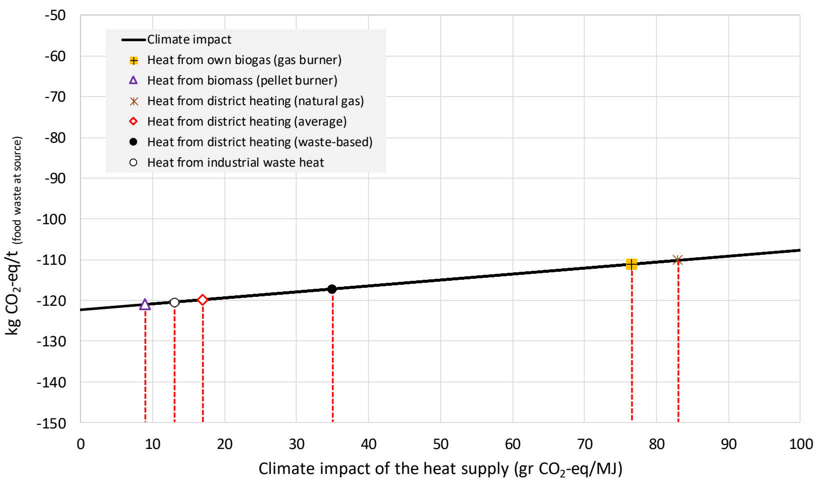

Figure 12. Effect of heat supply on climate impact of treating food waste through anaerobic digestion (KPI_2)

Based on these results, we can discuss the question of heat supply using different logics, especially if we contrast them against the reference situation, that is, using its own biogas. But first, we should note that the environmental impacts of using “own biogas” can have a special meaning and be viewed as a kind of “opportunity cost”—the biogas is used internally, so it is not delivered to the market, and therefore it does not replace fossil fuels. As a result, here we are observing a rather high impact for each MJ of own biogas that is used internally. Note that the climate impact of using own biogas in the reference example which includes “the equivalent amount of fossil fuels” is not substituted, and therefore it should not be confused with performance indicators that focus on the delivered methane, e.g., “climate impact of the delivered biomethane (ISO)” (see Section 4.2). If we calculate this performance indicator, we realize that it is 33 (24–45) g CO_2-eq/MJ $CH_{4\ (delivered)}$ as it focuses on the delivered biogas as fuel and by definition does not include the substitution of fossil fuels.

Once the reference biogas plant is modelled, it would be possible to define and compare more complicated scenarios with each other as well, e.g., scenarios that involve several changes at the same time. Nevertheless, most scenarios can be parametrically presented, which makes it possible to use the same model for calculating and comparing their KPIs.

6 Concluding discussions

Biogas production from source-separated FW is a relatively new development of municipal waste management systems and is expected to grow in many urban areas across the world. In this paper, we developed a methodological approach that improves the assessment of the performance of biogas production from FW through life-cycle assessment (LCA) and mass balancing. Our point of departure was the challenges that are commonly associated with the heterogeneity of the techniques and configurations in such systems, lack of clearly defined terminologies with sufficient detail and yet encompassing the whole value chain of biogas from FW, and narrow or compartmentalized approaches to assess their environmental or economic performance. Our suggested taxonomy not only defines in a generic manner the main processes, activities and flows within such systems, but also provides an easy way to perform analysis on different system levels. As observed by Cherubini and Strømman [59], it is a common practice for bioenergy studies to consider more than a single functional unit in their reportable results. In contrast to such practices that tend to focus on a single functional unit, our LCA approach considers a multi-functional purpose (waste management, energy conversion, and nutrient recirculation), and consequently, our suggested key performance indicators (KPIs) are based upon these multiple functions. Through a hypothetical and yet reasonably realistic example, we demonstrated the operational use of our methodological recommendations and showed how the study can benefit from a combination of approaches toward uncertainty management—namely global and local sensitivity analyses—for representing and propagating the uncertainties.

By considering our recommendations and adopting the defined taxonomy and KPIs, life-cycle-based comparisons between completely different biogas production systems from FW can become more robust. In addition, our methodological approach makes it becomes possible to investigate climate impact, energy use, nutrient recirculation, and cost—as well as any other typical LCA impact categories that one would like to add to the ones that we have recommended—of such systems in an integrated manner. The multi-level and modular view on the product system and the value chain of biogas from FW can be used by different types of actors for different types of analysis. The KPIs are defined with a very wide system perspective (L_3 or L_4) in order to make them more relevant on a societal level. Nevertheless, some actors, such as biogas producers, might prefer a narrower perspective. For example, instead of a system-wide KPI such as KPI_7 (resource cost), a biogas producer might be interested in a performance indicator that assesses the cost of handing FW through anaerobic digestion at L_2. Our approach offers the possibility to include such a PI.

There are other studies that have tried to provide methodological insights into the assessment of the performance of biogas production systems [9,13,14,60–65]. However, the distinctive characteristic of our study rests upon the integration of several aspects into a single methodological approach. We have not only emphasized proper definition and the taxonomy of the biogas from the FW value chain as well as the possibility of modular levels of analysis; we have also provided an integrative approach that brings different types of performance indicators together. Our suggested KPIs—and possibly several additional performance Indicators—are based on (1) typical LCA impacts such as carbon footprint and primary energy balance, (2) mass balance across the value chain, which is of particular relevance from the nutrients recycling and recirculation point of view, and (3) resource cost. This multifunctional approach presents a more holistic view of the performance of a biogas system, which may contribute to more sustainable decisions regarding investments and changes in existing biogas systems as well as future development of biogas solutions from FW. Furthermore, we have tried to provide a generic, yet more detailed, view of different parts of the value chain of biogas production from FW (see Section 3).

The KPIs assimilate important aspects that can provide useful input into decision-making processes regarding the future development of biogas solutions from FW. We believe that our methodological approach is in most part generic, despite our focus on the food waste. Aside from the provision of feedstock and pretreatment, most biogas production systems have common value chains. So, with some adjustments and additions, our taxonomy can be used for other biogas production systems as well. Additionally, even if our study focuses on Swedish conditions, the methodological approach is generally applicable to other geographical areas as well.

Acknowledgement

This work was performed for the Biogas Research Center (BRC). BRC is funded by the Swedish Energy Agency, Linköping University, and several participating organizations.

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