

Factsheet Pathway

Anaerobic (co-)digestion with application of digestate as fertilizer

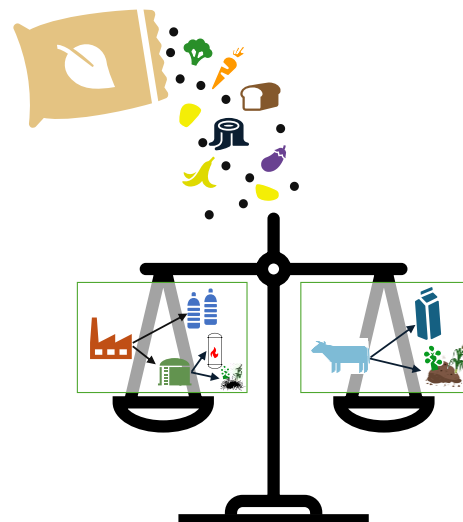
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Introduction

The CAT-BREVIA tool facilitates quantitative comparison of environmental benefit of directing residual biomass streams to different valorisation pathways and waste management options. Effects are quantitatively estimated for two indicators:

- Degree of circularity: an indicator for resource use efficiency that takes into account the yield to food, energy carriers and biobased materials.
- Consequential greenhouse gas (GHG) emissions effect, which accounts for substitution of primary materials/feedstocks by the (residual) material (like substitution of natural gas by biomethane) and other GHG emissions and mitigation effects up to the point of substitution.

This factsheet provides – after a general introduction of the tool – the modelled heuristics for valorisation pathway *anaerobic digestion with application of digestate as fertilizer*.



Typologies of anaerobic digestion pathways

Anaerobic digestion (AD) is a biological process whereby microorganisms convert organic material (i.e., a “substrate”), in the absence of oxygen, to biogas, consisting of methane (CH₄) and carbon dioxide (CO₂). The biogas can be upgraded to biomethane, which forms a substitute for natural gas. The remaining product is referred to as the “digestate”. The application of (processed) digestate as a fertilizer can contribute to the soil organic matter content and provides nutrients, but may also induce some greenhouse gas (GHG) emissions, specifically CH₄ and nitrous oxide (N₂O).

In general, three typical AD pathways can be distinguished based on the subsequent management and utilization routes of the digestate:

1. Digestate is applied as fertilizer. In general, this is the most cost-effective option; however, its implementation is subject to restrictions regarding the permitted feedstocks. This pathway is applicable to co-digestion facilities and certain industrial-scale anaerobic digesters, where national legislation may limit the range of permissible feedstocks and/or imposes quality requirements on the resulting digestate
2. Digestate is – possibly after a dewatering step – composted. Increasingly, organic waste treatment plants apply anaerobic digestion prior to composting.
3. Dewatered digestate is incinerated, where the water stream is treated as waste water and/or recycled in the process.

This factsheet describes the pathway in which anaerobic digestion – from which the biogas can be upgraded to green gas or is converted to electricity and heat – is combined with the application of digestate as a fertilizer.

CAT-BREVIA: Circularity Analysis Tool - Biomass Resource Valorisation Impact Analysis

The CAT-BREVIA tool was developed for estimating and comparing 'degree of circularity' and 'consequential GHG emission effects' associated with allocating a biomass residual flow to various valorisation pathways and waste management options.

Degree of circularity, an indicator for resource-use-efficiency

The CAT-BREVIA tool estimates and compares the yield of the application of bio-materials in 'valorisation pathways' to final products (food, energy carriers and biobased materials. The calculations are based on mass balance equations, describing conversion efficiency per macronutrient (proteins, lipids, carbohydrates, etc.).

The analysis of a valorisation pathway includes all significant effects, including those arising from residual streams generated within the pathway. For example, for feed applications, the assessment considers not only the production of animal-derived food products but also the contribution of the resulting manure to feed and food production through its use as a fertilizer.

The degree of circularity is calculated as the ratio of the energy content of the end products relative to that of the input material (as – often hypothetically – food), with two adjustments:

- Considering the specific nutritional importance of proteins in food, beyond their energetic value, and the generally lower agricultural yields of protein crops compared to energy crops (expressed in MJ ha⁻¹), an additional weighting factor is assigned to proteins in food.
- Distinct appreciation factors for final product categories: food, energy carriers and biobased materials:
 - *Food* is – based on societal preferences – considered here as the reference.
 - Generally, application for production of *energy carriers* is considered lower-value than for food production. This (societal) preference is reflected by lower or comparable prices for feedstocks for anaerobic digestion or biofuels production (compared to food and feed for livestock). Furthermore, energy carriers (like biomethane and biofuels) are commonly generated with substantially higher (energetic) efficiency from feedstocks than the conversion of livestock feed into food products. Based on these considerations energy carriers are assigned a lower appreciation factor (25%) compared to food products in the tool.
 - *Biomaterials* can be utilized multiple times throughout their life cycle, e.g. through recycling and incineration (with potential of energy recovery) at the 'end-of-life'. Therefore, a higher appreciation factor is assigned to biomaterials compared to energy carriers. Based on typical recycling rates for bioplastics found in literature (between 60 and 90%), here biomaterials are appreciated at 3x the value for *energy carriers*.

Appreciation factors for final product categories may be adapted with changing (societal) preferences.

The net increase of the *degree of circularity* resulting from the reallocation of a material from a reference valorisation pathway to an alternative valorisation pathway is defined as the difference between the *degrees of circularity* associated with the two pathways.

Consequential GHG emission effects

The CAT-BREVIA tool estimates consequential GHG emission effects, in accordance with common consequential greenhouse gas emission quantification recommendations. The following effects are taken into account:

- the use of energy and other processing inputs;
- the substitution of primary materials (such as commonly used animal feed or fossil fuels);
- for products (including produced residuals) that do not substitute a material:
 - carbon sequestration (in material or in the soil),
 - emissions of other greenhouse gases induced in the 'final' valorisation:
 - CH₄, with a Global Warming Potential (GWP) of 27 kg CO₂ equivalents (CO₂e) per kg,
 - N₂O, with a GWP of 273 kg CO₂e per kg.

For assessing the consequential effect of directing a material to a pathway, it is recommended to use marginal GHG emission factors. For substituted materials, generally using average/typical GHG emission intensities of primary materials is considered adequate. For electricity the tool provides proxies for 'marginal' emission factors (next to average emission factors) for many countries.

The net *consequential GHG emission effect* of reallocating a material from a reference to an alternative valorisation pathway or waste management option is defined as the difference between the *consequential GHG emission effects* of the two 'destinations'.

Note: The consideration of all consequential effects in this method fundamentally differs from attributional greenhouse gas emission accounting ('carbon foot printing').

To facilitate rapid assessments, the tool contains a database with information about average/typical compositions of diverse biomass materials, residual flows and products.

Disclaimer: The method relies on parameters derived from reference studies that are often limited in scope and/or based on average values. Consequently, its application to individual case studies may involve some inaccuracy and uncertainty due to the inherent generalizations and averaging assumptions.

The CAT-BREVIA tool is subject to ongoing development and refinement. New insights can lead to adjustments of pathway parameter values. Likewise, greenhouse gas emission factors, for example for energy carriers and crops, will be regularly updated. This will inevitably result in (generally small) differences generated with different versions of the tool. Results for scenarios calculated with different versions of the CAT-BREVIA tool should not be mutually compared.

More information can be found on

<https://circular-biomass-valorisation.com/quantification>.

The CAT-BREVIA tool was developed based on public funded research projects, supported by the Dutch Ministry of Agriculture, Fisheries Food security and Nature* and from EU**.

* In diverse BO projects the foundational method for indicator 'degree of circularity' was developed, including quantitative elaboration of diverse common valorisation pathways (feed for diverse livestock and other agricultural uses including organic waste management options. In the KomCirc project the method was applied for diverse specific pathways (including parameterisation of dedicated alternative valorisation pathways and other biomass streams). The KomCirc project received financial support from the Knowledge and Innovation Agenda agriculture, water, food. Within the KIA, the business community, knowledge institutions and government are working together on innovations for safe and healthy food (and a green living environment) for 9 billion people in a resilient world.

** In EU Agriloop project, the method was extended with the indicator 'consequential GHG emission effects' and some alternative valorisations, including bioplastics and microbial proteins. The Agriloop project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement No. 101081776, the UK Research and Innovation (UKRI) fund under the UK government's Horizon Europe funding guarantee, the Swiss State Secretariat for Education, Research and Innovation (SERI) and from the National Key Research and Development Program of China (NKRDPC).

Key references: Broeze et al. (2024) and Broeze et al. (2025).

Modelled effects: anaerobic digestion with application of digestate as fertilizer

Considered effects in indicator *Degree of circularity*

Anaerobic (co-)digestion contributes to circular exploitation of biomass through a combination of products, including:

- Products from anaerobic digestion:
 - green gas (energy carrier), which substitutes natural gas,
 - or (in case of local conversion): electricity + heat.
- The use of digestate as an organic fertilizer, providing nutrients and organic matter:
 - Nutrients, like nitrogen, from the material contributes to crop production as a fertilizer.
 - Organic matter is considered highly relevant for soil health, amongst other things for enhancing its structure and retaining moisture. Consequently, the application of persistent organic matter may contribute to crop productivity.

Considered effects in indicator *Consequential GHG emission effects*

Various effects of the pathway contribute to or mitigate GHG emissions (see *Figure 1*); CAT-BREVIA describes:

- Production of renewable energy; either
 - The substitution of natural gas by biomethane, which reduces GHG emissions.
 - The substitution of electricity, which reduces GHG emissions
- Slip of CH₄ from the digester and (optionally) biogas upgrading, which induces GHG emissions;
- Energy use in anaerobic digestion and (optionally) in biogas upgrading, which induces GHG emissions;
- The substitution of synthetic nitrogen (N) fertilizer by nitrogen in the digestate, which reduces GHG emissions.
- The supply of persistent organic matter to the soil through applied digestate, which may contribute to crop production; this mitigates other crop production, and consequently contributes to reducing GHG emissions.
- Sequestration of carbon (in persistent organic matter of the digestate) in the soil, which reduces GHG emissions.
- CH₄ and N₂O emissions from applied digestate in the field, which induces GHG emissions.

Quantitative details as modelled in the CAT-BREVIA tool are provided in the Appendix.

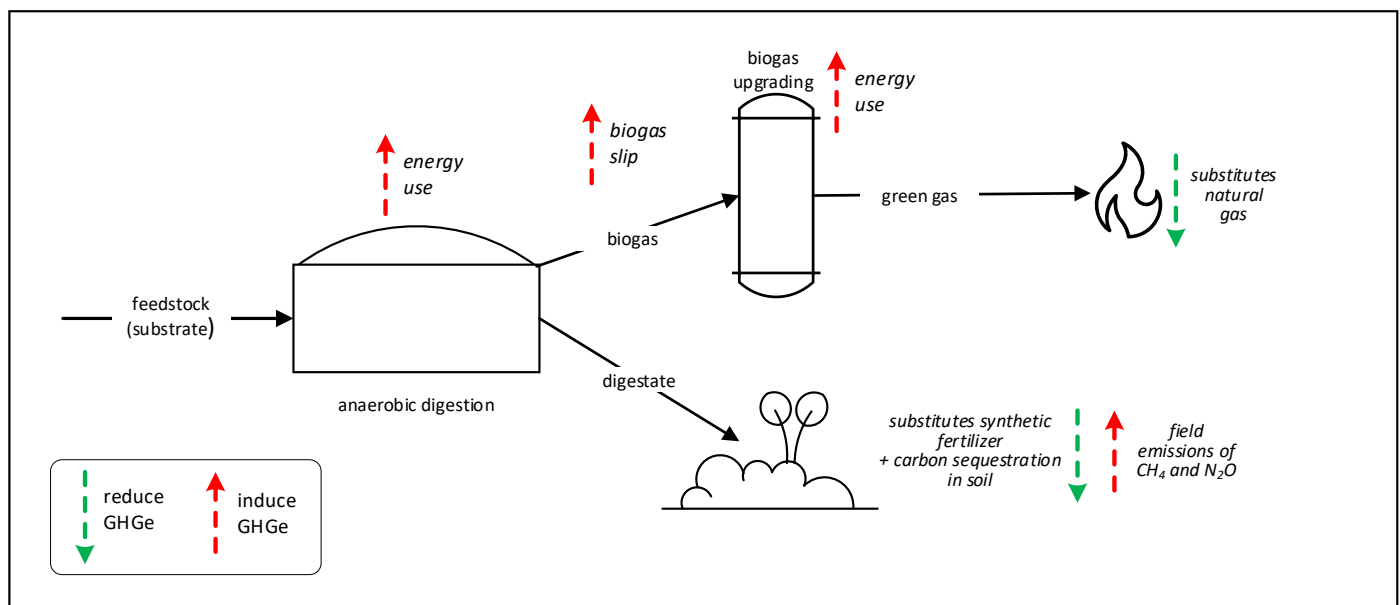


Figure 1 Process flow diagram of anaerobic digestion pathway (scenario with biogas upgrading to green gas), highlighting impacts on greenhouse gas emissions and mitigation (reduction) effects.

Appendix: Quantitative model of anaerobic digestion with application of digestate as fertilizer in the CAT-BREVIA tool

This appendix gives an overview of data, calculations and assumptions underlying the anaerobic digestion valorisation pathway as incorporated in the tool.

Effects in indicator degree of circularity

Production of biomethane

The yield of biomethane is estimated based on the chemical composition of the material in terms of macro-nutrients (see Table 1). For example, 1 kg of protein yields 0.33 kg of biomethane.

Table 1. Yield factor per macro-nutrient to biomethane

Macro-nutrient	Yield factor to biomethane (kg/kg)
Protein	0.33
Lipids	0.56
Sugar	0.26
Starch	0.26
Cellulose	0.20
Hemicellulose	0.15
Lignin	0
Other carbohydrates	0.22

Underpinning of the yield factors is provided by Broeze et al. (2025), based on Nova (2015) and Li et al. (2018).

For digestion with production of green gas, the total energetic content of the biomethane is counted as product. In case the biogas is locally converted to electricity (and heat), the (gross) yield to electricity and are estimated at 35% and 20% respectively.

Digestate: fertilizer function of nutrients

Note: although digestate may contain different valuable nutrients, the scope of CAT is limited to nitrogen (N).

In anaerobic digestion, N is retained in the digestate. Through application as fertilizer, this contributes to crop production; the actual yield effect is estimated as follows:

- o The utilization rate of N from digestate is estimated at 80% (Schröder et al., 2019).
- o The fraction of N that ends in the crop (relative to the amount of 'utilized' nitrogen), is estimated at $\frac{3}{4}$. This number is derived from a N balance in agricultural areas (CLO, 2025), and corrected by the utilization rates of organic sources.

Altogether, approximately $80\% \times \frac{3}{4} = 60\%$ of the N in applied material ends in crops.

In order to estimate the yield to food production, the allocation to food and feed crops is taken in consideration. In the Netherlands, of the produced crops, 22.5% is marketed as consumer products (like food and ornamental products), and 75% is used as animal feed (CLO, 2025). In animal production, approximately 30% of N ends in food proteins, and 60% in manure. Since manure is circularly applied as a fertilizer, this also contributes to the production of e.g., food. Altogether, the net yield from crops to food is estimated at 50%.

The combined effect is estimated at $50\% \times 60\% = 30\%$.

Comment: this result is based on data for the Netherlands. In many other countries, a larger part of the crops is valorised as food. For such situations the combined effect may be higher (up to 60% if all crops are used for food).

Digestate: organic matter

Organic matter is considered highly relevant for soil health, amongst other for retaining moisture and for structure. Consequently, the application of persistent organic matter in digestate may contribute to crop productivity.

It is assumed that all lignin and part of the cellulose and hemicellulose (100% minus the degradation fractions listed in Table 1) are retained as persistent organic matter in the digestate.

Contribution of a material to soil organic matter depends on the persistence of the material. The most persistent macro-nutrients in organic material are lignin, cellulose and hemicellulose. The actual

rate of decay depends on many contextual factors (like agricultural soil management, soil humidity and pH). Based on the rule-of-thumb that effective organic matter¹ from compost is broken down at a rate of 2% per year, here it is assumed that lignin breaks down at a rate of 1% per year, and (hemi)cellulose at 4% per year. Based on these assumptions, over its total lifespan a kg lignin is calculated to contribute 100 kg x years organic matter and (hemi)cellulose 25 kg x years.

The actual contribution of soil organic matter to crop production depends strongly on contextual conditions (like soil type and actual organic matter content). For a situation with low soil organic matter content, the marginal benefit of additional organic matter was estimated at approximately $\frac{1}{40}$ kg crop yield (in dry matter) per kg additional organic matter (Oldfield et al., 2021).

The combined marginal effect (also taking in consideration the yield from crops to food products as pointed out above) is, in a situation with low soil organic matter content (as described by Oldfield et al., 2021), estimated for

- o lignin: between 0 and $100 \times \frac{1}{40} \times \frac{1}{2} = 1\frac{1}{4}$ kg extra food (dry matter) production per kg lignin.
- o cellulose: between 0 and $25\% \times 25 \times \frac{1}{40} \times \frac{1}{2} \approx 0.08$ kg extra food (dry matter) production per kg cellulose.
- o hemicellulose: between 0 and $42\% \times 25 \times \frac{1}{40} \times \frac{1}{2} \approx 0.13$ kg extra food (dry matter) production per kg hemicellulose.

For situations where soil organic matter content is not a limiting factor (roughly where the organic matter content is around or above 2%, which is largely the case in North-Western Europe), the marginal effect of additional organic matter is not significant (Hijbeek et al., 2017).

Effects in indicator consequential GHG emission effects

The following GHG emission effects of anaerobic (co-)digestion are addressed:

- **Energy use in anaerobic digestion**
In anaerobic digestion, typically 1.8 kWh electricity and 110MJ heat are used per ton substrate (Lijo et al., 2014). The average dry matter content of substrate is assumed at 20%.
- **For digestion with production of green gas:**
 - o **Green gas production through upgrading biogas**
1 kg biomethane can substitute approximately 1.25 kg natural gas. The GHG emission intensity of natural gas is set at 2.67 kg CO₂e per kg natural gas (emission intensity is the combined effect of emissions in gas mining/production, distribution and use/combustion).
 - o **Energy use in biogas upgrading**
Upgrading biogas to methane requires – depending on chosen technology – between 0.15 and 1 kWh electricity per kg raw biogas (Iglesias et al., 2021). Based on typically 0.4 kg biomethane per Nm³ biogas, the specific energy use through membrane-upgrading (0.2 kWh per Nm³ biogas) is estimated at 0.5 kWh per kg biomethane.
- **For digestion with production of electricity and heat**
In case the biogas is locally converted to electricity (and heat), the (gross) yield to electricity and are estimated at 35% and 20% respectively.

GHG emission factors for electricity are derived from recognized sources (like co2emissionfactoren.nl) and ember-energy.org². Some sources report emission factors for electricity generation, whereas others report emission factors for electricity consumption. Conversion between these factors was done using transmission and distribution loss factors (World Bank³).

In consequential analyses – other than in attributional carbon footprint analysis – it is recommended to use marginal emission factors. For electricity determining marginal emission factors is very complex, since it involves understanding decision taking by various actors including long-term energy

¹ 'Effective organic matter' is the organic matter that is retained one year after application.

² <https://ember-energy.org/data/yearly-electricity-data/>

³ <https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS>

policy. As a work-around average emission factor for fossil-based electricity may be used as a proxy.
For net produced heat, considering the mostly low quality of heat, the factor proposed for average grid heat is used as proposed by co2emissiefactoren.nl.

- **Methane emissions from AD and biogas upgrading**
Slip is estimated at 2% of the produced biomethane.
- **Substitution of food production**
Supplied persistent organic matter (in digestate) may contribute to food production. It is assumed that the produced food substitutes wheat flour (with a carbon footprint of 0.632 kg CO₂e/kg⁴).
- **Substitution of synthetic fertilizer**
N in the digestate is considered to substitute synthetic N fertilizer, with a substitution factor 0.8 (Schröder et al., 2019). The GHG emissions associated to 1 kg of synthetic fertilizer-N is estimated from:
 - average GHG emission intensity of production in Europe (Vidovic et al., 2023): 3 kg CO₂e/kg N.
 - effect of N₂O emissions: emission factor for artificial fertilizers: 1.6% N₂O-N of applied N (IPCC, 2019). This means $16 \cdot 44 / 36 \approx 19.5$ g N₂O per kg applied N. GWP of N₂O is set at 273 kg CO₂e per kg (IPCC).
 The total effect is 8.3 kg CO₂e per kg replaced synthetic fertilizer-N.
- **Carbon sequestration in soil (persistent organic matter)**
Based on an assumed annual break down rates of 1% for lignin and 4% for (hemi)cellulose, the GWP-100 effect is estimated at 1.5 kg CO₂e per kg lignin and 0.4 kg CO₂e per kg (hemi)cellulose in the digestate.
- **Nitrous oxide emissions from digestate applied to soil**
The emission factor for N₂O from digestate applied to the soil is estimated at 0.8% N₂O-N of the N in the digestate (Van der Zee et al., 2021; Van Bruggen et al., 2023).

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⁴ Value for wheat flour in Europe (www.carboncloud.com, accessed 6 May 2025).