

CAT-BREVIA – Circularity Analysis Tool for Biomass Resource Valorisation Impact Analysis

Factsheet Pathway *Landfilling*

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Introduction

The CAT-BREVIA tool facilitates quantitative comparison of environmental benefit of destining residual biomass streams to different valorisation or 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 waste management option *landfilling*.

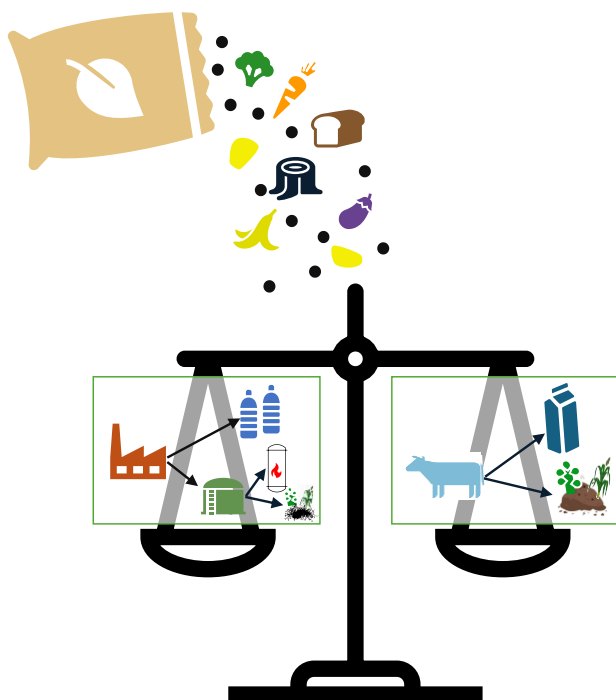
Landfilling remains one of the most widely applied waste management practices, although its use for organic waste is declining. The environmental impact of landfilling is dominated by the following factors:

- Methane emissions resulting from the anaerobic degradation of biodegradable organic matter.
- Nitrous oxide emissions originating from aerobic zones within the landfill and from aerobic treatment of leachate.
- The capture and management of landfill gas, which can substantially reduce methane emissions. Captured landfill gas may be utilized as a renewable energy source, thereby offsetting the use of fossil fuels and contributing to greenhouse gas mitigation.
- The long-term sequestration of carbon.

The environmental impact of landfilling is strongly influenced by the technological level of the landfill system, particularly with respect to operational management practices, aeration conditions, and the design and performance of the landfill cover. In addition, site-specific environmental factors, including climatic conditions and groundwater levels, may substantially affect emission patterns and the overall environmental performance of the landfill.

Reference guidelines published by the IPCC and UNFCCC distinguish a wide range of landfill categories based on these characteristics. Among these categories, the following landfill types are described in more detail below.

- managed – anaerobic, without landfill gas (LFG) capture,
- managed – anaerobic, LFG flaring (assuming 75% methane captured),
- managed – anaerobic, LFG to green gas (85% of the methane is captured and converted to green gas),
- managed poorly – semi-aerobic,
- unmanaged – deep, including filling inland water,
- unmanaged – shallow (<5 m waste),
- uncategorised solid waste disposal sites.



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: landfilling

Considered effects in indicator Degree of circularity

For landfill category *managed – anaerobic, LFG to green gas* the produced green gas is appreciated as ‘energy carrier’ in the method.

Considered effects in indicator Consequential GHG emission effects

CAT-BREVIA addresses the following effects contributing to or mitigating GHG emissions:

- methane emissions, which induces GHG emissions,
- nitrous oxide emissions, which induces GHG emissions,
- carbon sequestration, contributing to reducing GHG emissions,
- substitution of natural gas by upgraded LFG, which reduces GHG emissions,
- energy use in LFG upgrading.

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

Appendix: Quantitative model of landfilling in the CAT-BREVIA tool

Methane emissions

Two methods for estimating methane generation potentials in landfills have been considered:

1. Estimation method proposed by IPCC and UNFCCC
2. Practical biomethane potential in anaerobic digesters

Below both method are summarized and compared

Method 1. Estimation method proposed by IPCC and UNFCCC

Reference methods (as proposed by amongst others IPCC and UNFCCC) propose to estimate methane generation as the product of the “biomethane potential (BMP)” and the “fraction of degradable organic carbon (DOC_f)”. For highly decomposable wastes, e.g. food wastes, grasses and garden waste (excluding tree branches) fixed value for DOC_f is proposed: 0.7 (IPCC, 2019).

Table 1 presents predicted methane generation potential per macro-nutrient according to this method (0.7 x BMP).

Table 1. Theoretical biomethane potential (BMP) and predicted methane generation in landfills according to IPCC/UNFCCC method per macro-nutrient.

Macro-nutrient	BMP (kg/kg)	0.7 x BMP
Protein	0.38	0.27
Lipids	0.68	0.48
Sugar	0.28	0.20
Starch	0.30	0.21
Cellulose	0.30	0.21
Hemicellulose	0.30	0.21
Lignin	0.47	0.33
Other carbohydrates	0.30	0.21

Sources for BMP values: Nova (2015) and Li et al. (2018). Value for ‘other carbohydrates’ is estimated (average for carbohydrate types).

Method 2. Practical biomethane potential in anaerobic digesters

Conversion yields per macronutrient to methane in anaerobic digesters, obtained from practical observations are presented in

Table 2. Practical 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	0.18
Hemicellulose	0.14
Lignin	0
Other carbohydrates	0.22

Sources: Nova (2015) and Li et al. (2018). Value for ‘other carbohydrates’ is estimated (average for carbohydrate types).

Reflection on both methods

In the comparison of biomethane yield potentials obtained with the two methods, Method 1 appears to assign relatively high yield factors to more persistent macronutrients, such as cellulose, hemicellulose, and lignin, while assigning relatively low yield factors

to more readily degradable macronutrients. In this method, the DOC_f factor was introduced to account for differences between the materials used in the reference anaerobic digestion experiments, which primarily consisted of food waste, and the heterogeneous organic waste streams typically disposed of in practical landfill systems. As a result, the DOC_f factor serves as a correction for the lower degradability of the combined organic waste commonly present in landfills compared with the food waste materials used in the reference studies. Since Method 2 more accurately accounts for the physicochemical characteristics of the material, it was selected for implementation in the tool. This decision is supported by a comparative assessment of the results obtained using both methods:

- For representative food products (meat, rice, potatoes, apples, and tomatoes), the methane generation predicted by Method 2 is comparable to, or up to 20% higher than, that predicted by Method 1.
- To evaluate the effect of other organic materials that may be disposed of in landfills, leaves were used as a representative example. For this material, which is characterized by relatively high contents of lignin, cellulose, and hemicellulose, the methane generation predicted by Method 2 is approximately 35% lower than that predicted by Method 1.

These results indicate that both methods yield similar estimates of methane generation for the overall organic waste stream, comprising food waste and other organic materials. However, Method 2 provides a more accurate representation of the differing degradation characteristics of individual waste fractions, distinguishing between readily degradable materials and more persistent components. Consequently, Method 2 is considered to provide a more realistic estimate of methane generation potential across a broader range of organic waste materials.

The predicted methane generation is subsequently corrected for the influence of two additional factors:

- Oxidation of methane, represented by the oxidation factor (OX). IPCC proposes default OX values 0.1 (for managed sites, covered with methane oxidising material like soil or compost) and 0 (for all other situations).
- Partial decompose of the waste under aerobic conditions and collected/removed, described by the methane correction factor (MFC). IPCC proposes default MCF per type of landfill (**Error! Reference source not found.**).

Table 3. Default methane correction factors for selected types of landfills.

Type of site	MCF
managed – anaerobic, without LFG capture	1.0
managed – anaerobic, LFG flaring (75% recovery)	0.25
managed – anaerobic, LFG to green gas (85% recovery)	0.15
managed poorly – semi-aerobic	0.7
unmanaged – deep, including filling inland water	0.8
unmanaged – shallow (<5 m waste)	0.4

uncategorised solid waste disposal sites	0.6
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Nitrous oxide emissions

Nitrous oxide may be produced from nitrogen-containing organic material (e.g. in proteins) during decomposition under aerobic conditions. IPCC assumes that the yield rates are comparable to composting. For that, a heuristic was derived from two references:

- Beck-Friis et al. (2001) report 0.4 to 0.6% emission of N_2O-N of N in the substrate.
- From the results presented by Cuhls et al. (2015) comparable to slightly higher values (up to approximately 1%) were derived.

Altogether, here it is assumed that 0.6% of N is converted to N_2O-N .

Provided that nitrous oxide is generated and emitted in aerobic conditions, here it is assumed that total N_2O emissions should be corrected by a nitrous oxide correction factor (NCF). In absence of additional heuristics, here it is assumed that this factor is equal to the part of the waste that decomposes under aerobic condition (that is 1–MCF).

Table 4. Assumed nitrous oxide correction factors for selected types of landfills.

Type of site	NCF
managed – anaerobic, without LFG capture	0.0
managed – anaerobic, LFG flaring (75% recovery)	0.0
managed – anaerobic, LFG to green gas (85% recovery)	0.0
managed poorly – semi-aerobic	0.3
unmanaged – deep, including filling inland water	0.2
unmanaged – shallow (<5 m waste)	0.6
uncategorised solid waste disposal sites	0.4

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Carbon sequestration in the landfill

Persistent carbohydrates are expected not to break down completely in anaerobic conditions, which is reflected by the substantial difference between the theoretical methane yield factor and yields obtained in practical anaerobic digestion (Table 2). Here it is assumed that the fraction that is not degraded reflects the fraction of carbon retained in the landfill: 100% for lignin, 40% for cellulose and 53% for hemicellulose.

The validity of this heuristic is supported by the practical observations presented by De la Cruz et al. (2013).

Substitution of green gas through captured methane

(only for landfill type 'managed – anaerobic, LFG to green gas')
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).

Energy use in LFG upgrading

(only for landfill type 'managed – anaerobic, LFG to green gas')
Upgrading LFG 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 0.25 kg biomethane per Nm³ LFG, the specific energy use through membrane-upgrading (0.2 kWh per Nm³ LFG) is estimated at 2 kWh per kg biomethane.

Methane emissions in LFG upgrading process

(only for landfill type 'managed – anaerobic, LFG to green gas')
Slip is estimated at 2% of the produced biomethane.

Methane emissions from FLG flaring

(only for landfill type 'managed – anaerobic, LFG flaring')
Typically 0.3% of the methane in flaring gas escapes in the flare gas.