

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

Factsheet Pathway *PHA production*

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Introduction

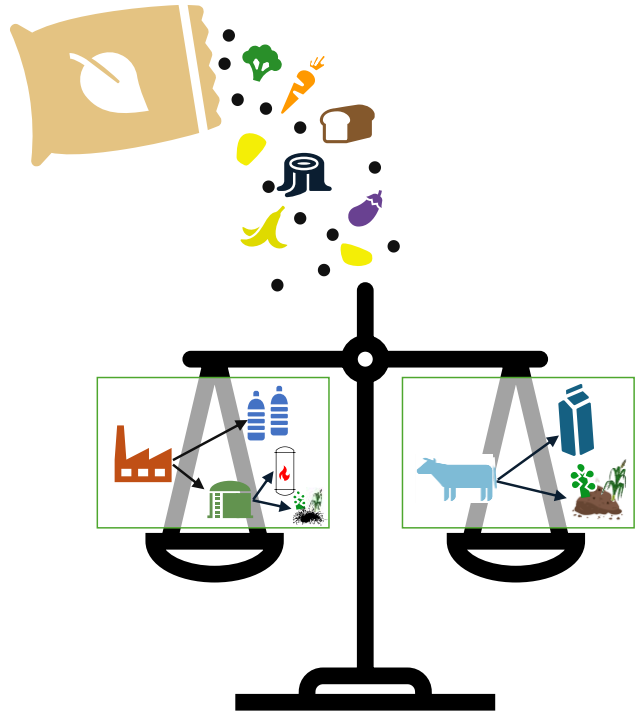
The CAT-BREVIA tool facilitates quantitative comparison of environmental benefit of directing residual biomass streams to different valorisation pathways and waste management options. Effects are quantitatively estimated for two indicators:

- 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.

Within the Agriloop¹ project, novel pathways for the high-value valorisation of agricultural residues were further developed. Among the pathways investigated was the production of polyhydroxyalkanoates (PHA), a group of biopolymers that can be used as bioplastic. To enable early assessment of the environmental performance of this material in comparison with other valorisation pathways, and to support the identification of the most suitable residue streams, a PHA production pathway was incorporated into the tool.

Given that PHA production processes are still at a relatively early stage of development – with expected substantial improvements in process performance expected in the future – whereas many conventional valorisation routes for agricultural residues are represented in the tool using performance factors derived from current, largely optimized systems, the PHA pathway was modelled using prospective yield factors. This approach is considered the most appropriate for supporting decision-making on the future utilisation of residual biomass streams.

This factsheet provides – after a general introduction of the tool – the modelled heuristics for valorisation pathway *PHA production*.



¹ 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).

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), higher additional weighting factor is assigned to proteins in food: whereas in the tool other components are appreciated at their specific heat of combustion, proteins in food are appreciated at 3 times their specific heat of combustion.
- 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 of biomaterials 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 redirecting 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).

The PHA production pathway described in the CAT-BREVIA tool

The PHA production pathway described in the tool is largely based on a pathway proposed by Saavedra del Oso et al. (2023).

Considered effects in circularity/resource-use-efficiency assessment

The pathway of PHA production contributes to circular exploitation of biomass through co-production of different products :

- The production of PHA, a bioplastic.
- The production of biomethane through anaerobic digestion of generated residual stream.
- 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 consequential GHG emissions accounting

The pathway will affect total GHG emissions in multiple ways (see Figure 1), including:

- The substitution of fossil plastics by PHA, which reduces GHG emissions by the prevention of fossil plastic production and it's end-of-life waste management.
- The substitution of natural gas with biomethane, which reduces GHG emissions.
- Slip of CH₄ from the digester and biogas upgrading, which induces GHG emissions.
- Energy use in the PHA production pathway, in anaerobic digestion and 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 may contribute to crop production, which mitigates other crop production, and consequently reduces 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 induce GHG emissions.

These GHG emission effects are included in the CAT-tool (see Appendix for more detailed information).

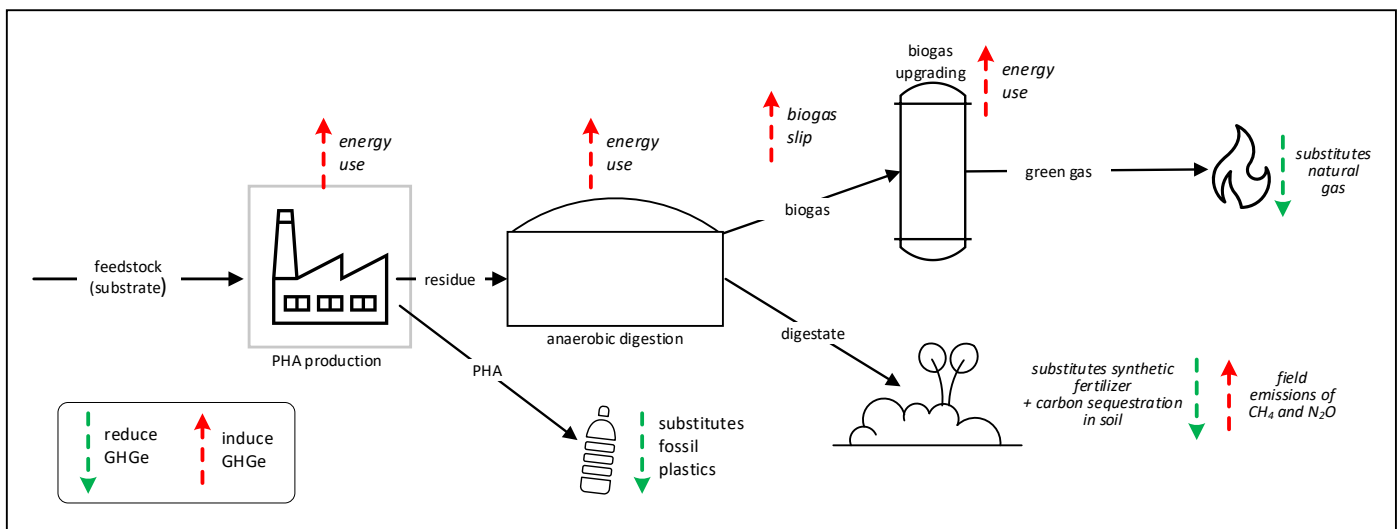


Figure 1. Flow chart of the PHA production pathway, showing the system's GHG emission effects.

Appendix: Quantitative model of PHA production pathway in the CAT-BREVIA tool

This appendix gives an overview of data, calculations and assumptions underlying the valorisation pathway *PHA production* as incorporated in the tool. The described pathway is largely based on scenario 2 from Saavedra del Oso et al. (2023).

Degree of circularity

We have estimated typical yield factors for conversion of material to PHA from Saavedra del Oso et al. (2023), see Figure 2.

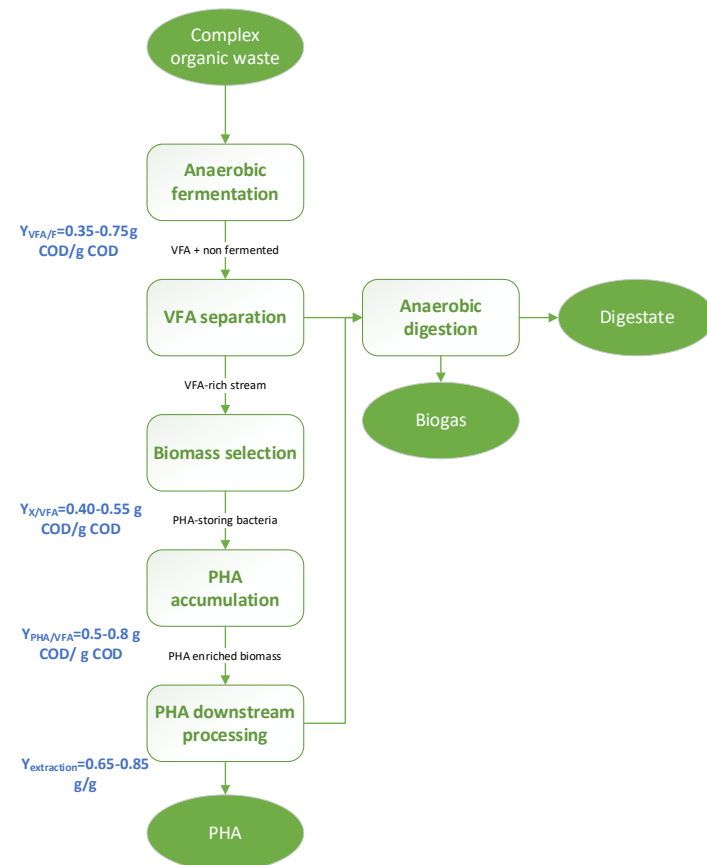


Figure 2. Processing steps and yield factors for PHA production from a residue stream (derived from Saavedra del Oso et al., 2023, yield factors for scenario 2)

In the indicated sequence of processing steps, the yield of anaerobic fermentation to VFAs strongly depends on the processing conditions (like temperature, pH and retention time in fermentation steps) and feedstock characteristics. Considering the feedstock composition, the higher yield factor (0.75) is anticipated for readily digestible components like lipids and simple carbohydrates, whereas we assume that lignocellulose compounds are not degraded in the fermentation and that the lower value (0.35) provided is assumed to apply to the 'other carbohydrates' fraction.

For the further processing steps, we assume:

In VFA separation 90% of VFA ends in the VFA-rich stream.

In the PHA accumulation step the yield to PHA is on average 65%.

In the downstream processing on average 75% of the generated PHA is extracted.

We estimate the combined yield per macronutrient as follows:

- for lipids and simple carbohydrates:
 $0.75 \times 0.90 \times 0.65 \times 0.75 = 0.329 \text{ g COD}_{\text{PHA}} / \text{g carb.-COD}$
- for the 'other carbohydrates' fraction:
 $0.35 \times 0.90 \times 0.65 \times 0.75 = 0.153 \text{ g COD}_{\text{PHA}} / \text{g carb.-COD}$
- for proteins a typical yield factor (including degree of hydrolysis) was derived from Duong et al. (2021) ($0.6 \text{ g COD}_{\text{VFA}} / \text{g prot.-COD}$). Consequentially, as for carbohydrates the yield to PHA from proteins is estimated at
 $0.60 \times 0.90 \times 0.65 \times 0.75 = 0.263 \text{ g COD}_{\text{PHA}} / \text{g prot.-COD}$

From above COD yield factors, the mass yield factors in **Error! Reference source not found.** were derived. In these estimates COD factors (g COD per g material) for lipids, proteins, starch, sugar and 'other carbohydrates' are assumed 2.8, 1.3, 1.2, 1.1 and 1.3 g

COD per gram material. COD factor of PHA varies strongly amongst types of PHA. Calculated values for a set of PHA variants (incl. PHBV) range from approximately 1.2 to 2.3. Here, an average is assumed: 1.7 g COD per g PHA.

Table 1. Yield factor per macro-nutrient to PHA

Macro-nutrient	Yield factor to PHA (kg/kg)
Protein	0.20
Lipids	0.54
Sugar	0.23
Starch	0.21
Cellulose	0
Hemicellulose	0
Lignin	0
Other carbohydrates	0.12

Remark: The yield factors derived above are on the high side compared to values derived from other references. The actual yield will strongly depend on specific material properties and processing conditions (including e.g. duration of the fermentation step). In order to represent the potential yield in prospective (optimised) situations, here the high yield factors are used.

Note that considering the large variation of COD factors for different the types of PHA, the actual mass yield may strongly vary amongst the types of PHA. For simple PHA (with generic chemical formula $(C_6H_{11}O_4N)_n$) the COD factor is at the low end of the range mentioned above: approx. 1.2 g COD per g material. Consequently, based on above heuristics the yield to this type of PHA is estimated at 1.4 times the yield to "average" PHA (as predicted by the yield factors in **Error! Reference source not found.**). On the other side, for PHBV the estimated COD factor is relatively high (2.3 g COD per g PHBV) which implies that the estimated yield to PHBV is approximately $3/4^{\text{th}}$ of the predicted yield to "average" PHA.

Circularity effects of anaerobic digestion of the residue stream

The residue is anaerobically digested. Details of this valorisation are described in the *Factsheet Anaerobic digestion with application of digestate as a fertilizer*. Considering that the substrate's nutritional value is substantially converted to PHA, it is assumed that the remaining biogas yield compared to direct digestion is reduced to:

- for simple carbohydrates: 20%,
- for complex carbohydrates: 80%,
- for proteins 20%.

Furthermore, it is assumed that all N ends in the digester.

Consequential GHG emission effects of this pathway

PHA production

It is assumed that PHA substitutes fossil plastics, with the following GHG emission effects:

- Fossil plastics production (with typical GHG emission intensity of 3 kg CO₂e per kg).
- End-of-life waste management: considering that – in contrast with fossil plastics – CO₂ emissions from PHA end-of-life waste management may be neglected (because of the renewable biogenic origin), for fossil plastics also the GHG emissions induced in end-of-life waste management are taken in consideration (with associated GHG emissions 1.7 kg CO₂e per kg plastic (ETC WMGE, 2021))

Energy use in PHA production

Estimate from Saavedra del Oso et al. (2023) scenario 2: 1.28 kWh electricity and 16.5 MJ heat per kg produced PHA.

Effects due to anaerobic digestion of the residue

As explained above, a fraction of the material is directed towards anaerobic co-digestion. Climate impact effects due to anaerobic digestion of that stream are described in the *Factsheet Anaerobic (co-)digestion*.

References

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