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Abbreviations and acronyms

ADP	Abiotic depletion potential
AP	Acidification Potential
CaCO3	Calcium Carbonate
EP	Eutrophication Potential
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MC	Mixed culture
NaOH	Sodium hydroxide
NREU	Non-renewable energy use
ODP	Ozone layer depletion potential
POCP	Photochemical oxidation potential
SDS	Sodium dodecyl sulphate
UNEP	United Nations Environment Program

1 Executive summary

The AFTERLIFE project proposes a flexible, cost- and resource-efficient process for recovering and valorising the relevant fractions from wastewater (WW). The AFTERLIFE process will separate out the different components of value using a series of membrane filtration units that will separate all the solids in the wastewater. These will then be treated to obtain high-pure extracts and metabolites or, alternatively, to be converted into value-added biopolymers, polyhydroxyalkanoates (PHAs). In addition to the value extracted from the solids, the remaining outflow of the water will be ultrapure and ready for re-use. Therefore, the overarching objective of the AFTERLIFE project is to demonstrate an innovative wastewater treatment that simultaneously recovers compounds of interest while converting the remaining organic matter into a high-volume added value biopolymer. The project is funded by the European Commission via Horizon 2020 (https://afterlife-project.eu).

As part of the project a hotspot life cycle assessment (LCA) has been carried out by nova-Institut GmbH to identify environmental hotspots at an early stage of the development in order to guide the process design optimization, using a feedback loop approach.

The analysis is based on the current developments of each work package and uses the mass and energy flows provided by the responsible project partners.

The following key outcomes could be obtained:

- The results of this hotspot LCA give an early understanding of the environmental performance (impacts on ecosystems, human health and depletion of resources) of the AFTERLIFE PHAs, essential oils, amino acids and polyphenols production at their current *status quo* of development.
- Currently wastewater from sweet and candies manufacturing seems to be the most promising feedstock to produce PHA compared to wastewater from cheese and juice and other products from citric fruits manufacturing.
- The foreground AFTERLIFE processes are based on primary mainly experimental lab scale data provided by the project partners and are subject to optimization in the course of the project.
- Particularly, the VFA production steps, the PHA recovery and steam-distillation (sources of major environmental impacts) are subject to optimization. Further research activities should tackle this aspect and an upscaled process may lead to better results.
- The AFTERLIFE process at this stage do not yet include heat integration. Further improvements in the LCA will be achieved when this is included.
- The main limitations of this environmental study are due to the data quality of the inventories. Some inputs are based on secondary data (literature) or on lab scale processes (lab experiments or simulation models (calculated or estimated data), therefore scoring badly in completeness.
- Given that some uncertainty is present at the data inventory level the potential environmental impacts are to be considered informative and expected to become lower along the development path with increasing knowledge and decreasing uncertainty.

To conclude, this LCA will be updated in a final report (deliverable D7.2 “Final Life-cycle assessment” due at M46, at the end of the project,) including optimization, feedback loops and a more detailed assessment of the AFTERLIFE-process with the most promising wastewater as feedstock. The full LCA will be based on measured data from the pilot plant, which is being set up at the facilities of BBEUP.

2 Introduction

The overarching objective of the AFTERLIFE project is to demonstrate, at TRL-5, an innovative wastewater treatment that simultaneously recovers compounds of interest while converting the remaining organic matter into a high-volume added value biopolymer. Specifically, it sets out to:

- Develop the filtration system for recovering suspended and soluble solids in wastewater by using membrane filtration units.
- Develop the process for recovering and purifying valuable compounds in the concentrates extracted in the filtration step.
- Develop an anaerobic/aerobic process for converting the low value-added organic matter into PHAs.
- Optimize the resources in the process, following a circular economy approach
- Design and optimize the AFTERLIFE process from a holistic perspective following a Multidisciplinary Design Optimization (MDO) approach
- Conduct a demonstration, at a pilot scale, using real industrial wastewater to generate the end products
- Prove the economic and industrial feasibility for AFTERLIFE process along with a comprehensive Lifecycle Analysis (LCA) and cost assessment.
- Promote exploitation of the project's results and expand its impact.

With regards to the environmental performance of the newly developed production pathways, a life cycle assessment, following the well-established LCA standards ISO 14040 and ISO 14044, will be performed. The potential impacts investigated include, among others, global warming, acidification and eutrophication potentials and fossil resources consumption.

The focus of the assessment is on identifying environmental hotspots, in order to determine (at an early stage of the development) approaches to guide further optimization within the project's technology development work packages, using a feedback loop approach.

Summing up, this report aims principally at identifying environmental hotspots in order to guide the process design optimization. The following sections describe the environmental assessments conducted as part of WP7 and are structured as follows:

- LCA framework;
- Goal and scope definition;
- Life Cycle Inventory analysis;
- Life Cycle Impact Assessment;
- Conclusions and further work.
- In the appendix supporting information can be found.

3 Life Cycle Assessment framework

An increased awareness of the importance of environmental protection, as well as possible impacts associated with the manufacturing and consumption of products and services, has raised increasing interest in the development of methods to better understand, measure and diminish these impacts. Life Cycle Assessment (LCA) is a method to quantitatively assess (based on physical metrics) the potential environmental impact of a product or service throughout its entire life cycle by quantifying all inputs and outputs of material and energy flows and assessing how these flows affect the environment (Figure 1). It assesses environmental impacts such as climate change or eutrophication as well as the impacts on natural resources and/or human health.

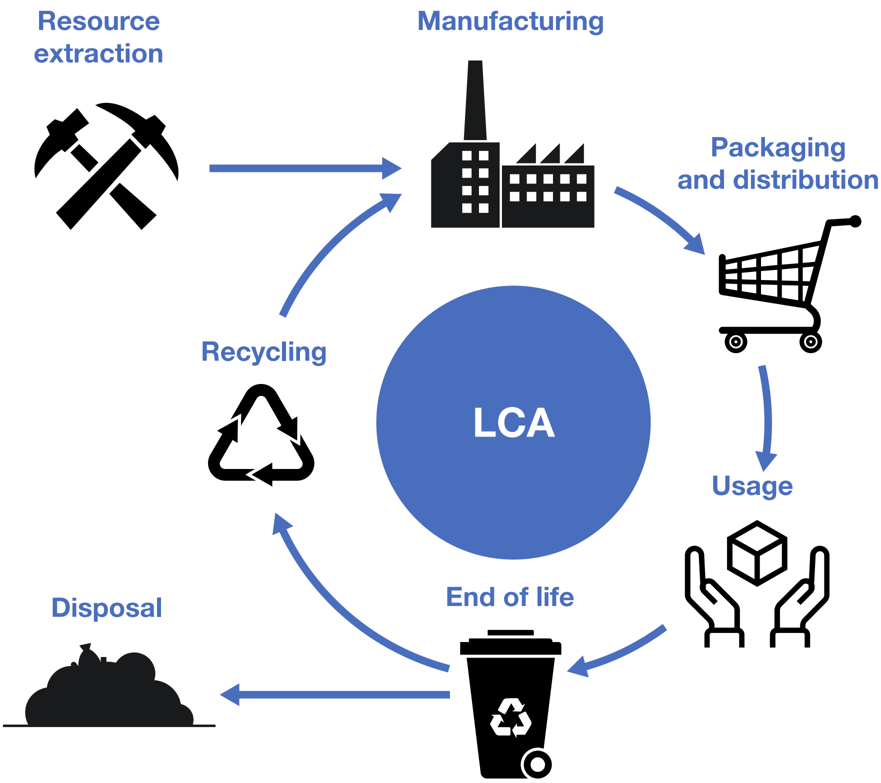

Figure 1 The life cycle model

LCA is an internationally standardized method laid out in ISO 14040:2006 and ISO 14044:2006. The strength of LCA is that it studies a whole product system. This avoids sub optimisation that may be the result if only a few processes are focused on. Since the whole life cycle is studied, LCA is not site-specific.

An LCA study consists in four different phases:

1. Goal and scope definition
2. Life Cycle Inventory analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation of the results

In the goal and scope definition phase, the product to be studied and the purpose of the study are decided on. The functional unit for which the study refers is also defined. Many other choices related to the modelling are made during the goal and scope definition.

In the life cycle inventory analysis (LCI) phase, the system model is built according to the requirements of the goal and scope definition. The system model is a flow model of the system with certain types of system boundaries. The result is a mass and energy balance for the system.

The Life Cycle Impact Assessment (LCIA) aims to indicate the impacts of the environmental loads quantified in the inventory analysis by classifying the inventory parameters to the type of environmental impact that they contribute to and finally by calculating the relative contribution of the emissions and resources consumption to each type of environmental impact (characterization). Such calculations are based on scientific models of cause-effect chains in the natural system. Sometimes these results need to be interpreted and aggregated even further. This can be done in different ways, for instance with formalized and quantitative weighting procedures.

The last phase is the interpretation in which the findings of both, the inventory analysis and the impact assessment are evaluated, in relation to the defined goal and scope, in order to reach conclusions and recommendations. The relationships between these phases have been illustrated in Figure 2, which shows that an LCA study is a highly iterative process among the different phases. Four critical issues in LCA methodology determine the outcomes of an LCA study: the definition of the functional unit, system boundary issues in general and allocation of environmental burdens among product and co-products in particular, the type and quality of data used in the study and how the impact assessment is made.

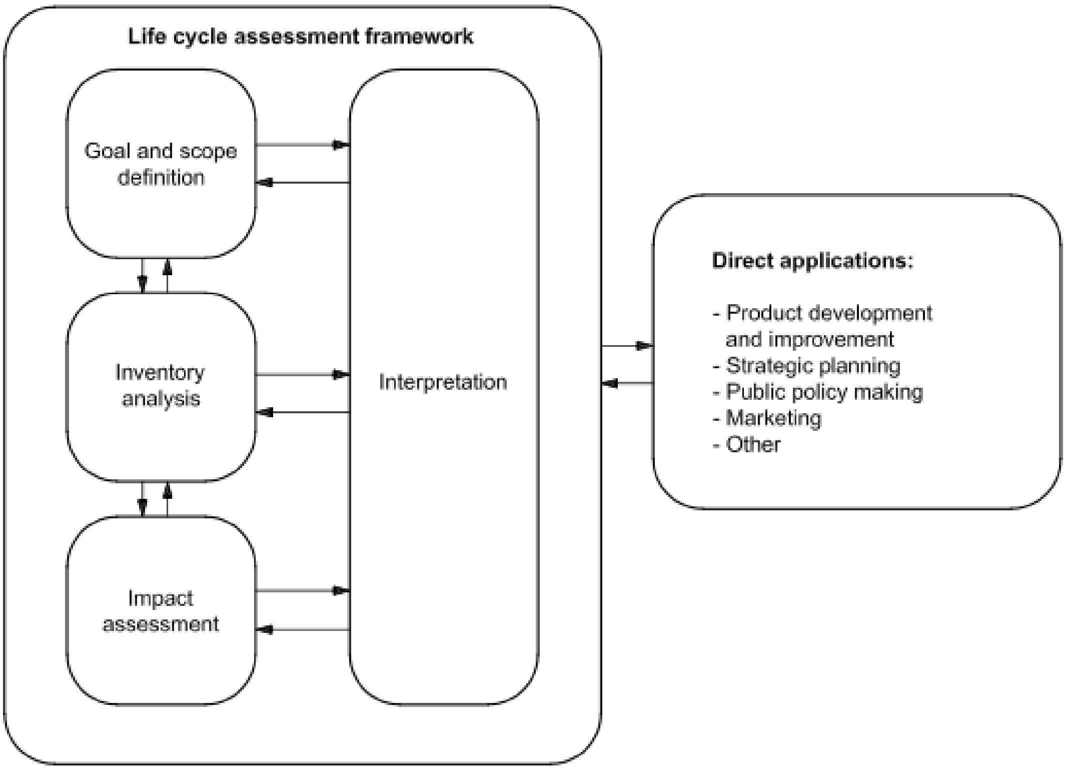

Figure 2 Stages of an LCA (DIN EN ISO 14044 2006)

The results of an LCA can be used for revealing hotspots which can lead to identification of approaches to mitigate the impacts for the development of less harmful processes and products (product and process design and decision making). The LCA may also enable the comparison of different products (benchmarking) and can support marketing and public policies, for instance, to support LCA-based eco-labelling. Another important application of LCA is that of learning, e.g. exploring the environmental properties of the product system studied and learning about relationships of the production system.

A final word: it must be noted that “positive” LCA results do not necessarily mean a process is sustainable. One limitation of the LCA is that the method is restricted to quantify only the ecological aspect of sustainability, thus, excluding from the assessment economic and social factors other than when used as basis for weighting.

This report compiles the goal and scope, the inventory data as well as the LCA results along with their interpretation and corresponding recommendations. This study has been conducted widely according to the requirements of ISO 14040 and ISO 14044. Deviations are marked and justified explicitly in the report.

4 Goal and scope definition

This chapter describes the goal and scope together with the methodological framework of the LCA study. More precise, it comprises the objectives and intended application of the study, a general description of the product function and product system, the system boundaries together with the system function and functional unit as well as the methodological framework.

4.1 Goal

The goal of the study is assessing the potential environmental impacts of the AFTERLIFE process. The assessment focuses particularly on the identification of potential environmental hotspots in order to guide the optimisation of the scaled-up of the AFTERLIFE process.

4.2 Scope

The LCA will be conducted under an attributional approach, i.e. based on inventory of the emissions and removals from the processes used in the life cycle.

4.2.1 Targeted audience

The results and inventory data of this LCA have a public dissemination level. Targeted audience are within the project, the project partners and externally all interested stakeholders.

4.2.2 Geographical and time representativeness

The individual process steps of the AFTERLIFE process were developed and tested at the labs and facilities of the responsible project partners. For example, the pre-treatment of the different wastewater was developed at Lurederra in Spain, filtration at VTT in Finland, VFA and biogas production at Innoven in Italy, PHA-production at Nova ID in Portugal and CSIC in Spain and PHA-recovery at BBEU in Belgium.

At the current status of the project each process step was developed in a different location and therefore the goal of the study is to reflect the European situation. Hence, the corresponding background data, i.e. all materials and utilities are considered from datasets of production in Europe (RER) whenever available. Otherwise global (GLO) production data are considered. Later the pilot plant will be located in Belgium at the facilities of BBEUP.

Primary data reflects the current status of the process designs for the AFTERLIFE process. As such, this is a preliminary assessment which will be updated and completed at the end of the project (deliverable D7.2, due in M46).

4.2.3 Function and functional unit

The functional unit provides a reference to which the inputs and outputs are related. (Klöpffer and Grahl 2009). It defines qualitative and quantitative aspects of the good or service under study along the questions: “what”, “how much”, “how well”, and “for how long”. Further the role of the functional unit definition in LCA is to ensure that the environmental assessment of products or processes are based on a fair comparison.

The functional unit in this assessment is defined as one kg of PHA polymer granulate (namely poly(3-hydroxybutyrate) (P3HB)) with a purity of 99.2 %.

4.2.4 Product system, system boundaries and cut-off criteria

The assessment includes all life cycle stages (production steps) from cradle-to-gate, that is,

1. Acquisition of raw materials, utilities and auxiliaries including transports
2. AFTERLIFE production process

as described exemplarily in Figure 3 for the AFTERLIFE process with Jake wastewater input.

4.2.4.1 Feedstock

The starting material called feedstock is wastewater from several origins. Three different profiles of food processing industries were evaluated as wastewater suppliers:

- Sweet and candies manufacturing (represented by the company JAKE, Spain)
- Cheese manufacturing (represented by the company HERITAGE, Belgium)
- Juice and other products from citric fruits (represented by the company CITROMIL, Spain)

Jake

Jake SA uses water for human consumption for its entire activity and consumes between 40,000 and 50,000 m^3/year, including the process water plus the one used for cleaning and staff use. The volume of concentrated wastewater generated by Jake is between 6,000 and 8,000 m^3/year (between 22,000 and 24,000 m^3/year without concentrating). Considering that of every 1,000 L of wastewater entering into the evaporator tank 650 L are evaporated and 350 L of condensate are generated. Therefore, the evaporation ratio is 65%. Jake products incorporate as an ingredient between 30-40% of the water that enters the line. Part of this water evaporates in the drying process of the product. The most relevant stage in relation to the generation of wastewater is the washing phase of the supplying and mixing of ingredients tanks and the cleaning of equipment and facilities. Gums & Jellies line produces 2/3 of wastewater. Jake uses these concentrated wastewaters for the production of biogas through an anaerobic fermentation with excellent results due to its high content of sugars. These tanks continuously supply waste water to a concentrator through evaporation that concentrates between 60 and 65% of the residual water. The concentrate goes to an expedition deposit from which every day a concentrate cistern is sent to a biomethanization plant where it is valued for the production of biogas. Qualitatively the characteristics of Jake SA wastewater are similar throughout the year as a result of a more or less similar daily activity. The high content of sugars (mainly sucrose and glucose, but also relevant amounts of fructose and maltotriose) (this content varies between 3.25 and 11.13%). It causes high COD values (see Table 1), and according to the information received by the company, causes high viscosity that makes later membrane filtration difficult.

Heritage

The activity of HERITAGE 1466 is focused on the production of Herve cheeses which comprises two different production lines or processes involving the production of: cheeses “a Pate Demi Dure” (PDD line) and cheeses “a Pate Molle” (PM line), as the main products delivered by this milk processing and cheese manufacturing company. Belgian cow milk is the only raw material used in both production lines, and rennet plus distinct ferments are used as additives.

The wastewater generated by HERITAGE derives exclusively from the cleaning operations of the facilities and equipment. Such wastewater contains milk and cheese residues and small amounts of milk whey. Therefore, they can contain remains of fat, proteins, peptides and amino acids. Among sugars, mainly lactose, may appear too.

Citromil

Citromil consumes between 20,000 and 30,000 m^3/y of public supply water. Citromil's consumption of water includes water for the manufacturing processes as well as the equipment and facilities cleaning water. Approximately 90% of the total consumed water is discharged to the public sewerage network after being properly treated. So, both lines of Citromil generate between 18,000 and 27,000 m^3 of wastewater per year. Both lines of work have tanks for collecting and distributing the generated wastewater. These tanks have sufficient capacity to homogenize the wastewater that they collect in one day and are situated before the primary treatment carried out by the company. Then, these wastewaters are sent to the active sludge treatment plant where these waters are treated.
In the extraction process, the oil is separated from the rest of the products. While the juice is extracted, the fruit's crust is scraped and pressed, dragging the obtained products with small showers of water. The scrape dragged by the water is pressed against the sieves of the finishers in two successive stages: separating the sieved and dried solids by pressure on the one hand and the emulsion of oil and water on the other hand.
This oil-water emulsion is fed constantly to the centrifuges, obtaining an oil-water emulsion richer in oil (cream), and water with solids. The cream is again centrifuged (polishers) to remove all the remaining water and solids from the essential oil. The obtained essential oil is introduced into stainless steel decanting tanks with a conical bottom, to decant the waxes by gravity and to obtain a clean oil.
The water with solids obtained in the centrifuges go through a decanter where they are pressed, eliminating a large part of the solids and obtaining water that contains small quantities of oil that has been dragged from the centrifugation stage. This water is distilled to obtain distilled essential oil. After distillation, the distillated oil is decanted, filtered and packed and the water resulting from the process is considered wastewater from the oil line.
In the juice line, about 100 m^3 of wastewater per day is generated in the months of production. There are three stages that generate waste water, reception, transport and washing of the fruit, cleaning of equipment and cleaning of facilities. Wastewater is collected in two tanks with 25 m^3 capacity each before being sent to the pre-treatment and to the treatment plant.
In the line of essential oils, the wastewater passes through steps to extract essential oils and finally they are collected in a tank of 9 m^3 of capacity. This production line generates approximately 10 m^3 of wastewater per day.

Essential Oil Line (E.O.)

Wastewaters generated by the line of essential oils extraction are much more interesting for the purposes of this project than those generated in the juice line. In the case of the Essential Oils Line, the main issue detected for the processing of this wastewater is the presence of an important amount of pulp. This suspended mater clogs easily membrane filters and, thus, should be removed prior to membrane filtration processes. However, the pulp can contain valuable compounds to be utilized. Among the compounds of interest present in this stream are Hesperidin and Limonene, however

Hesperidin is poorly soluble in water. Therefore, another issue to be tackled in pretreatment operations is to determine the fraction in which Hesperidin is enriched after pretreatment.

Juice Line

Wastewater from the Juice Line is poor in compounds of interest, but the high volume of wastewater produced in the process (approx. 90% of total wastewater of Citromil) makes it necessary to integrate a treatment process. The removal of suspended solids in this stream is the main issue for pretreatment operations in order to proceed with further processes within the AFTERLIFE project (ultrafiltration, RO, etc.).

Table 1 Characterization of wastewater and VFA and PHA conversion rates

	gCOD / L WW	gVFA / gCOD	gPHA / gVFA
Jake	135	0.6	0.67
Heritage	3.01	0.3	0.67
Citromil E.O.	46.2	0.2	0.67

Table 2 states the annual production yields according to the starting material, the annual generated wastewater and yields of Table 1.

Table 2 Annual production yields related to starting material

<table>
<tr><th rowspan="2">WW origin</th><th>WW</th><th>PHA (mixed cultures)</th><th>Essential Oils (pure)</th><th>Polyphenols (pure)</th><th>Total amino acids (pure)</th></tr>
<tr><td>m3</td><td colspan="4">ton</td></tr>
<tr><td>Jake</td><td>23 000</td><td>586</td><td></td><td></td><td></td></tr>
<tr><td>Heritage</td><td>15 000</td><td>7</td><td></td><td></td><td></td></tr>
<tr><td>Citromil E.O.</td><td>1 800</td><td>8.73</td><td>1.53</td><td>0.73</td><td></td></tr>
<tr><td>Citromil E.O.</td><td>1 800</td><td>8.73</td><td>1.53</td><td>0.58</td><td>1.39</td></tr>
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4.2.4.2 Production from Jake wastewater

For Jake wastewater the results of the tests showed that a direct use in the VFA-production is most suitable. Therefore, no filtration is considered. The process scheme is described in Figure 3.

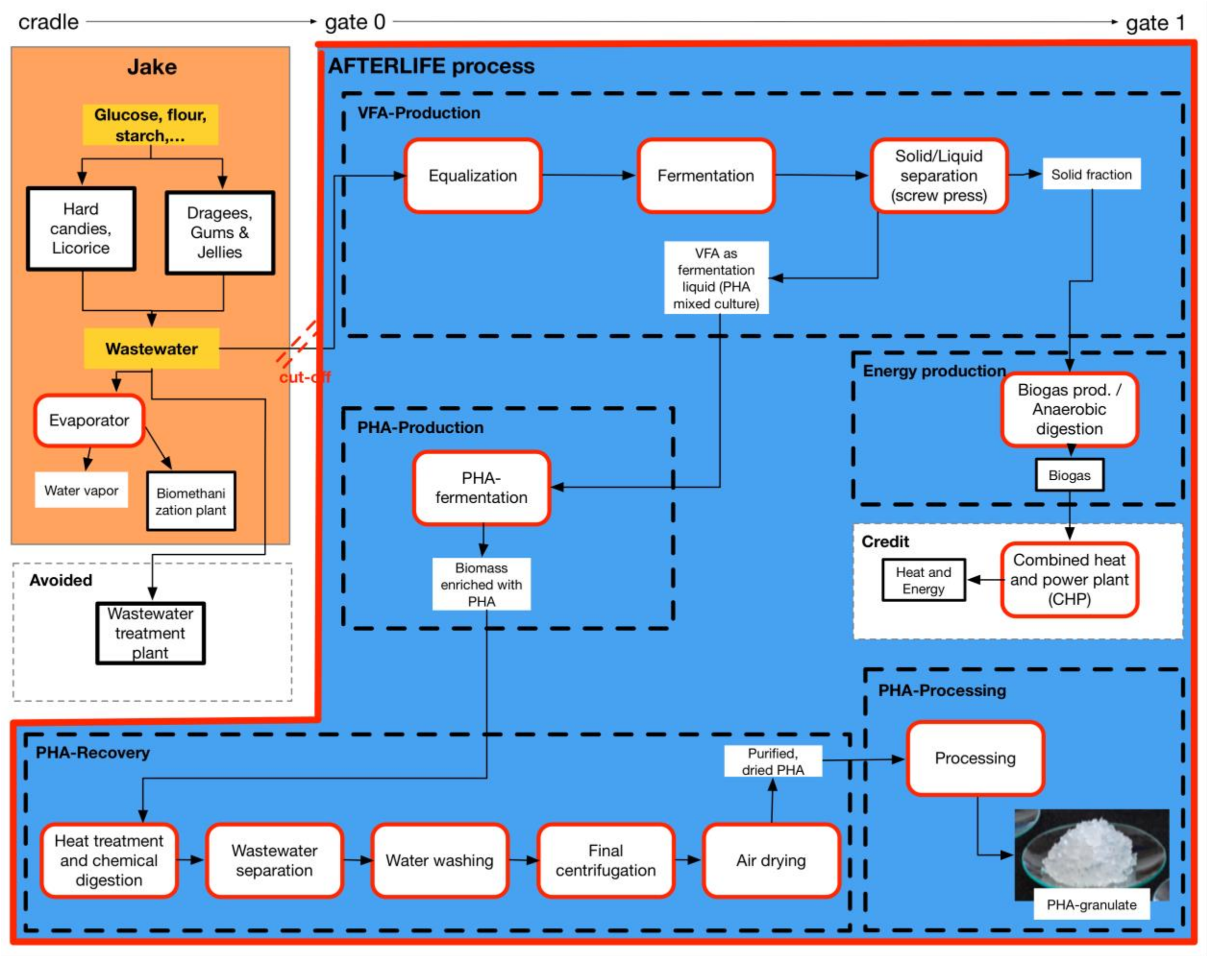

Figure 3 AFTERLIFE process scheme of Jake WW

VFA-production

The purpose of the anaerobic fermentation process implemented in AFTERLIFE is the production of volatile fatty acids (VFAs) from the organic compounds. In a first step the wastewater is equalized with Calcium carbonate ($CaCO_3$) and mixed for the further processing. The fermentation is done under heating and mixing in a bioreactor, which produces the fermentation liquid, which consists the VFAs. The fermentation liquid is further purified via a screw press adding polyelectrolite which separates solid from liquids. The solid fraction is sent to the anaerobic digester for biogas production, while the purified liquid containing VFAs is sent to the PHA production.

PHA-production

Interest is currently focused on the use of mixed microbial cultures coming from wastewater and waste treatment plants, with the aim of turning waste materials into resources. The merits of mixed culture (MC) fermentation are the utilization of organic wastes as the substrate and the absence of a requirement for septic processing. Moreover, a mixed culture may be more robust than a pure culture because it can grow on various organic compounds and adapts easily to the variable substrate composition of the wastes and to the variable environments. As seen previously, the type of VFAs used to feed an MC greatly influences the PHA composition and thus determines the mechanical and thermal properties of the polymer extracted. Hence, only the VFA-production via MC was assessed.

The production of the PHA biopolymer is performed from the VFAs produced during the anaerobic fermentation process. A mixed culture two stage process, consisting in a selection reactor and accumulation reactor, will be implemented and operated. The culture selection will be performed under feast and famine regime, aiming at selecting a high and stable PHA-storage capacity microbial culture and producing the biomass required in the subsequent stage (accumulation reactor) where the PHA-production occurs (maximize PHA cell content). Such a strategy allows the selection of the PHA producing bacteria since the accumulated PHA is a source of carbon during the scarcity periods. The VFAs from the VFA-production are supplemented in the selection reactor with micronutrients. The accumulation reactor is fed with the VFA-stream directly to maximize PHA production.

PHA-recovery

Once produced, the polymer should be separated from the cellular biomass. Different strategies are developed during the project for polymer recovery. In this case, the parameters of recovery (percentage of initial polymer recovery after extraction) and purity (percentage of PHA in the recovered solid) are for modelling the extraction process. It is known that recovery and purification of the polymer account for a huge part of the PHA total production cost and environmental impacts. Consequently, PHA-recovery is a key issue to make the overall process economically and environmentally acceptable. The method to be chosen must lead to high extraction yield and high polymer purity, and PHA degradation must be minimized or nullified during extraction.

PHA-processing

The purified, dried PHB is continuously fed into a plastic extruder. A rotating screw forces the plastic into the heated barrel were the material is melted. Melted material is pressed through a round die, which gives the material the final form. The material is usually cooled down and cut into granulates or pellets, which later can be compounded with additives such as colourant and UV inhibitors.

4.2.4.3 Production from Heritage wastewater

For Heritage wastewater tests resulted that a pre-treatment of several filtration steps would be more suitable than a direct use in the VFA-production. A FOG adsorption with elastomeric material was tested but was neglected in this assessment. The process scheme is described in Figure 4.

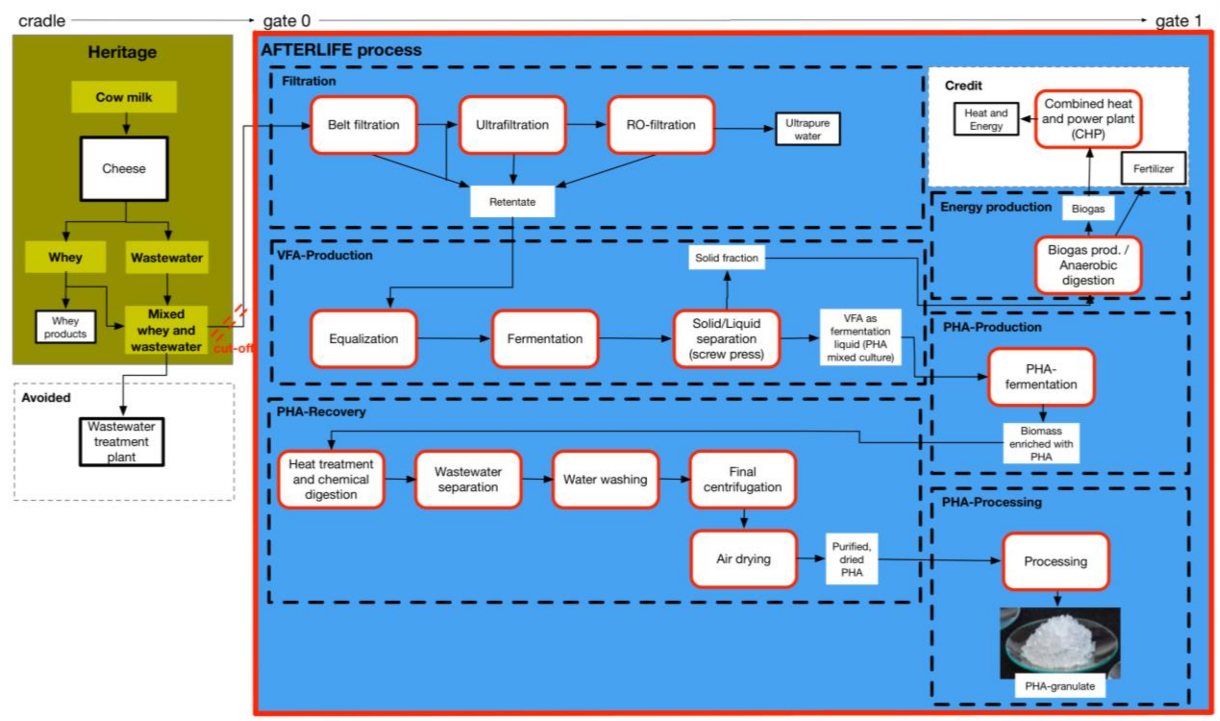

Figure 4 AFTERLIFE process scheme of Heritage WW

Filtration

The wastewater is filtered through cascaded membrane filtration steps. The wastewater enters the filtration unit which is processed through belt-, ultrafiltration and reverse osmosis. The retentate of each filtration step is further processed into the VFA-production process. The water obtained after the last filtration step is suitable for reuse in the AFTERLIFE-process. VFA-production, PHA-production and PHA-recovery steps are described under Chapter 2 as process are assumed to be similar except yields which are described in Table 1.

4.2.4.4 Production from Citromil E.O. line WW

The difference between the Citromil E.O. WW and Jake are the additional filtration steps and the purification of valuable compounds. The full AFTERLIFE process of Citromil E.O. WW can be seen in Figure 5.

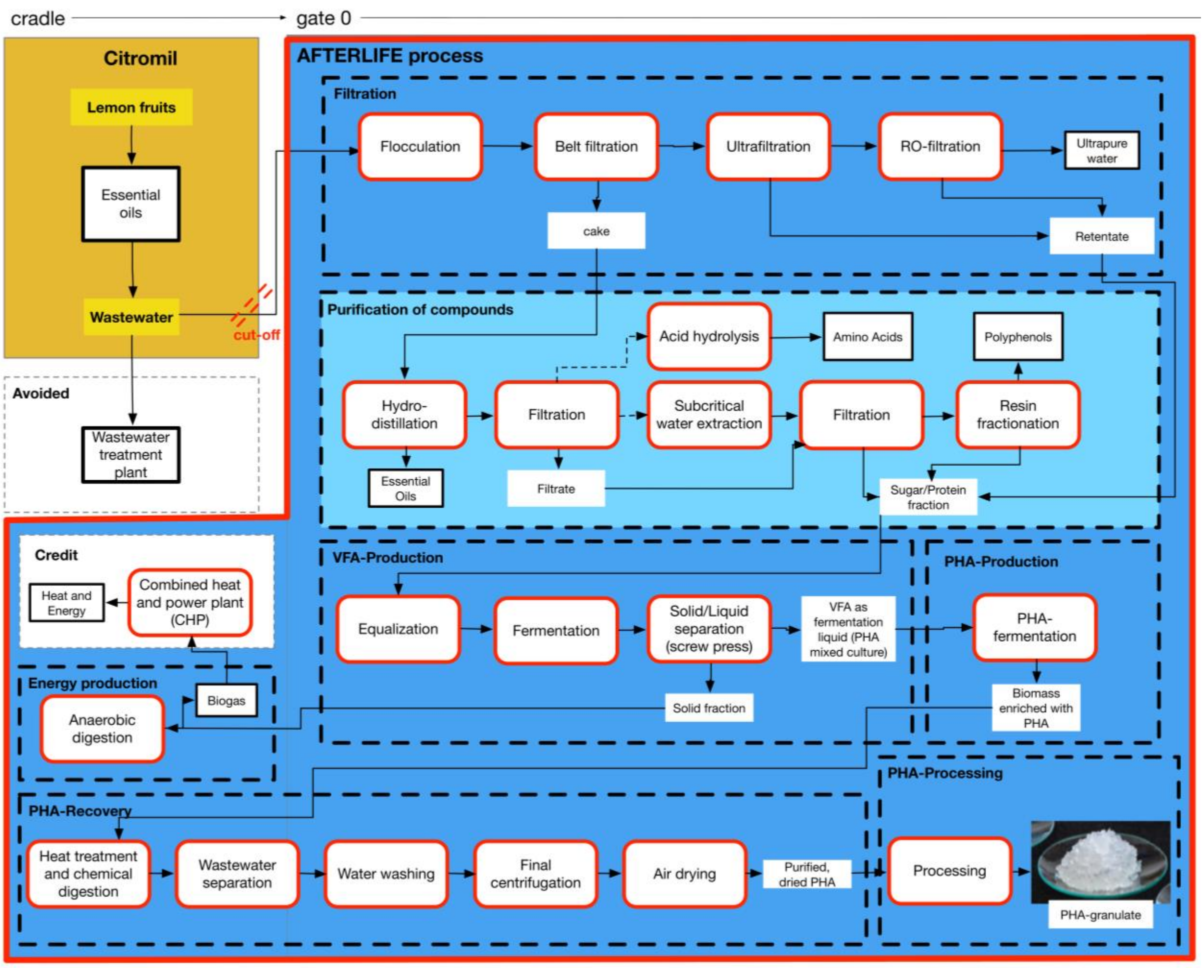

Figure 5 AFTERLIFE process scheme of Citromil E.O. line WW

The starting material is treated in a flocculation step and a filter cake is obtained after the belt filtration. The cake can be treated with hydro- or steam-distillation to obtain essential oils.

Essential oil distillation

Two techniques need to be distinguished: hydro-distillation and steam-distillation.

Hydro-distillation, also known as water distillation, is a technique where the raw material is immerged in water and the solution is heated until vapor formation. Celabor produced, in their tests, 46 ml of essential oils per kg wet cake.

Steam-distillation is carried out by BBEU passing dry steam through the raw material whereby the steam volatile compounds are volatilized. Tests resulted in 8 ml essential oils per kg wet cake (see Deliverable 2.3).

Filtration after E.O. distillation

After the distillation the first step of the process consists in the filtration of the wet cake in order to separate the particles in suspension after the hydro- or steam-distillation step. The residue is treated in subcritical water extraction. As most of the actives remains in the residue after the filtration step (81%) especially for Hesperidin and Diosmin while Limonin and Eriocitrin are distributed in both.

Subcritical water extraction is a promising green-oriented and cost-effective process for the recovery of polar and slightly apolar compounds. Its main advantage is the use of water as solvent and represents an alternative to conventional extraction with solvents such as ethanol, acetone. Residue is extracted with water under subcritical conditions. The major issue is the high wet content of the wet cake which lead to some leaks from the cells. The use of subcritical water allows the destruction of hydrogens bonds, ions interaction and Van der Waals forces that could non-covalently link secondary metabolites to carbohydrates or proteins.

Combination

The final step of the extraction process consists in the combination of the extract obtained after the subcritical water extraction with the filtrate obtained at the filtration step.

Resin fractionation

The fractionation process was carried out on the filtered wet cake. A purity of 22.71% polyphenols could be retrieved. The polyphenols can be further purified to around 69% with centrifugal Partition Chromatography technique (CPC). This step was not included in the assessment.

The retentate of ultra- and RO-filtration could be utilized for the valorisation steps as described in Figure 5, but were considered to be used directly in the VFA-production. Further all other sugar/protein fraction that result during the purification of compounds are considered to be used in the VFA-production as feedstock as described in Figure 5.

Acid hydrolysis

The residue that can be treated in subcritical water extraction can optionally utilized in an acid hydrolysis to obtain amino acids. Experiments showed that per kg residue of filtration after distillation 0.5 kg total AA can be retained with oxalic acid in a thermoreactor.

Further processing

VFA-production, PHA-production, PHA-recovery and PHA-processing steps are described under 0 as processes are assumed to be similar except yields which are described in Table 1.

Biogas/Energy production

The anaerobic digestion converts the organic matter into carbon dioxide and methane, which can be used as a source of energy for the process. The anaerobic digestion of the solid fraction of the VFA-production as well as other biomass waste to produce methane and later energy e.g. for internal use in the AFTERLIFE process is tested by Innoven and was not considered in this analysis, but could be considered in a future analysis.

4.2.5 Allocation

Within LCA, allocation occurs whenever a process produces more than one product (multi-output process), in which case the environmental burden caused by the process needs to be distributed over the different products.

ISO 14040 recommends avoiding allocation wherever possible, though the expansion of the product system, i.e., through the inclusion of a related product system. For bio-based materials, system expansion is an option when the co-products from the bio-based process can also be produced by means of other processes, typically using petrochemical feedstock.

System expansion is also applicable if combustible co-products are used to generate steam or power, which replace steam or power from fossil sources. Another related alternative is the substitution method, which involves identifying the product or function that is replaced or "substituted" by the co-product/co-function of the main product which is being studied, and then quantifying the emissions which would have occurred if this product had been produced. The emissions which would have occurred are then credited to the main product which is being studied.

However, both procedures are subject to shortcomings. In practice, system expansion is difficult to achieve and the substitution approach may fail to quantify the environmental impacts of a specific product with sufficient accuracy. Especially assigning a credit for an equivalent product can involve considerable uncertainty.

For partitioning based on allocation, the most common methods are allocation based on physical parameters such as mass or based on the economic value of the streams generated See Figure 6). Partitioning of the environmental impacts based on mass can generally be considered as appropriate when the economic value of the product and co-product is similar, which is frequently not the case for biomass derived products. Therefore, mass allocation can lead to misleading or distorted interpretation of the results for these product systems. Economic allocation is a fairer choice to solve partitioning caused by multi-functionality in these cases.

By taking the economic value (revenue) of different products and co- and by-products as a basis for allocation, economic partitioning addresses the economic motivation behind a multi-functional process. The rationale is that allocation should be based on the reason for the existence of the multi-functional process and its co-products, which is most often economic (Baumann and Tillman 2004).

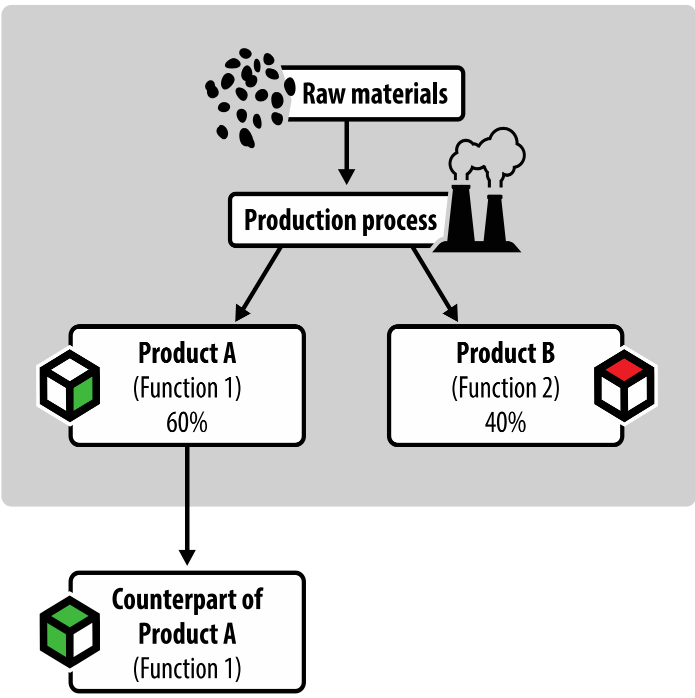

Figure 6 Schematic description of physical allocation

In this LCA, allocation for the feedstock (wastewater) was not applied as the wastewater is considered as waste, hence without any environmental burden.

By-products of the purification of value-added compounds were considered in the hotspot assessment and were allocated at the specific process step based on mass as described in Table 3.

Table 3 Allocation of by-products Citromil E.O. line

Process /Product	Hydrodistillation	Steamdistillation	Filtration after distillation	Filtration after subcritical water extrac.	Resin fractionation
Essential Oil	4.62%	0.81%			
Stream	95.47%	99.06%			
Residue (to subcritical water extraction or acid hydrolysis)			58.80%		
Filtrate			41.20%		
Solids (to VFA-production)				11.80%	
Liquid (to resin fractionation)				88.20%	
Polyphenols					16.50%
Sugar-protein fraction (to VFA-production)					83.50%

As the reuse of water of the RO-filtration step was not considered all impacts of the filtration steps were allocated to the retentate and/or filter cake.

5 Life Cycle Inventory analysis

The Life Cycle Inventory (LCI) consists of detailed tracking of all flows into and out of the product system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance as well as wastes occurring in each process step. The in- and outputs of all necessary processes were collected during the data collection phase from the project partners and literature.

5.1 General considerations

An important part of an LCA case study report is to state data sources, data gaps, taken assumptions and identified limitations that have to be considered when interpreting and concluding the results. In the context of this case study, the following should be considered.

5.1.1 Sources of Life Cycle Inventory data

Foreground data for wastewater to PHA-granulate processes were provided by the responsible project partners throughout email, conference calls, and/or in person-meetings. Further data of each process step were gathered through an excel data collection sheet, which was sent to the involved project partners.

For background processes (e.g. feedstocks, materials, utilities and waste treatment), data were used from the Ecoinvent inventory database (versions 3.4) and USLCI-database. This database is internationally recognized, both from a qualitative (completeness of data, quality of validation process) as well as from a quantitative perspective (scope of included processes). Background production data from Ecoinvent were kept as local (Europe, RER) as possible. When no local processes (RER) were available global data (GLO) were used as a reasonable alternative.

5.2 Inventory data

The detailed inventory data are stated in a separate excel file and a summary of the most important input and output data can be found in Table 4.

Data for the hotspot LCA of the AFTERLIFE processes are obtained from the following sources:

- **Primary data**
    - Filtration (VTT)
    - VFA-production (Innoven)
    - PHA-production (nova ID)
    - PHA-recovery (BBEU)
    - Purification of compounds from (Celabor, CTC and Lurederra).
- **Secondary data**
    - Data on background processes are based on the ecoinvent v3.4 database, literature and one dataset of the USLCI-database.

Table 4 In- and output of the AFTERLIFE process related to each wastewater and material used

ecoinvent dataset	Unit	JAKE	Heritage	Citromil E.O.			
Output							
purified PHB from PHA recovery and purification JAKE (EU) AFTERLIFE	kg	1	1	1			
pure flavonoids (EU) AFTERLIFE	kg				1		
Essential oils from steam distillation (EU) AFTERLIFE	kg						1
amino acids from acid hydrolysis (EU) AFTERLIFE	kg					1	
Input							
Jake wastewater (EU) AFTERLIFE	m3	0.04					
Heritage wastewater (EU) AFTERLIFE	m3		2.123				
Citromil wastewater (EU) AFTERLIFE	m3			0.169	0.244	0.51	0.009
Boric acid, anhydrous, powder {GLO}	kg	1.16E-13	1.63E-12	1.38E-13			
Calcium carbonate, precipitated {RER}	kg	0.199	2.65	0.238			
Copper sulfate {GLO}	kg	2.31E-14	3.26E-13	2.76E-14			
Electricity, medium voltage {RER}	MJ	3.01	4.62E+01	7.18	1.56	2.01	0.032
Ethanol, without water, in 99.7% solution state, from fermentation{CH}	kg	1	1	1.67	1.53		
Iron(III) chloride, without water, in a 12% iron solution state {GLO}	kg	1.16E-12	1.63E-11	1.38E-12			
Manganese dioxide {GLO}	kg	9.25E-14	1.30E-12	1.11E-13			
Polyacrylamide {GLO}	kg	0.095	1.26	0.123	0.0136	0.0283	0.000527
Potassium hydroxide {GLO}	kg	2.31E-14	3.26E-13	2.76E-14			
Sodium sulfate, anhydrite {RER}	kg	0.211	0.211	0.211			
Steam, in chemical industry {RER}	kg	0.441	6.21	0.318			
Sulfuric acid {GLO}	kg	4.08	4.08	4.08			
Wastewater, average {Europe without Switzerland}	m3	0.104	0.248	0.127	0.049		

Water, deionised, from tap water, at user {Europe without Switzerland}	kg	103.1	241.28	719.51	875.88	1826.01	34
Zinc monosulfate {GLO}	kg	9.25E-14	1.30E-12	1.11E-13			
steam produced by BBEUP AFTERLIFE (EU)	kg			53.7	77.78	162.14	3.02
Heat, district or industrial, natural gas {Europe without Switzerland}	MJ			197.19	285.59	595.4	11.08
High impact polystyrene resin, at plant/RNA	kg			0.005	0.011		
Electricity, medium voltage {BE}	MJ				1.85	3.87	0.072
Citric acid {RER}	kg					8.04	

5.2.1 Use of proxies

When necessary to fill data gaps, approximations based on estimates were considered and where no information was available for example for certain chemical substances proxies were used. The use of proxies is reported in the Table 5.

Table 5 ecoinvent dataset chosen as proxy for input substances

Input of process	Proxy chosen from LCI-databases
Iron chloride hexahydrate (FeCl3.6H2O)	Iron(III) chloride, without water, in a 12% iron solution state (GLO)
Manganese chlorid (MnCl2.4H2O)	Manganese dioxide (GLO)
Polyelectrolite	Polyacrylamide (GLO)
Potassium iodide (KI)	Potassium hydroxide (GLO)
Sodium dodecyl sulfate (SDS)	Sodium sulfate, anhydrite (RER)
Zinc sulfate (ZnSo4.7H2O)	Zinc monosulfate (GLO)
Resin, styrene-divinylbenzene	High impact polystyrene resin, at plant/RNA (from USLCI-database)
Oxalic acid	Citric acid (RER)

5.2.2 Assumptions

Due to the fact that some process information, mass and energy flows are not available the following assumptions at inventory level were made in order to perform LCA:

- Retentate of UF- and RO-filtration of CItromil E.O. line to be used directly in the VFA-production steps instead of the purification of compounds steps.
- Only mixed culture PHA-production is considered
- An ethanol recovery of 95% in the PHA-recovery was assumed based on BBEU, by that only the lost amount (5%) were considered in the assessment. The same assumption was made for the used ethanol for the desorption of the resin.
- A recovery rate of 95% of the resin was considered
- The purification step of the essential oil from 22.71% to 69% by CPC was neglected
- A purity of 100% of amino acids, essential oils and polyphenols were assumed
- For the PHA processing:
  - Additives and other materials needed for the compounding are neglected
  - Only the electricity of the compounding is included
  - Material losses during compounding are neglected
- The infrastructure for example reactor, facility or other equipment needed for the foreground AFTERLIFE process was neglected, as the focus of this assessment are the environmental hotspots of the process itself. Specially in low-TRL assessments, it might increase complexity and completeness, but will add uncertainty.
- Electricity is supplied by medium voltage grid based on the average transformation technology and the average electricity loss during transmission in EU.

- Biogenic carbon incorporated in the final products such as PHA is not considered and not stated in the results. A biogenic carbon uptake of around 2.04 kg CO_2 / kg PHA can be assumed (Fernandez-Dacosta, Posada et al. 2015). Note that higher GHG emission savings are obtained from biogenic carbon present in the product assessed, as it can be accounted for as carbon storage. However, it should be noted that is very likely that this CO_2 is emitted again to the atmosphere in the "gate-to-grave".
- The use of process waste such as the solids of the VFA-production into biogas-production may lower the environmental impacts of the AFTERLIFE-process. As according to preliminary calculations, the methane produced converts into low amounts of electricity and heat at the moment. The biogas-production will be therefore neglected in this assessment, but will be included with the latest developments in a future LCA.

5.2.3 Data quality assessment and limitations

Since LCA is a tool founded on quantification, uncertainty is present at the data inventory level. Incorrect estimations or modelling assumptions, outdated data and data gaps are sources of uncertainty. A qualitative analysis of the uncertainty of the inventory data was carried out, to validate the LCIA results (see Table 6). Indications on the quality of data include the evaluation of the reliability and completeness of the data itself, combined with the evaluation of the representativeness (temporal, geographical and technological) of the processes used to model it. The inventory data quality assessment is assessed according to (Weidema and Wesnæs 1996). The indicators are explained in the Annex Chapter **Error! Reference source not found.**, **Error! Reference source not found.**.

Table 6 Data quality assessment of AFTERLIFE process steps

Processes	Source	Importance	Reliability	**Completeness**	**Temporal correlation**	**Geographical correlation**	**Further technological correlation**
1 primary; 2 literature		Low, medium, high	Indicator score (1, 2, 3, 4, 5)				
Filtration	1	Low	2	4	1	1	1
Purificatio of compounds	1, 2	Medium	2/3	4	1	1	1
VFA-production	1	High	2	3	1	1	1
PHA-recovery	1, 2	High	3	3	1	1	1
PHA-processing	2	Low	2	2	3	2	2

The main limitations of this environmental study are due to the data quality of the inventories. On the one hand, the purification of compounds and PHA-production are based on experimental and lab scale data as well as assumptions based on literature. On the other hand, for the filtration steps and VFA-production steps upscaled data was provided by VTT and Innoven. Further the PHA processing is fully based on literature. All in all, the data quality is low due to incomplete data, estimated and calculated data and low TRL processes, mostly lab or experimental data. Therefore, high uncertainties of the results are expected.

6 Life Cycle Impact assessment (LCIA)

Life cycle impact assessment (LCIA) evaluates the significance of potential environmental impacts by using LCI results. It associates inventory data with specific environmental impact categories and category indicators, attempting to understand these impacts. (DIN EN ISO 14040 2006) SimaPro v8.5 LCA software was used to model environmental impacts in this study and to generate the life cycle inventories and impact assessments on which the conclusions are based.

LCIA provides the foundation for analysing the potential contributions of resource extractions and emissions in a life cycle inventory (LCI) to a number of potential impacts. LCI results are, according to ISO 14044, classified into impact categories, each represented by a category indicator. The scientifically robust, and internationally recognized, CML-IA 3.05 baseline-method characterisation factors have been applied and the midpoint impact categories used, are described in Table 7. Additionally, the non-renewable energy use in MJ was assessed.

These impact categories are midpoint impacts and are determined through aggregation of data on emissions to potential impacts in various categories. No weighting was applied and therefore these midpoint indicators focus on single environmental problems, for example climate change or acidification. In the case of global warming potential, for instance, it is measured in terms of CO_2 tonne equivalents and is contributed to by a number of air borne emissions. Carbon dioxide itself is a contributor, as is carbon monoxide (CO) and methane (CH_4). The impact factor weight assigned to these chemicals depends on their impact on global warming relative to the impact of CO_2 emissions, i.e. CH_4 has a higher impact than CO_2 by a factor of 25. Using the midpoint impacts does not provide any insight into assessing the endpoint impacts of the process. These are typically grouped in terms of loss of biodiversity, damage to human health etc. Converting midpoints to endpoints simplifies the interpretation of the LCIA results. However, with each aggregation step, uncertainty in the results increases and therefore these are not examined in this study.

Table 7 Impact categories of this study

Abbrev.	Impact category	Description	Unit	Reference
GWP	Global warming potential with a timeframe of 100 years	Emissions of greenhouse gases that cause an increase in temperature of the lower atmospheric layers (for example CO_2, CH_4, N_2O, CFC, CO…)	kg CO_2 eq.	(Stocker, Qin et al. 2013)
	Ozone formation, Human health	Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NOx and non-methane Volatile Organic Compounds (NMVOCs) and can have a substantial negative impact on human health or on the ecosystem.	kg NOx eq	(Huijbregts, Steinmann et al. 2016)
	Ozone formation, Terrestrial ecosystems		kg NOx eq	
	Fine particulate matter formation	Fine Particulate Matter with a diameter of less than 2.5 µm (PM2.5) represents a complex mixture of organic and inorganic substances.	kg PM2.5 eq	
	Terrestrial acidification	Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in acidity in the soil.	kg SO_2 eq	
	Freshwater eutrophication	Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen.	kg P eq	
	Marine eutrophication	Marine eutrophication occurs due to the discharge of nutrients into the sea or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen.	kg N eq	
	Terrestrial ecotoxicity	The chemical 1,4-dichlorobenzene (1,4-DCB) is used as a reference substance in the midpoint calculations by dividing the calculated potential impact of the chemical by the potential impact of 1,4-DCB emitted to urban air for human toxicity, to fresh water for freshwater ecotoxicity, to seawater for marine ecotoxicity and to industrial soil for terrestrial ecotoxicity.	kg 1,4-DCB	
	Freshwater ecotoxicity		kg 1,4-DCB	
	Marine ecotoxicity		kg 1,4-DCB	
LU	Land use	Focuses on the relative species loss due to local land use, which covers the process of land transformation, land occupation and land relaxation.	m2a crop eq	

	Water consumption	Water consumption is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds or disposed into the sea.	m3	
CED	Cumulative Energy Demand	Primary energy use throughout the life cycle, including energy consumed during extraction, manufacturing and disposal of the raw and auxiliary materials	MJ	(Frischknecht, Jungbluth et al. 2007)
NREU	Non-renewable energy use	Quantification of the energy content of non-renewable energy resources (fossil, nuclear and biomass)	MJ	(Frischknecht, Jungbluth et al. 2007)
ADP (minerals)	Depletion of abiotic resources (minerals)	The depletion is determined for each extraction of minerals based on concentration reserves and rate of de-accumulation	kg Sb eq.	CML-IA baseline 2016
ADP (fossil fuels)	Depletion of abiotic resources (fossil fuels)	The depletion is determined for each extraction of fossil fuels based on concentration reserves and rate of de-accumulation	MJ	CML-IA baseline 2016

7 Results and discussion

The result and discussion are the phase of the LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of the AFTERLIFE process.
Considering the goals of this hotspot LCA the following analysis have been carried out:
Hotspot analysis for AFTERLIFE-process in order to:

- understand the environmental impact of producing PHA-granulate from different wastewaters.
- assist further process optimisation in the second-half of the project.
- guide optimisation of the conceptual process designs under development in work package 5 (Integrated process design and MDO optimisation) of the project.

The following sections present the study results with first an overall comparison of the different wastewater used and a detailed dive into each process environmental hotspots focusing on global warming potential.

7.1 Overview

Figure 7 shows the relative results of each different WW used in relation to the impact categories assessed. Results clearly indicate that PHA produced with Jake WW as input has the lowest environmental impact in comparison with WW from Heritage and Citromil E.O. line. Impact are depending on the impact category up to 6-7 times lower.

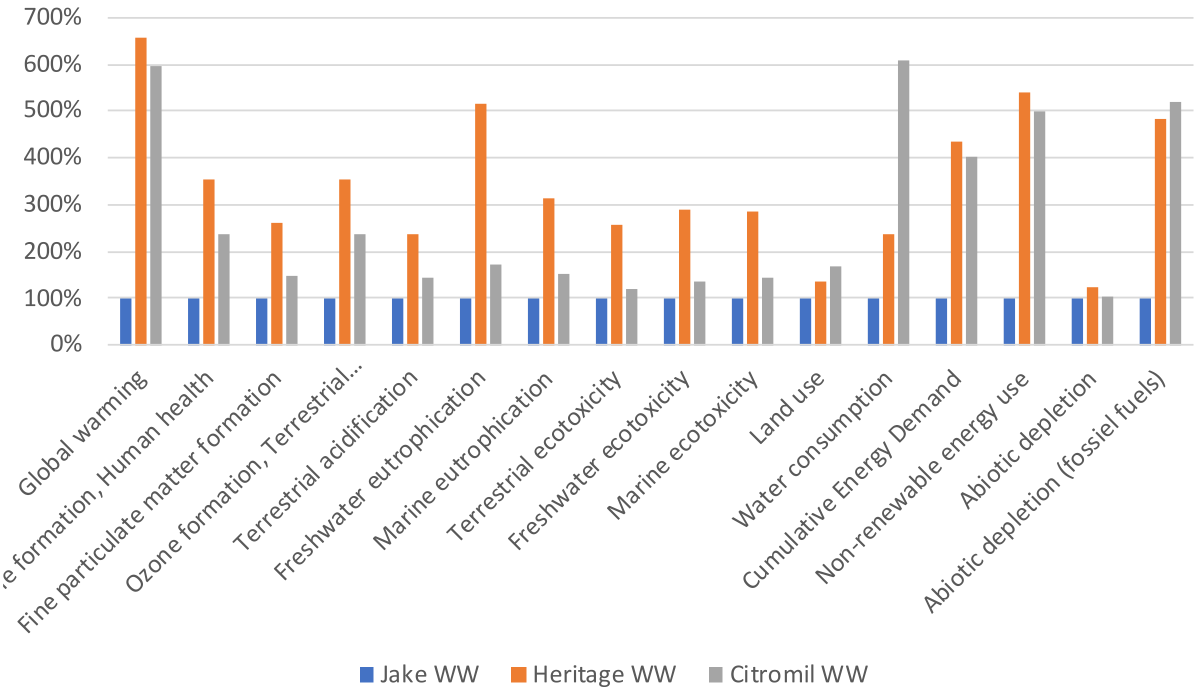

Figure 7 Comparison of different WW used in the AFTERLIFE process

Figure 8 states the global warming potential of one kg PHA by input material and WW origin. Highest impacts are from heat used for the steam distillation for Citromil E.O line WW, electricity, CaCO3 and Polyacrylamide for the Heritage WW. Overall the greenhouse gas warming potential (GWP) of PHA from Heritage WW and Citromil WW are around 6 times higher compared to PHA from Jake. Jake WW performs that well in comparison due to the fact that most PHA per m^3 WW can be produced, in other words the yields are considerably higher compared to other WW (see Table 2). Further a reason could be that most experiments were done firstly on the Jake WW, which means the data on the Jake WW to PHA production is the most precise one.

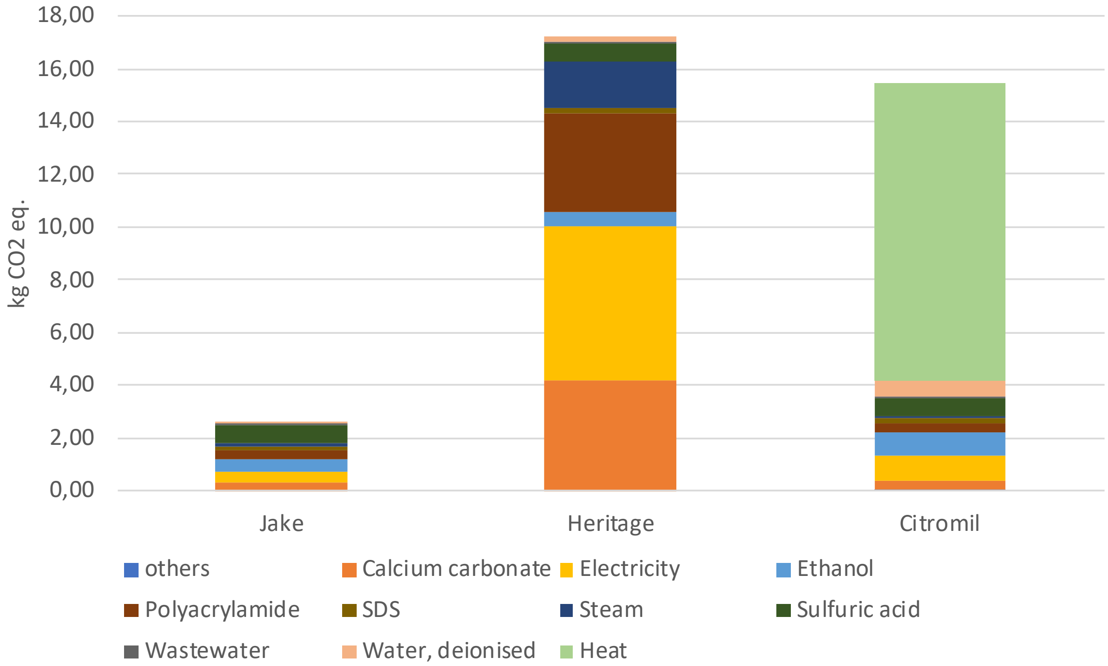

Figure 8 Global Warming Potential per kg PHA and input material

7.2 Hotspot analysis for Jake wastewater

The highest environmental impacts throughout all process steps is the PHA-recovery and purification as presented in Figure 9.

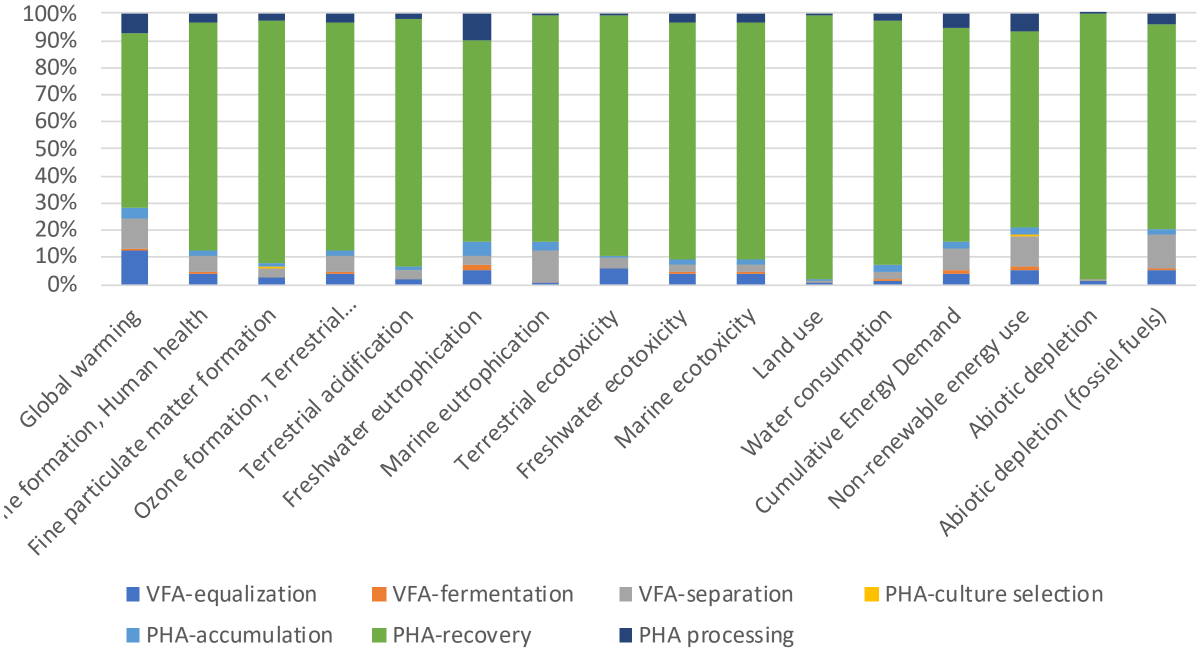

Figure 9 Environmental impact per process step – Jake WW

The GWP by process step and material is shown in Figure 10. The highest impact of the process is due to the $CaCO_3$ consumption in the VFA-equalization step, the polyacrylamide used in the VFA-separation and the use of ethanol, sulfuric acid, SDS and steam of the PHA-recovery. The impacts of energy usage such as electricity and heat are low compared to the impacts of materials.

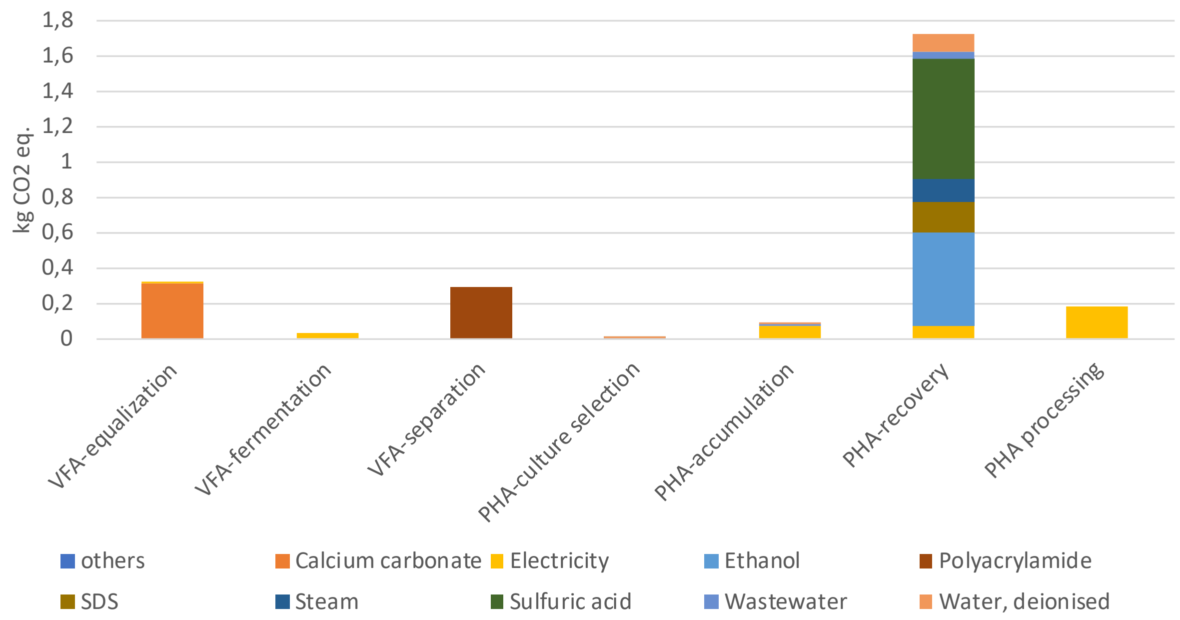

Figure 10 Global Warming Potential per kg PHA – Jake WW

7.3 Hotspot analysis for Heritage wastewater

The environmental hotspots of PHA from Heritage WW are the PHA-recovery, VFA-separation and equalization (see Figure 11), which each around 20% to 40% contribution depending on the impact category. The VFA-steps contribute more to the overall results because the amount of WW processed to these steps compared to the amount of PHA produced is much higher.

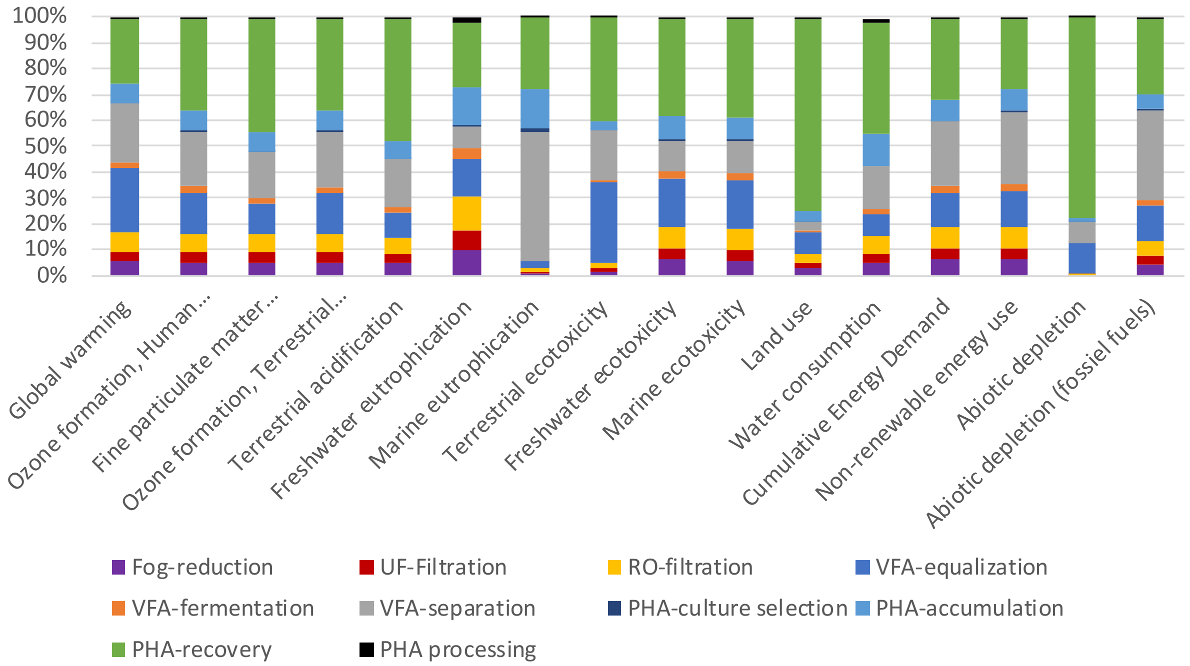

Figure 11 Environmental impact per process step – Heritage WW

Similar to PHA from Jake WW, also the PHA from Heritage has high impact due to materials such as $CaCO_3$, Polyacrylamide and sulfuric acid. Here additional impact arises from the electricity use of the filtration steps but these impacts are small compared to the material impact from VFA-steps and PHA-recovery.

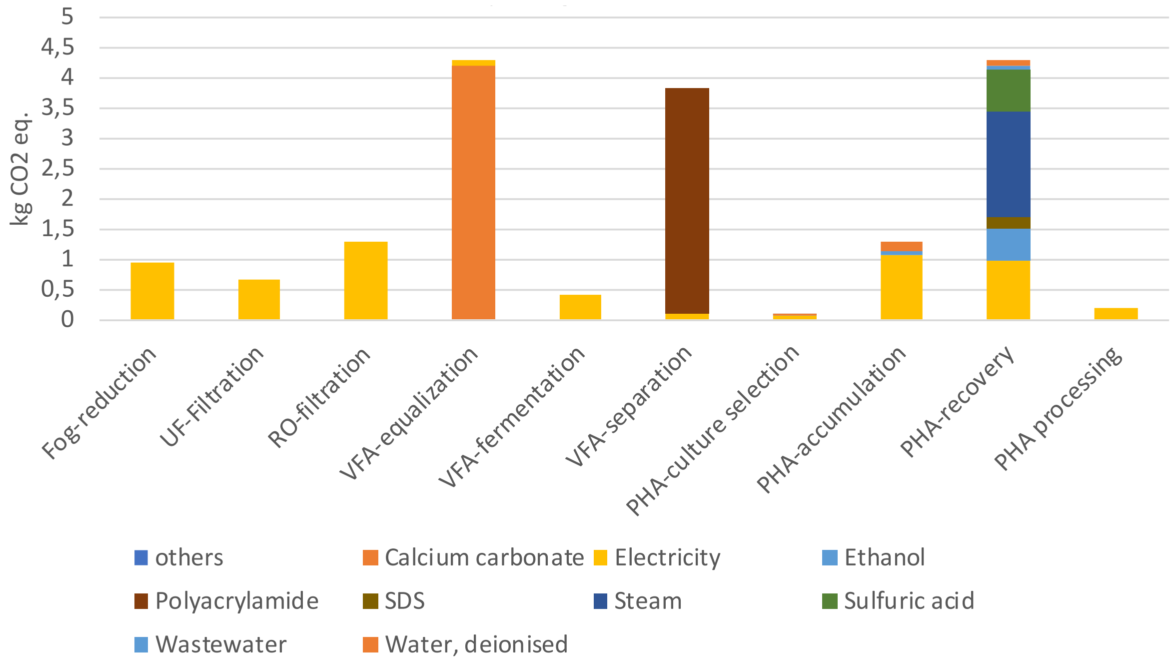

Figure 12 Global Warming Potential per kg PHA – Heritage WW

7.4 Hotspot analysis for Citromil E.O. wastewater

The hotspots of each process step for all considered impact categories can be seen in Figure 13. Hotspots are the steam distillation and the PHA-recovery of PHA from Citromil E.O. WW. The resin fractionation can be considered a hotspot for the impact categories land use and marine eutrophication.

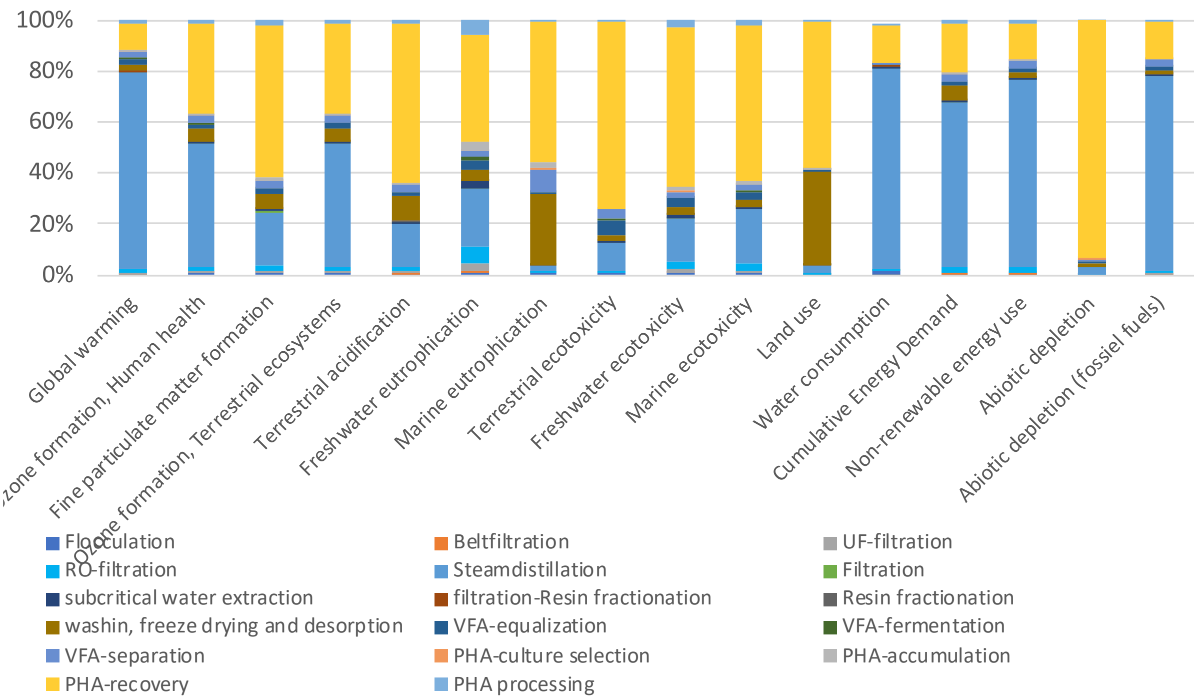

Figure 13 Environmental impact per process step of PHA – Citromil E.O. WW

Most of the GWP impact are allocated to the PHA-granulate produced (see Figure 14) due to the chosen mass allocation as described in section 4.2.4. Therefore, also the PHA-granulate has its highest impacts due to the steam-distillation. Figure 14 also shows that by producing amino acids lower yield of polyphenols are expected and a lower GWP for PHA can be achieved as around half of the GWP impact from the steam-distillation is allocated to the amino acids. By having several by-products, the environmental impacts can be allocated to these products, which may be beneficial for the main product of the process.

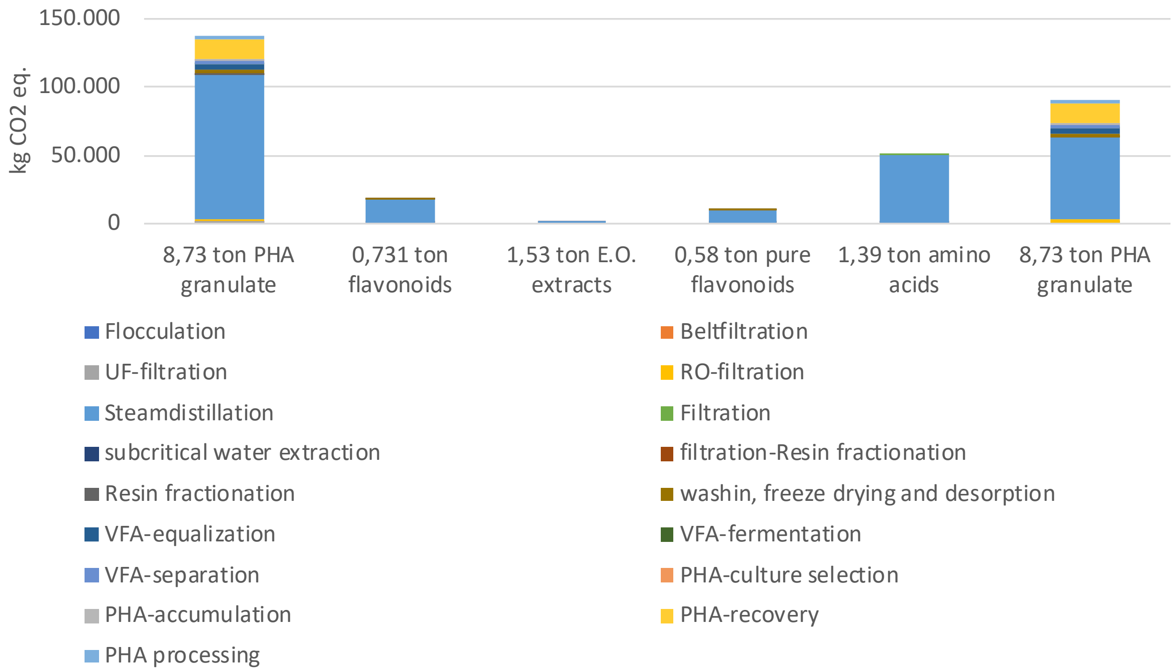

Figure 14 Global Warming Potential per annual produced products – Citromil E.O. WW

As the steam-distillation has by far the highest GWP impacts, other energy and material contributions cannot be seen in Figure 15. Therefore, in Figure 16 the GWP-impacts are shown without the steam-distillation impacts. Again, main GWP-impacts are due to the material use in the resin fractionation, VFA-separation, VFA-equalization and PHA-recovery. Still overall main impacts are due to energy usage such as steam and electricity.

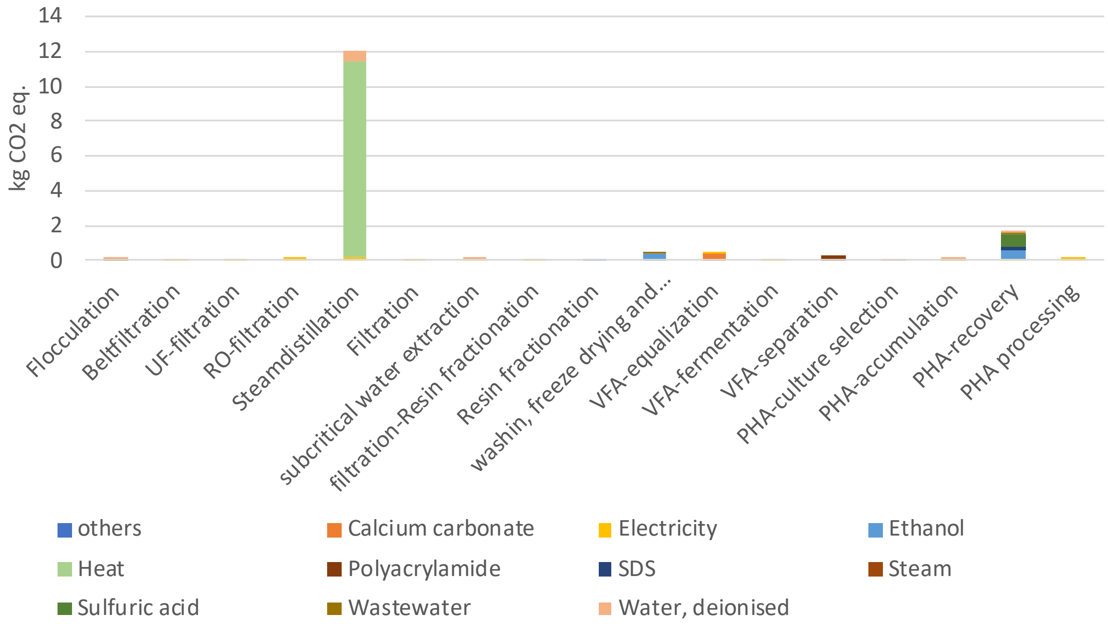

Figure 15 Global Warming Potential per kg PHA – Citromil E.O. WW

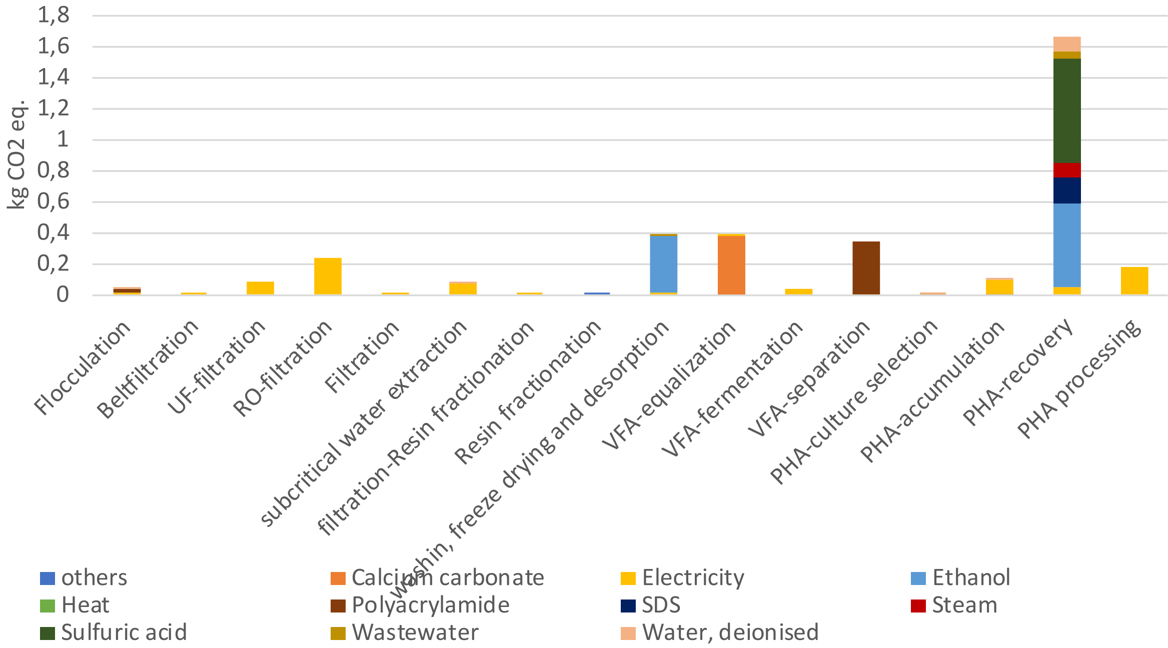

Figure 16 Global Warming Potential per kg PHA (without steam distillation) – Citromil E.O. WW

The extraction of essential oils was testes via hydro- and steam-distillation and the yields are stated in section 4.2.4. In Figure 17 both methods are compared. The results show that even with a higher yield the GWP-impacts of the consumed electricity for the hydro-distillation are around 3 times higher compared to steam with lower yield. Furthermore, it has to be noted that the hydro-distillation was done in smaller scale (around 3 L compared to 20 L). Therefore, the steam-distillation seems to be the favourable option and as the steam-input is based on first tests the consumption can be lowered in the near future.

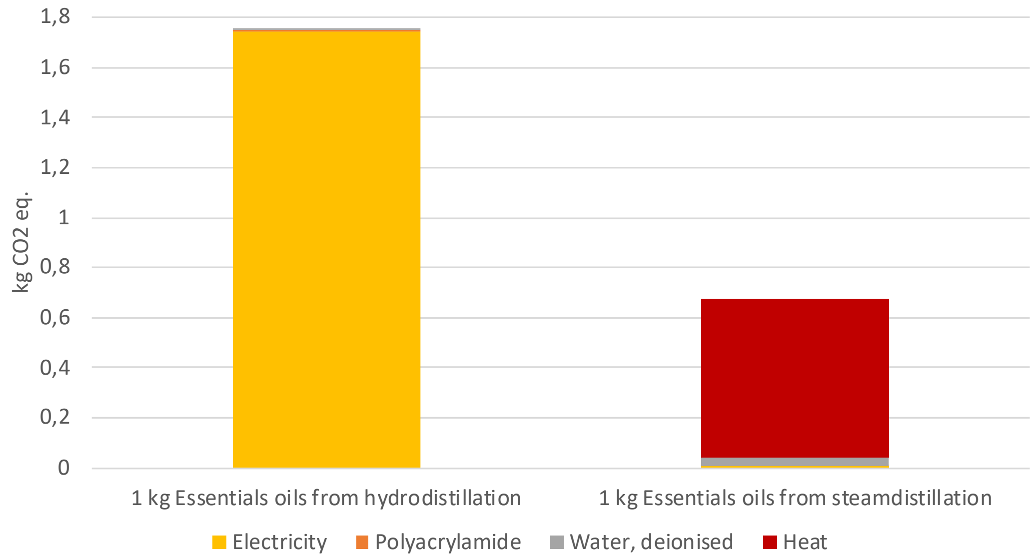

Figure 17 Global Warming Potential per kg essential oil (hydro- vs. steam-distillation) – Citromil E.O. WW

8 Conclusions and further work

Based on the analyses in previous chapters, the following conclusion are drawn up for this hotspot LCA study:

The results of this hotspot LCA give an early understanding of the environmental performance (impacts on ecosystems, human health and depletion of resources) of the AFTERLIFE PHAs, essential oils, amino acids and polyphenols production at their current *status quo* of development. The identification of hotspots at this stage of the project can lead to identification of approaches to mitigate the impacts of the AFTERLIFE process. At the moment PHA produced from Jake WW seems to be the most promising feedstock.

As a consequence, the findings of this hotspot LCA can inform other WPs and improve the quality of the full TEE and full LCA performed in WP7 in a sustainable integrated development at the end of the project (Figure 18). At this stage the environmental impacts of the AFTERLIFE process were presented in M21 at the GA in Belgium and in M27 at the GA in Madrid to received feedback from the consortium, to learn and to develop the LCA-model further to the results presented in this report.

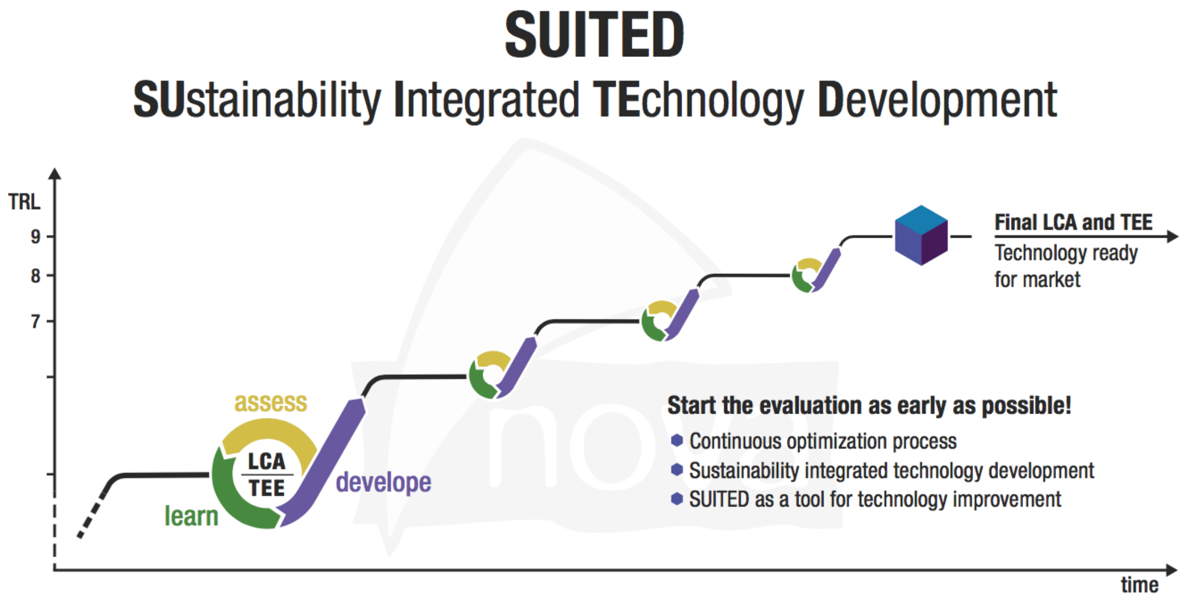

Figure 18 Sustainability integrated development

The foreground AFTERLIFE processes are based on primary mainly experimental lab scale data from the project partners and are subject to optimization in the course of the project. Particularly, the VFA production steps, the PHA recovery and steam-distillation (sources of major environmental impacts) are subject to optimization. Further research activities should tackle this aspect and an upscaled process may lead to better results. The AFTERLIFE process at this stage do not yet include heat integration. Further improvements in the LCA will be achieved when this is included. The main limitations of this environmental study are due to the data quality of the inventories. On the one hand, some inputs are based on secondary data (literature), are based on lab scale processes (lab experiments or simulation models from measured or estimated data, therefore scoring badly in completeness. Due to lack of some LCI data, proxies were used for the resin, oxalic acid, polyelectrolite and others, which leads to unreliability when assessing the environmental performance of these inputs.

LCA is a tool founded on quantification. The LCAs carried out in this study take place during the experimental and modelling stage of development. Given that some uncertainty is present at the data inventory level the potential environmental impacts are to be considered informative and expected to become lower along the development path with increasing knowledge and decreasing uncertainty (see Figure 19).

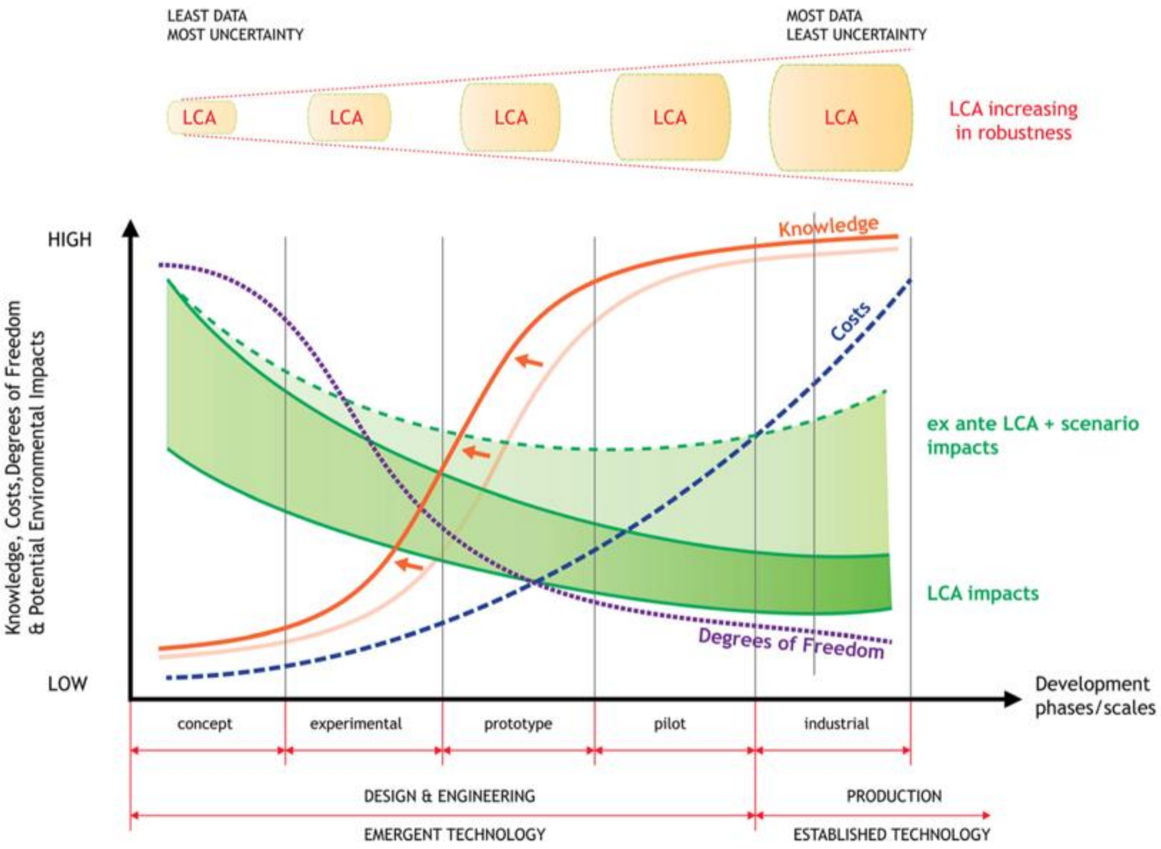

Figure 19 Technology development related to LCA (Villares, Işıldar et al. 2017)

To conclude, this LCA will be updated in a final report (deliverable D7.2 “Final Life-cycle assessment” due at M46, at the end of the project,) including optimization, feedback loops and a more detailed assessment of the AFTERLIFE-process with the most promising wastewater as feedstock. The full LCA will be based on measured data from the pilot plant, which is been set up at the facilities of BBEU. Additionally, complementary to the LCA the following analyses will be included:

- Final Techno-economic Assessment (M46)
- Social and socio-economic impacts of the processes and products developed in the project (M46)

9 Appendix

9.1 Inventory data quality assessment

Table 8 Indicator of Inventory data quality assessment adapted from (Weidema and Wesnæs 1996)

Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites over adequate periods	Representative data from an adequate number of sites over shorter periods	Representative data from a smaller number of sites and shorter perios or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or over shorter periods
Temporal correlation	Less than 3 years difference to year of study	Less than 6 years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years difference
Geographic correlation	Data from study area	Average data from larger area that includes the studied area	Data from areas with similar production conditions	Data from areas with slightly similar production conditions	Data from unknown areas or areas with very different production conditions
Further technological correlation	Data from studied businesses, processes and materials	Data from studied processes and materials from different businessess	Data on studied processes and materials from a different technology	Data on related processes or materials with the same technology	Data on related processes or materials with different technology

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