CHEERS

Producing novel non-plant biomass feedstocks and bio-based products through upcycling and the cascading use of brewery side-streams

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Abbreviations and Acronyms

AoP = Areas of Protection
BES = Bio-Electrochemical System
BSG = Brewer’s Spent Grains
CAPEX = Capital Expenditure
CED = Cumulative Energy Demand
CEPCI = Chemical Engineering Plant Cost Index
CFF = Circular Footprint Formula
CFs = Characterization Factors
CH_4 = Methane
Cl_2 = Chlorine
CO_2 = Carbon dioxide
D1.4 = D1.4 First feasibility study of CHEERS approach at the case study site
DSP = Down Stream Process
EC = Equipment Cost
EF = Environmental Footprint
E-LCA = Environmental Life Cycle Assessment
EoL = End-of-Life
EP = Eco Points
ERA = European Research Area
ESM = Ecological Scarcity Method
FU = Functional Unit
GHG = Greenhouse Gas
GWP = Global Warming Potential
IBU = International Bitterness Unit
ILCD = International Reference Life Cycle Data System
IPCC = Intergovernmental Panel on Climate Change
IRR = Internal Rate of Return
IUCN = International Union for Conservation of Nature
JRC = Joint Research Council
LCI = Life Cycle Inventory
LCIA = Life Cycle Impact Assessment
LCSA = Life Cycle Sustainability Assessment
LF = Lang Factor
NaCl = Sodium chloride
NaOH = Sodium hydroxide
NGO = Non-Governmental Organizations
NPV = Net Present Value

OEF = Organisation Environmental Footprint
OEFSRs = Organisation Environmental Footprint Sector Rules
OPEX = Operational Expenditure
PBP = Payback Period
PEF = Product Environmental Footprint
PEFCRs = Product Environmental Footprint Category Rules
PSIA = Product Social Impact Assessment
PSILCA = Product Social Impact Life Cycle Assessment
QALY = Quality-Adjusted Life Years
SAR = Species-Area Relationship
SCP = Single Cell Protein
SDGs = Sustainable Development Goals
SETAC = Society of Environmental Toxicology and Chemistry
S-LCA = Social Life Cycle Assessment
TCI = Total Capital Investment
TEA = Techno-Economic Assessment
TRL = Technological Readiness Level
UNEP = United Nations Environment Programme
VC = Value Chain
VFA = Volatile Fatty Acids
WP = Work Package
ZHAW = Zurich University of Applied Sciences

Executive Summary

This methodology report outlines the planned approach for conducting the Techno-economic Assessment (TEA) and Life Cycle Sustainability Assessment (LCSA) within the CHEERS project. The project, funded under Grant Agreement (GA) no. 101060814, aims to develop innovative bio-based products valorising side streams from beer production. The TEA and LCSA will provide a comprehensive perspective of the impacts of the CHEERS biorefinery by considering the environmental, social, and economic impacts associated with the bio-based products throughout their life cycle.

The CHEERS biorefinery enables 5 different value chains (VC) using two different platforms for the transformation of by-products from the brewing industry into valuable products, increasing the economic value of the side streams from beer production and reducing the environmental impact of this process. The TEA and LSCA of CHEERS solutions will be assessed at three process capacity scales for valorising the by-products of small-, medium-, and large-scale breweries.

The functional unit for the TEA and LCSA are the products (insect flour, animal feed, disinfectant, ectoine and pet food) from the valorisation of the by-products resulting from 1 hl beer production (about 20 kg of brewers spent grain as well as 0.3-1 m^3 of wastewater and 3.5 kg of CO_2, and 0.17 kg of CH_4), via the microbial and insect platform in the CHEERS biorefinery.

To ensure accuracy of the assessments, the TEA and LSCA will adopt a standardized and scientifically sound methodology, involving data gathering from different members of the CHEERS consortium through questionnaires and a thorough literature review and will collect relevant data to establish the life cycle inventory for each bio-based product, considering the specific context of the CHEERS project.

The TEA and LCSA will cover a wide range of economic, environmental, and social indicators covering the whole life cycle of the CHEERS biorefinery. This includes environmental indicators like greenhouse gas emissions, cumulative energy demand and biodiversity impact, social indicators like working conditions, corruption, and inequality as well as economic indicators like net present value and payback period.

For quantifying the environmental and social impacts, the project will work with modelling assessment tools, including SimaPro and openLCA software. These tools will facilitate a comprehensive analysis, considering a wide range of environmental and social factors.

This comprehensive approach to assess the CHEERS biorefinery informs decisions by considering environmental, social, and economic sustainability across the entire life cycle of the valorisation.

1 Introduction

Europe is currently facing the challenge of balancing industrial activities and economic growth with environmental preservation. To address this issue and promote sustainability and competitiveness in the industrial sector, Europe's resource independence is of utmost importance. In response, the European Commission has introduced initiatives such as the Circular Economy Action Plan, the Bioeconomy Strategy, and the EU Green Deal. Within this framework, the establishment of sustainable and innovative local biorefineries holds great potential to contribute to the self-sufficiency of the European Union and enhance industrial competitiveness. Moreover, these biorefineries align with EU policies on the environment and climate, further supporting the overall objectives.

The European bioeconomy sector needs to innovate and deliver scalable concepts to efficiently use the available and sustainably accessible biomass. The goal of the CHEERS project is to develop a scalable biorefinery concept for the European bioeconomy sector and raising its technology readiness level. The focus of the CHEERS project is on valorising biomass side streams from breweries via microbial and insect platforms to produce bio-based products such as food and feed ingredients, cosmetics, and chemicals. The overall aim of the project is to optimize resource efficiency and increase circularity while minimizing the impact on biodiversity.

The sustainability of the CHEERS biorefinery, employing innovative biological platforms will be validated through demonstration-scale operations at Mahou San Miguel's brewery in Spain. In the CHEERS project, the environmental, social, and economic sustainability performance will be compared to non-plant biomass alternatives using a Life Cycle Sustainability Assessment (LCSA) approach. As part of the LCSA, an Environmental Life Cycle Assessment (E-LCA), a Social Life Cycle Assessment (S-LCA) as well as a Techno-Economic Assessment (TEA) will be conducted, taking into account the ecological, social and economic dimensions associated with the project's processes and products.

This report describes the methodological approaches for the TEA and LCSA of the CHEERS biorefinery. The goal of this deliverable is to describe the approach for validating the economic feasibility of CHEERS biorefinery as well the environmental benefits of valorising agricultural side streams with an emphasis on resource, water and energy efficiency in order to show the contribution of the CHEERS project to the progress of the European bioeconomy sector, sustainability, resource efficiency and innovation.

1.1 Biorefinery Concept and the Value Chains

The CHEERS project introduces a novel biorefinery concept, drawing inspiration from nature's biodiversity, specifically insect and microbial platforms. Its primary goal is to valorise the currently underutilized or wasted secondary streams, such as brewer’s spent grain, yeast, wastewater, CO_2, and CH_4, obtained from the brewing industry. The objective is to convert these side streams into innovative bio-based products that can compete effectively in the market (Figure 1).

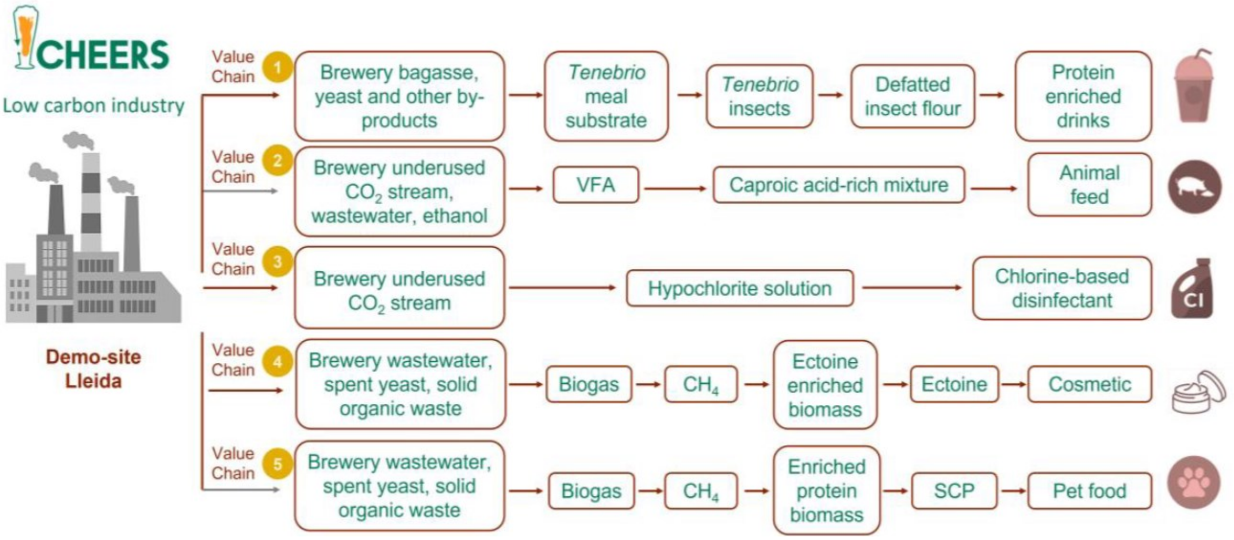

Figure 1: New bio-based value chains proposed in CHEERS

The brewery sector serves as a prominent illustration of bio-based industries, wherein significant quantities of low-value organic solid by-products like brewer's spent grains (BSG) (in the CHEERS proposal and Grant Agreement it is called bagasse), wastewater, and biogenic gases (e.g., CO_2 and CH_4) are currently underutilized or wasted, resulting in a loss of valuable carbon resources. This situation presents unique and untapped business opportunities.

BSG is the residual barley malt left over during the initial stage of the brewing process, amounting to around 20 kg per hectolitre of beer produced. As a result, it serves as the primary solid by-product of the brewing industry, generated in significant quantities worldwide by breweries of various scales throughout the year. Currently, BSG finds its primary applications in the production of animal feeds and fertilizers due to its nutrient content, as well as an alternative energy source (Rachwał et al., 2020). More recently, it has also gained attention in biotechnological processes, serving as a substrate for cultivating microorganisms and producing enzymes.

However, its high moisture content makes it prone to rapid deterioration caused by microbial activity. Storage under normal environmental conditions can promote the growth of microorganisms such as fungi and yeasts, leading to the decomposition of the BSG. The water content of BSG is very high, ranging from 77% to 81% by weight (Mussatto et al., 2006). Using BSG to produce biogas is possible, but not economically viable using the standard conventional anaerobic digestion because it takes much time and the biodegradability is not high (Panjičko et al., 2017).

Additionally, the cleaning processes in the brewing industry involved in tanks, bottles, machines, and floors result in the production of large quantities of polluted water. The production of 1 litre of beer is estimated to generate 3-10 litres (0.3-1 m^3 per hectolitre) of waste effluent, depending on production volume and water usage. This highlights the significant water consumption associated with beer brewing processes (Simate et al., 2011). Biogas from anaerobic digestion of that wastewater and sludge treatment will mostly be used for power or heat production and subsequent CO_2 discharged to the atmosphere. This leads to a total of 3.5 kg of CO_2, and 0.17 kg of CH_4 per hectolitre beer produced. Table 1 provides a comprehensive overview of the total quantity of waste streams and by-products generated within a one-year timeframe. Table 2 presents the existing applications of MAHOU SAN MIGUEL side-streams and suggests alternative uses as proposed in the CHEERS project.

Table 1: Main waste and by-products mass flows available for CHEERS technologies deployment at Lleida case study site.

Description	Unit	Measurement
Spent yeast extract (89.4% humidity)	ton/y	1 566
Brewer's spent grain (76.3% humidity)	ton/y	28 381
Biogas (65% CH_4)	Nm^3/y	303 231
CO_2 fermentation surplus (100% CO_2)	ton/y	3 928
Wastewater (99.6% humidity)	m^3/y	520 000
Expired ethanol and dealcoholized products inlet (95.7% humidity)	ton/y	3 410.4

Table 2: Current and foreseen side-stream valorisation scenarios in the brewery sector

Side-stream	Current use	New use proposed by CHEERS
Brewer's spent grains (Bagasse)	BSG (20 kg wet BSG per hl beer) as low-grade animal feed	Insect protein
CO_2 from beer fermentation	Large breweries: 0.35 kg CO_2/hl beer used for beer carbonation and 3.15 kg CO_2/hl beer discharged to the atmosphere.	Caproic acid (coupled to wastewater treatment), hypochlorite
Biogas from wastewater and sludge treatment	Heat & power (and subsequent CO_2 discharged to the atmosphere).	Caproic acid, hypochlorite, ectoine, high-quality single-cell protein

1.2 CHEERS project

In the CHEERS project several work packages are involved (Figure 2).

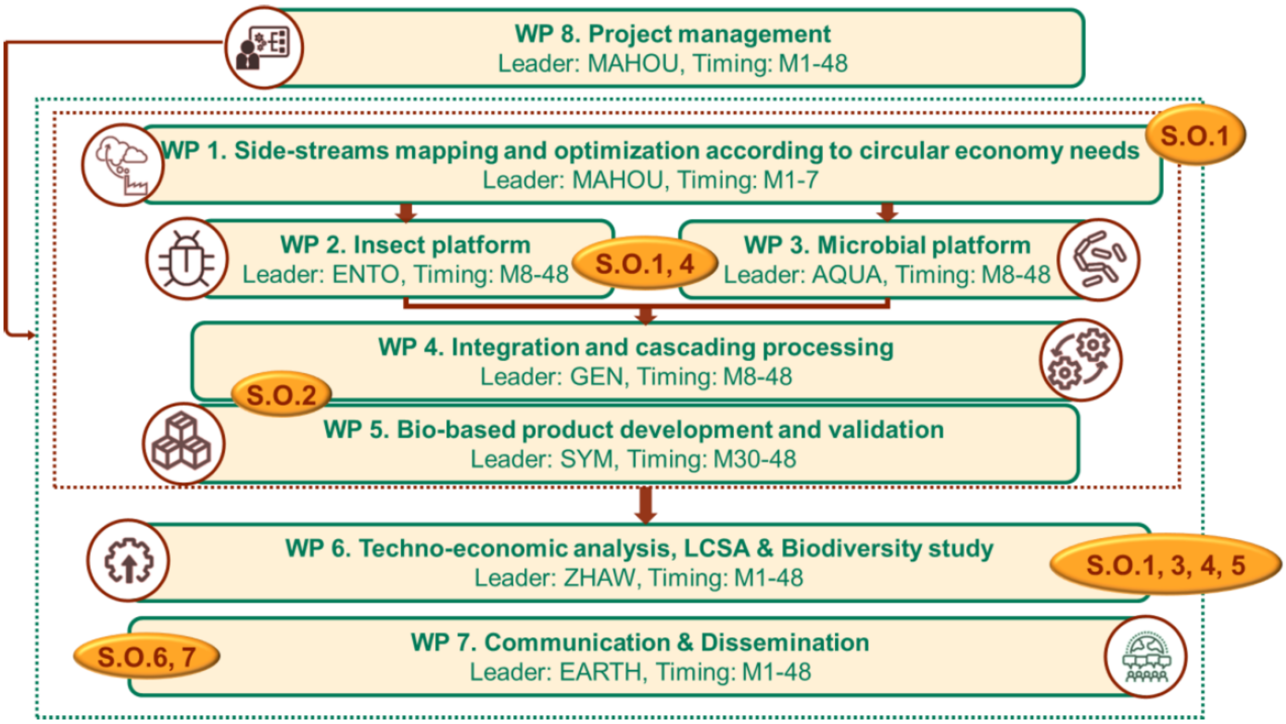

Figure 2: Graphical overall structure of the work proposed in CHEERS and WP interrelation

In the CHEERS project, Work Package 1 (WP1) focuses on creating an inventory of side-streams from common bio-based industries. This inventory will help tailor process technologies to the specific conditions of the case study site. It will also provide input for a feasibility study of CHEERS, which will analyse regulatory and market barriers related to the project's bio-based products.

The data generated in WP1 will guide the design, construction, and long-term validation of insect and microbial-based technologies in WP2 and WP3.

Work Package 4 (WP4) will involve biomass processing, purification of target bio-products, and upcycling of remaining streams. The bio-products obtained at the demonstration scale will be characterized, and formulation and validation activities for final products will be conducted in WP5.

Work Package 6 (WP6) (current document belongs to WP6) will be responsible for the final evaluations of the techno-economic, environmental (including biodiversity), and social performance of the bio-based products. This evaluation will be based on the results gathered from WP2 to WP5. WP6 will also develop an exploitation and business plan. WP7 will develop a specific strategy for dissemination and communication to support the social and economic impact of CHEERS.

Work Package 8 (WP8), coordinated by MAHOU SAN MIGUEL and AINIA, will oversee the financial and technical monitoring of the project. It will also manage intellectual property rights, risks, and innovation.

2 Literature Review

To broadly understand the valorisation approach undertaken in the CHEERS project and to assess the environmental burdens associated with the utilized by-products within the system, a thorough literature review was conducted (Table 3). The primary objective of this literature review was to identify existing research studies that investigate the valorisation of waste streams and by-products from breweries and other food industries, specifically focusing on the approaches and allocation keys employed to quantify the environmental benefits in transitioning towards a bio-based circular economy.

The review process involved examining the research methodologies, data sources, and analytical tools used in the selected studies with a particular focus on employed allocation keys for the benefits associated with the side stream utilisation. It aimed to understand the key parameters considered for assessing environmental burdens, such as energy consumption, greenhouse gas emissions, water usage, and waste generation.

Furthermore, the review sought to identify any gaps or limitations in the existing literature, which could inform the approach taken within the CHEERS project. This literature review provides a broad overview of recent studies. It focuses on LCA studies of bio-based products and the incorporation of recycling models in LCAs.

In their meta-analysis of 31 life cycle assessment (LCA) studies on bio-based products and incorporating a recycling model in LCA, Olofsson & Börjesson (2018) propose alternatives to the zero-burden assumptions commonly applied to biomass residues. They argue that considering the upstream impacts through a straightforward recycling and allocation model allows for a more comprehensive understanding of the environmental characteristics of primary production systems, particularly in relation to by-products and residues. The authors emphasize the importance of LCA studies on residue valorisation in acknowledging the value of residues by taking into account their upstream impacts. This approach serves to prevent misconceptions that residues are inherently environmentally preferable resources and ensures that inadvertent support for high-impact primary production systems is avoided. Olofsson & Börjesson emphasise that LCA practices should adapt to recognize the potential value of residues, enabling informed decisions that contribute to a low-impact, bio-based, and circular economy.

Recent studies have highlighted that the environmental impact of insect production is largely influenced by the feed, with more than half of the impact attributed to it (Halloran et al., 2016; Salomone et al., 2017; Smetana et al., 2016). According to Smetana et al. (2021), who reviewed 24 selected LCA studies of insect production, the environmental hot spots of insect mass productions are associated with the energy use (electricity, fuel, natural gas). This use of energy is related to high impacts in categories of global warming potential, non-renewable energy use, water and land use. The type of feed and the modelling of its assessment were in many cases essential in determining the environmental impact of insect productions. The choice of by-product allocation rules, substitution criteria and waste scenarios were crucial for the wide range of environmental impacts presented for food processing by-products, food waste and manure (Smetana et al., 2021).

However, there is no consensus on how to allocate the environmental burdens to by-products used as feed. The main reason for this being methodological challenges because they are often without economic value. Some studies assume zero burden for by-products or food waste, considering only the transport impact (Bacenetti et al., 2015; Salomone et al., 2017). However, this approach can lead to misleading conclusions, as high-impact systems using by-products may appear more environmentally friendly than other resources (Olofsson & Börjesson, 2018). According to Petit et al. (2020), there is a lack of consensus in the French spirits sector regarding the allocation rule between distillation products and cereal by-products for distiller's grains.

Allocating environmental impact based on mass or through economic or biophysical approaches is not always feasible for food by-products. Substitution of by-products with comparable products has been suggested as a solution. For instance, vegetable waste was assumed to replace oats in pig feed based on energy content (Eriksson et al., 2015).

A study of Chen et al. (2017) examines the environmental performance of caproic acid production from mixed organic waste using chain elongation. A life cycle assessment (LCA) was conducted to evaluate the environmental impact at both lab-scale and pilot-scale systems. Ethanol use was identified as the main contributor to environmental impact. To improve the environmental performance, future research and industry efforts should focus on reducing ethanol use and enhancing the recovery efficiency of the extraction solvent (Chen et al., 2017). The study does not consider the emissions and life-cycle impacts associated with the generation of the mixed organic waste used as feedstock. The organic waste used is considered low-grade waste and exists regardless of caproic acid production. The environmental impacts of waste generation should be allocated to the processes or products that generate the waste. In cases where waste is considered a by-product, the environmental impacts may be allocated to the waste. However, the study's organic waste is complex and not easily classified as a by-product.

Wastewater from the food industry on the other hand is increasingly valued as a renewable energy source and a resource for valuable products. Its reuse and valorisation contribute to water scarcity solutions, improve treatment facility efficiency, reduce environmental impact, and offer economically valuable products (Costa et al., 2022). Elginoz et al. (2020) performed a comprehensive life cycle assessment of volatile fatty acid production from dairy wastewater, examining both laboratory-scale and full-scale scenarios. The study revealed that in the laboratory-scale analysis, electricity usage for mixing and heating, as well as material usage and disposal, had the most significant environmental impact. In the full-scale analysis, the main contributors were the energy consumption for reactor heating and the addition of sodium hydroxide (NaOH) during operation. To mitigate these impacts, the authors propose alternative chemicals to sodium hydroxide (NaOH), co-treatment of dairy wastewater with alkaline wastewater, exploration of lower temperatures, and the implementation of high-efficiency heating devices.

Although wastewater could be considered a valuable by-product, the authors adopted an allocation method inspired by Chen et al. (2017), allocating the impacts from the waste-generating processes to the dairy production process. Djuric Ilic et al. (2018) refers, that waste that enters the waste management system with a "zero-burden" by relieving the previous actors in the waste life cycle of any environmental responsibility (i.e., by shifting the entire environmental burden to the waste management system) does not capture the problems of waste generation.

Table 3: Brief literature list of first literature review (list not conclusive)

Author	Year	Study	Topic
Bacenetti et al.	2015	Mitigation strategies in the agro-food sector: The anaerobic digestion of tomato purée by-products. An Italian case study	Tomato "bagasse"
Bava et al.	2019	Rearing of Hermetia illucens on Different Organic By-Products: Influence on Growth, Waste Reduction, and Environmental Impact	Insect rearing on different organic by-products (i.e., brewer's spent grain)
Chen et al.	2017	Production of Caproic Acid from Mixed Organic Waste: An Environmental Life Cycle Perspective	Lab and pilot-scale system LCA of caproic acid production from organic waste
Corona et al.	2018	Life cycle assessment of adipic acid production from lignin	Lignin is a substance within BSG (Lignin is a waste stream in lignocellulosic biorefineries)
Costa et al.	2022	Valorization of wastewater from food industry: moving to a circular bioeconomy	Wastewater
Djuric Ilic et al.	2018	No zero burden assumption in a circular economy	Allocation
Elginoz et al.	2020	Ex-ante life cycle assessment of volatile fatty acid production from dairy wastewater	Forecast LCA of volatile fatty acid (VFA) from dairy wastewater
Eriksson et al.	2015	Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study	Allocation of food waste management
Halloran et al.	2016	Life cycle assessment of edible insects for food protein: a review	Insect
Mussatto et al.	2006	Brewers' spent grain: generation, characteristics and potential applications	Brewer’s spent grain
Olofsson & Börjesson	2018	Residual biomass as resource – Life-cycle environmental impact of wastes in circular resource systems	Meta-analysis of 31 life cycle assessment (LCA) studies on bio-based products and incorporating a recycling model in LCA
Panjičko et al.	2017	Biogas production from brewery spent grain as a mono-substrate in a two-stage process composed of solid-state anaerobic digestion and granular biomass reactors	Brewer’s spent grain
Petit et al.	2020	Environmental Evaluation of New Brewer’s Spent Grain Preservation Pathways for Further Valorisation in Human Nutrition	Brewer's spent grain
Salomone et al.	2017	Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens	LCA Food waste for insects
Simate et al.	2011	The treatment of brewery wastewater for reuse: State of the art	Brewery wastewater
Smetana et al.	2016	Sustainability of insect use for feed and food: Life Cycle Assessment perspective	Insect
Smetana et al.	2021	Environmental aspects of insect mass production	Review of 24 LCA studies of insect

Several studies emphasize the importance of considering the upstream impacts of biomass residues and by-products in order to gain a more comprehensive understanding of the environmental characteristics of primary production systems. This approach helps prevent misconceptions about the environmental impact of residues and ensures informed decisions towards a low-impact, bio-based, and circular economy.

One common theme across the studies is the allocation of environmental burdens to by-products used as feed, which presents methodological challenges due to their often lacking economic value. Some studies assume a zero burden for by-products, which can lead to misleading conclusions, making high-impact systems using by-products appear more environmentally friendly than other resources. Substitution of by-products with comparable products has been suggested as a potential solution.

Additionally, the environmental impact of insect production is heavily influenced by the type of feed, and the choice of feed assessment and modelling plays a crucial role in determining the overall environmental impact of insect production. For caproic acid production from mixed organic waste using chain elongation, the main contributor to environmental impact was identified as ethanol use, indicating the need for research and industry efforts to reduce ethanol consumption and enhance extraction solvent recovery efficiency. Wastewater from the food industry is increasingly valued as a renewable energy source and a resource for valuable products, contributing to water scarcity solutions and reducing environmental impact. However, allocation methods for the environmental impacts of wastewater and waste generation remain a subject of discussion.

3 Design of TEA and LCSA

3.1 Goal

This deliverable describes the methodological approach for conducting Life Cycle Sustainability Assessment (LCSA) and Techno-Economic Assessment (TEA) within the CHEERS project. This includes the description of the system boundaries, functional unit, allocation approaches as well as scale-up and optimisation for both TEA and LCSA, while ensuring a comprehensive and aligned approach for both the TEA and LCSA.

It is crucial to ensure that the goals of both LCSA and TEA are well-defined and aligned, enabling a coherent assessment of the system's sustainability and economic performance. Defining clear system boundaries is essential for both LCSA and TEA. It enables a comprehensive assessment of the environmental, social, and economic impacts associated with the entire life cycle of the studied system. Consistency in the mass and energy data at the unit operation level is critical in both TEA and LCSA. It ensures that the environmental and economic evaluations are based on the same underlying data, allowing for accurate and consistent results.

The temporal and geographical representation of the study should be consistent between TEA and LCSA. This ensures that the timeframes and geographic boundaries considered in both analyses align, enabling meaningful comparisons and comprehensive assessments.

By considering these topics and ensuring their alignment and consistency, the methodology guideline for LCSA and TEA within the CHEERS project is the basis for a robust and integrated approach to evaluate the sustainability and economic aspects of the studied system. By following this guideline, it can ensure a systematic and integrated approach to evaluating the sustainability and economic aspects of the project.

Furthermore, this report will serve as the basis for the preparation the final report on TEA and LCSA. The insights and methodologies presented here will contribute to the development of a robust and comprehensive analysis.

3.1.1 TEA

The goal of the TEA is to assess the technical viability and economic performance of the CHEERS system aimed to valorise the by-products of beer production (namely brewer’s spent grains (BSG), yeast, wastewater, and CO_2 from fermentation) produced in European breweries.

Each process's technical viability and readiness will be verified through data obtained from demonstration-scale activities. The integrated model developed in Task 6.1 will be revised and updated based on this information. AINIA will analyse and optimize the technical and economic feasibility of various biorefinery configurations. The outcomes will be evaluated through sensitivity and risk analyses to identify any critical areas that may hinder the feasibility of a technology and to determine the most effective commercialization strategy. Cost estimations and profitability analysis will also be conducted as part of this assessment.

The economic analysis of CHEERS system will be performed for three different production capacity scales. To a consistent comparison of these results, the three studies will be carried out for the Spanish base-case scenario. Additionally, to assess the effect of geographical location of the industrial facility on the economic feasibility of the CHEERS system will be assessed through a sensitivity assessment in which the operational cost categories will be calculated on the base of the national prices of more relevant energy and material cost, as well as other cost as labour costs.

Additionally, several CHEERS configurations (by modifying the target fraction of the by-products and intermediate flows that goes to the different value chains) will be assessed by using the economic indicators (payback period (PBP), net present value (NPV)) and the relative waste generation indicator.

3.1.2 LCSA

In collaboration with AINIA and EARTH, ZHAW will conduct a comprehensive Life Cycle Sustainability Assessment (LCSA) for the CHEERS biorefinery from cradle to gate. This assessment will specifically prioritize the evaluation of biodiversity impacts and other adverse environmental effects. The assessment will follow internationally recognized standards and methodologies such as ISO 14040/14044 (ISO, 2006, 2017), EU International Reference Life Cycle Data System (ILCD) (European Commission, 2010) and Product Environmental Footprint (PEF) (Fazio et al., 2018) methods, and the UNEP Guidelines on social LCA (UNEP, 2020). Through this LCSA, the project aims to gain a holistic understanding of the environmental and social implications associated with the evaluated processes.

The goal of LCSA is to provide a comprehensive evaluation of sustainability performance of the CHEERS biorefinery to valorise by-products from beer production (namely BSG, yeast, wastewater, and CO_2 from fermentation) produced in European breweries by considering not only its environmental impacts but also social and economic dimensions. By taking a holistic perspective, LCSA aims to identify potential hotspots, trade-offs, and synergies across different life cycle stages and sustainability dimensions.

The key dimension of LCSA include the assessment of the (1) **environmental impacts (E-LCA)**, (2) **social impacts (S-LCA)** and (3) **economic impacts (TEA)**.

The environmental LCA (E-LCA) evaluates the resource consumption, emissions, and other environmental impacts associated with the entire life cycle of a product or system, including raw material extraction, manufacturing, use, and disposal. The social LCA (S-LCA) considers social dimensions such as human health and safety, labour conditions, social equity, community impacts, and stakeholder engagement throughout the life cycle.

The techno-economic assessment (TEA) assesses the economic viability and costs associated with the different life cycle stages, including production, operation, maintenance, and end-of-life management.

Identifying **improvement opportunities**: By analysing the sustainability performance across various dimensions, a comprehensive and consistent LCSA across the different dimensions helps identify potential areas for improvement, guiding decision-makers to implement more sustainable practices and policies with regard to the triple bottom line.

Overall, the goal of LCSA is to provide a comprehensive and balanced assessment of the sustainability performance of the CHEERS biorefinery, promoting informed decision-making, and supporting the development of more sustainable alternatives.

3.1.2.1 Environmental Life Cycle Assessment (E-LCA)

The CHEERS biorefinery will go through a comprehensive assessment of its environmental impacts across the entire life cycle. This assessment will consider various environmental impact categories, including but not limited to greenhouse gas (GHG) emissions, primary energy demand, biodiversity impacts, and resource depletion. Additional impact categories recommended by the Joint Research Council (JRC) of the European Commission will also be analysed. One specific aspect of this subtask will involve conducting a life cycle biodiversity impact assessment. This assessment aims to quantify the positive or negative impacts of the project's activities on biodiversity within both the industrial sites and their associated supply chains. By evaluating these factors, the project seeks to understand and address the potential environmental implications of its activities on biodiversity and the natural environment.

3.1.2.2 Social Life Cycle Assessment (S-LCA)

Additionally, the CHEERS biorefinery will go through an assessment of its social impacts and socio-economic benefits, which will adhere to the UNEP-SETAC guideline for Social Life Cycle Assessment (UNEP, 2020) (S-LCA). The assessment process will involve determining activity variables, defining subcategories for the LCSA, and identifying key stakeholders.

The S-LCA will follow to a structured framework, aligning with established scientific protocols and guidelines. It will be conducted alongside with the E-LCA, ensuring a comprehensive and integrated evaluation of both social and environmental dimensions. By adopting this parallel approach, the project aims to provide a robust and holistic understanding of the social impacts and socio-economic benefits associated with the CHEERS biorefinery.

Through the S-LCA, key social factors and impacts will be systematically analysed, considering the diverse stakeholders involved in the biorefinery's value chain. This assessment will contribute to a deeper comprehension of the project's implications on social equity, human rights, labour practices, community well-being, and other pertinent socio-economic dimensions. The findings from the S-LCA will be complemented by the results obtained from the E-LCA, forming a comprehensive evaluation framework for the CHEERS biorefinery's sustainability performance.

3.1.2.3 Techno-Economic Assessment (TEA)

Finally, the CHEERS biorefinery will go through a comprehensive Techno-Economic Assessment (TEA) of its total cost of ownership, which includes both capital and operational costs, as well as cost reductions. This analysis will be conducted in parallel with the E-LCA and S-LCA, maintaining consistency in terms of functional unit and approach.

The analysis will consist of two main steps: cost identification and cost benefits analysis. Cost models will be developed to estimate the product costs based on various parameters. By considering both capital expenditure (CAPEX) and operational expenditure (OPEX), the analysis will identify the conditions necessary to ensure the economic feasibility of the CHEERS biorefinery.

This analysis will provide insights into the financial aspects of the biorefinery, allowing for a comprehensive evaluation of its economic viability. By examining the cost structures and considering potential cost reductions, the project will identify strategies to enhance the economic performance of the CHEERS biorefinery. This assessment will contribute to making informed decisions regarding the financial sustainability and profitability of the biorefinery.

3.2 Functional Unit

Within the scope of the CHEERS project the functional unit equates to the products (insect flour, animal feed, disinfectant, ectoine and pet food) from the valorisation of the by-products resulting from 1 hl beer production (about 20 kg of BSG as well as 0.3-1 m^3 of wastewater and 3.5 kg of CO_2, and 0.17 kg of CH_4), via the microbial and insect platform in the CHEERS biorefinery.

FU: Products from the valorisation of the by-products resulting from 1 hl beer production

The choice of this functional unit "Products from the valorisation of the by-product resulting from 1 hl beer production" is made considering the specific characteristics of the by-products generated in the brewing industry. It acknowledges that the number of by-products varies across different types of breweries and scales of operation. By utilizing this FU, the study aims to provide a more adaptable and applicable approach that can be extrapolated to various brewers.

The selection of this FU enables a more flexible analysis that can accommodate the diverse production volumes and by-product quantities encountered in different brewery settings. This approach ensures that the findings and recommendations of the study can be relevant and useful for a broader range of breweries, regardless of their specific size or production capacity.

Additionally, by focusing on valorising specific quantities of BSG, CO_2, and wastewater, the study highlights the potential for resource recovery and sustainable utilization of these by-products. It underscores the importance of finding innovative and environmentally beneficial ways to manage and extract value from brewery waste streams.

Overall, the choice of the functional unit "Products from the valorisation of the by-products resulting from 1 hl beer production" in the study recognizes the variability in by-product generation among breweries and aims to develop recommendations and strategies that can be widely applied throughout the brewing industry.

3.3 System Models and Boundaries

As explained above, the CHEERS biorefinery enables 5 different value chains (VC) using two different platforms for the transformation of by-products from the Brewing industry into valuable products, increasing the economic value of the side streams from beer production and reducing the environmental impact of this process. In addition, the 5 processes considered interact by sharing part of the inputs, and by generating intermediate products that will be inputs for other processes. Below is an overview of the value chains considered and then the two platforms (insect and biological) are explained (Figure 3).

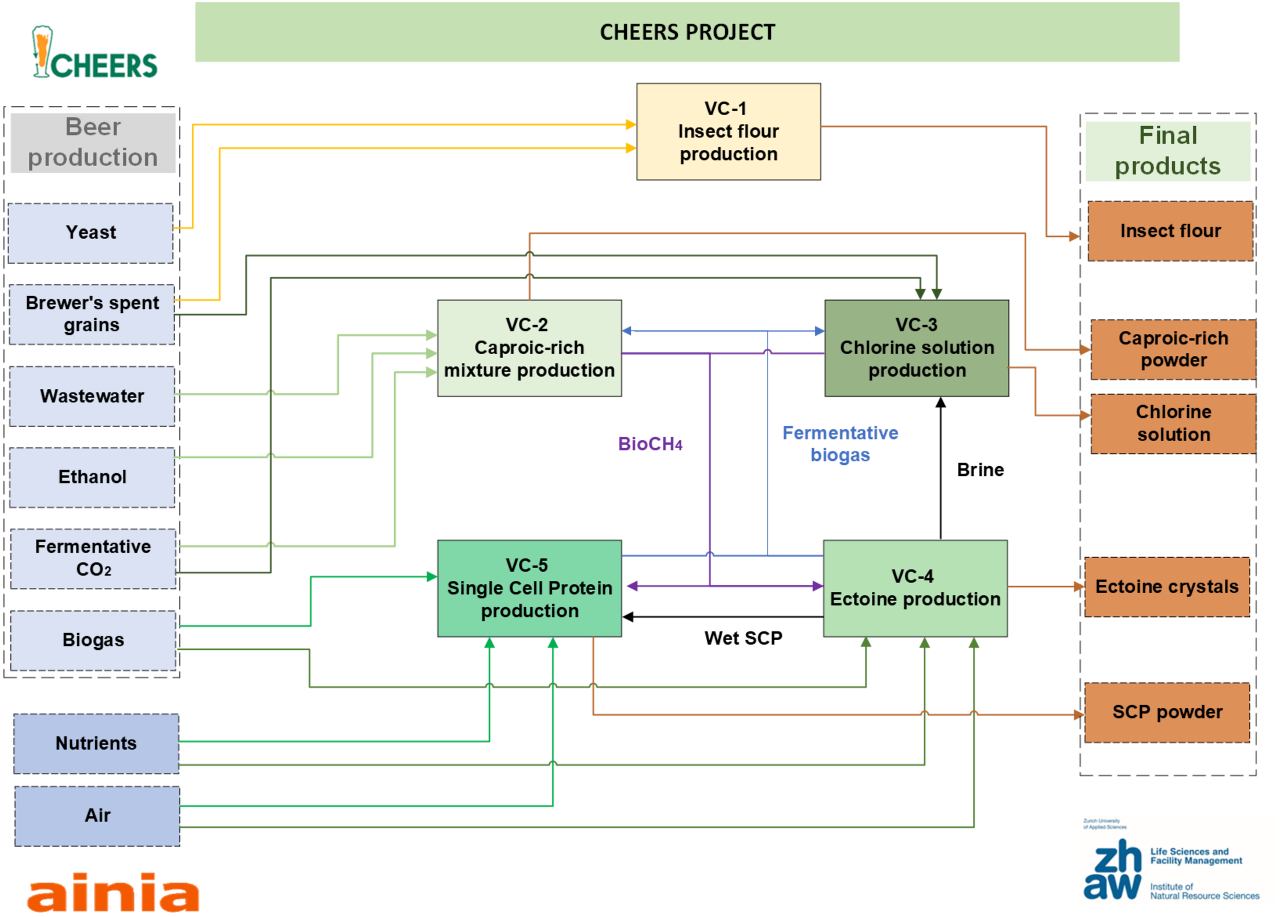

Figure 3: CHEERS project overview diagram. In yellow the VC of the insect platform and in green the VC of the microbial platform.

3.3.1 Insect Platform for Insect Flour Production

The insect platform in the CHEERS biorefinery transforms BSG in mealworms with two consecutive processes (1) mealworm breeding and (2) mealworm production. In the production phase of using larvae to obtain insect meal and activities related to the production of adults, it is essential to highlight that the resulting frass can be utilized as a by-product. However, there is a need to expand the information concerning mealworm processing. Once the larvae reach the appropriate size, they will be euthanized through freezing, a method that also facilitates preservation until processing. Subsequently, a degreasing procedure will be employed using a cold extractor, with the fats obtained being further utilized. After that, its size will be reduced by grinding and its protein content will be extracted.

Finally, by means of a drying spray and a high-pressure homogenizer, a flour rich in insect proteins suitable for the formulation of different beverages will be obtained. The pretreatment of brewer's spent grain, which is currently not considered in deliverable "D1.4 First feasibility study of CHEERS approach at the case study site" (D1.4), is an important aspect to consider due to its high moisture content, which accelerates its decomposition process. Figure 4 shows the system model of the processes of this value chain (VC-1) and Figure 5 shows the details at the operational unit level. The processes of mealworm breeding, and mealworm production are described in more detail in D1.4.

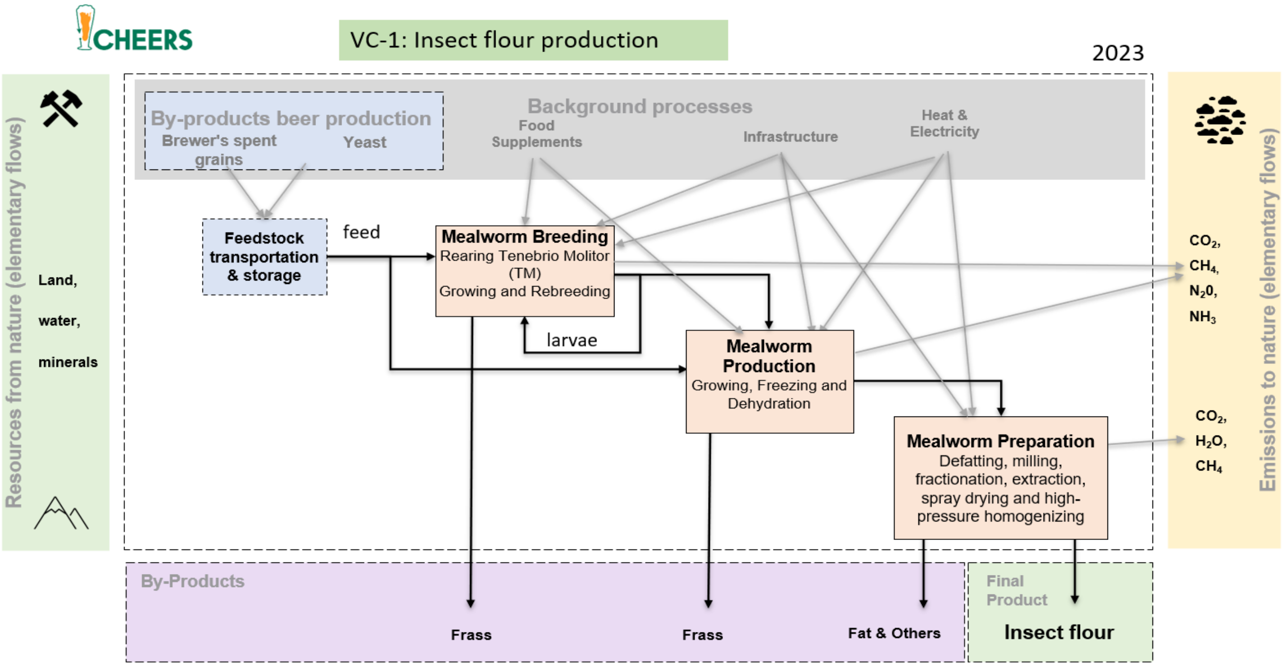

Figure 4: System model of Insect flour production (VC-1)

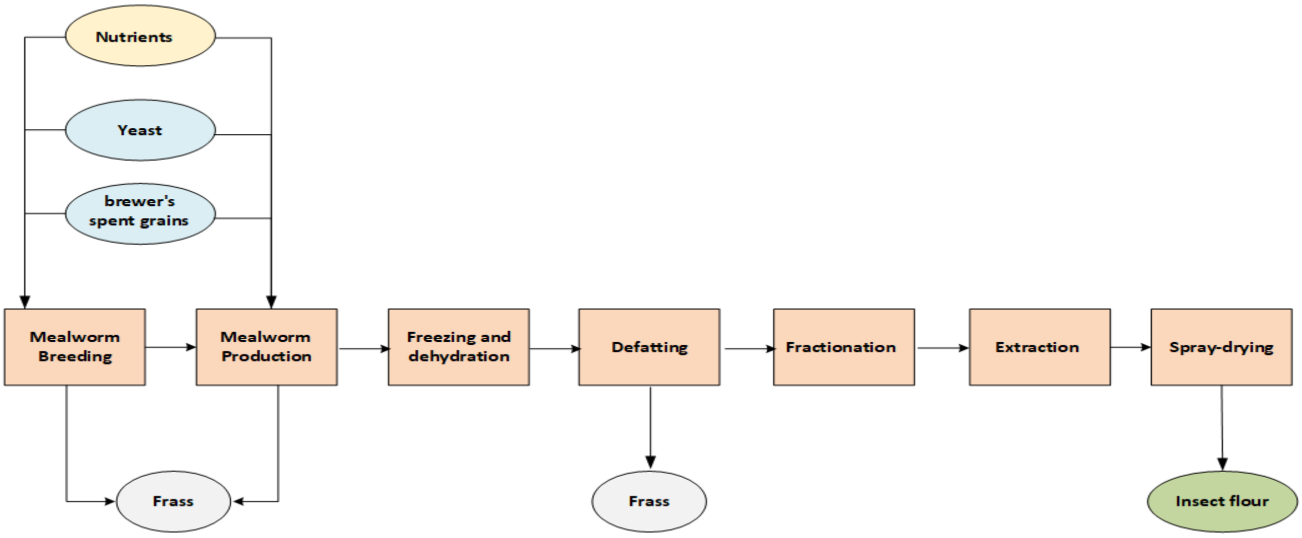

Figure 5: Flow chart of Insect flour production (VC-1) operational units

3.3.2 Microbial Platform

The biological platform is based on four value chains that will valorise the CO_2 from the fermentation of the brewery, the wastewater generated in the process and BSG, as well as other by-products of the brewery to product value-added products, including (1) ectoine crystals, (2) Single cell protein (SCP) powder, (3) a caproic-rich powder and (4) chlorine solution (Figure 6). All these biological processes carried out in innovative biofermentors are supplemented by a post-treatment train focused on the extraction and purification of the products of target value.

The VC proposed for the biological platform are highly interconnected. The exhaust gases of the biological processes of VC-2 and VC-3 can be used as inputs in the VC-4 and VC-5 and vice versa, thus allowing to reduce the demands of external contribution of CO_2 and CH_4. In addition, there are also relationships between liquid streams, such as the brine of VC-4 is sent to the bio-electrochemical System (BES) of VC-3, or solid fractions, such as the SCP generated in VC-4 is treated in the SCP extraction process of VC-5.

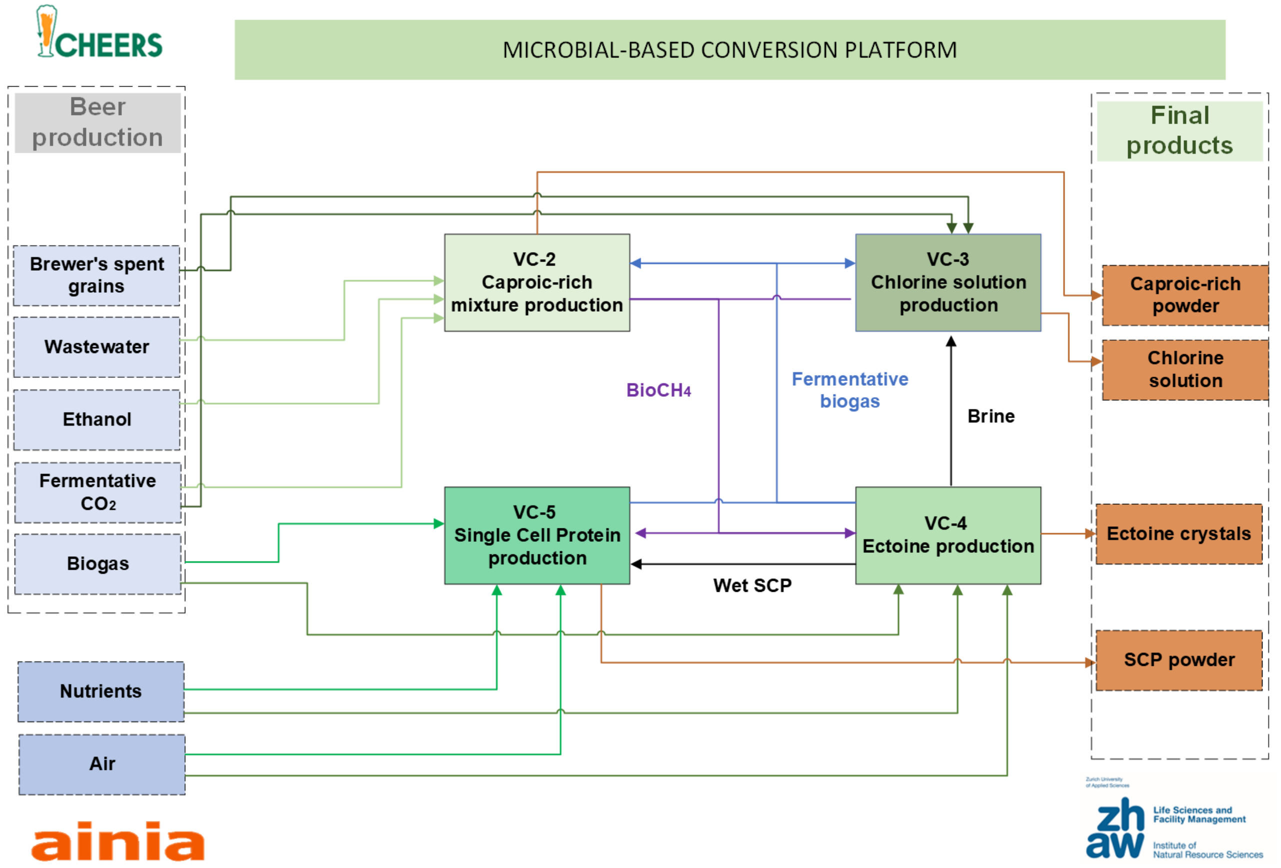

Figure 6: Interrelation of the value chains of the microbiological platform

3.3.2.1 Caproic-rich powder production

The contribution of CO_2 for the biological processes to produce a caproic-rich powder can also come from VC-4 and VC-5 and the methane-rich stream generated throughout this value chain can be valorised in VC-4 and VC-5 (Figure 7).

The caproic acid-rich mixture concentration makes use of a culture broth. The culture broth that is generated in the elongation will be taken to a treatment train to concentrate the mixture of volatile fatty acids (VFAs) and obtain the final product in powder form. For this, the culture broth (with a concentration of VFA estimated at 20g/l and 10% total solids) will first be taken to a centrifugation to clarify the medium. At this stage, a solid fraction will be generated, which must be managed before it leaves the system, and a liquid stream where the VFAs of interest will be contained. The clarification will be completed by solid/liquid filtration. In the solid/liquid filtration, a solid fraction will also be generated that will have to be managed as previously discussed.

After that, a microfiltration will be applied to begin concentrating the VFAs. In this stage, two liquid streams will be generated, one concentrated with VFAs and a rejection stream. The rejection stream must be treated before disposal or being reused. The last membrane process will be nanofiltration. In this case, an amount of water corresponding to 64% of the inlet flow will be added to the nanofiltration (Diafiltration) and analogously to the microfiltration stage, a liquid stream will be obtained that must be managed and another enriched in VFAs.

Finally, spray-drying technology will be applied to obtain a VFA salt rich in caproic acid in powder form. With this technology, the Caproic acid-rich mixture concentration process is completed, allowing the KPIs set for this stage (90 g/l of VFA with 50% caproic) to be achieved. The water that is removed in this last stage is lost in the form of steam. These operational units are shown in the Figure 8. The biological processes and operational requirements of the VC-2 caproic-rich powder production (VFA production and microbial chain elongation) are described in more detail in D1.4.

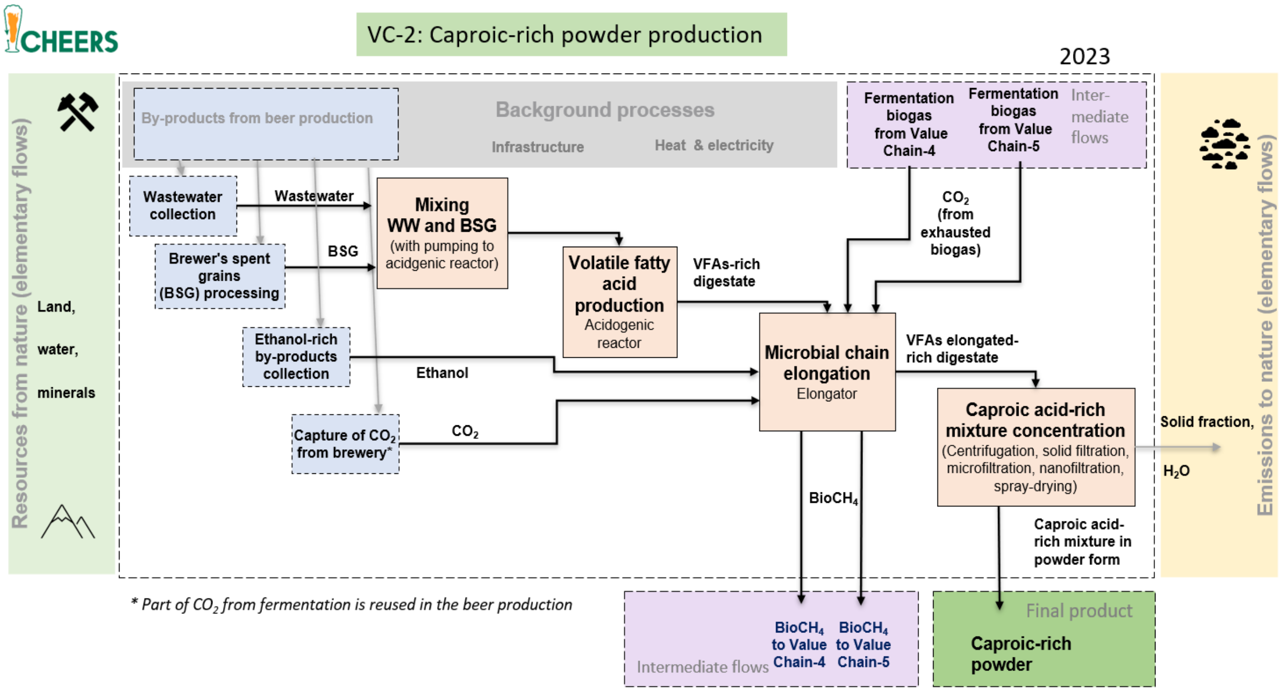

Figure 7: System model of Caproic-rich powder production (VC-2)

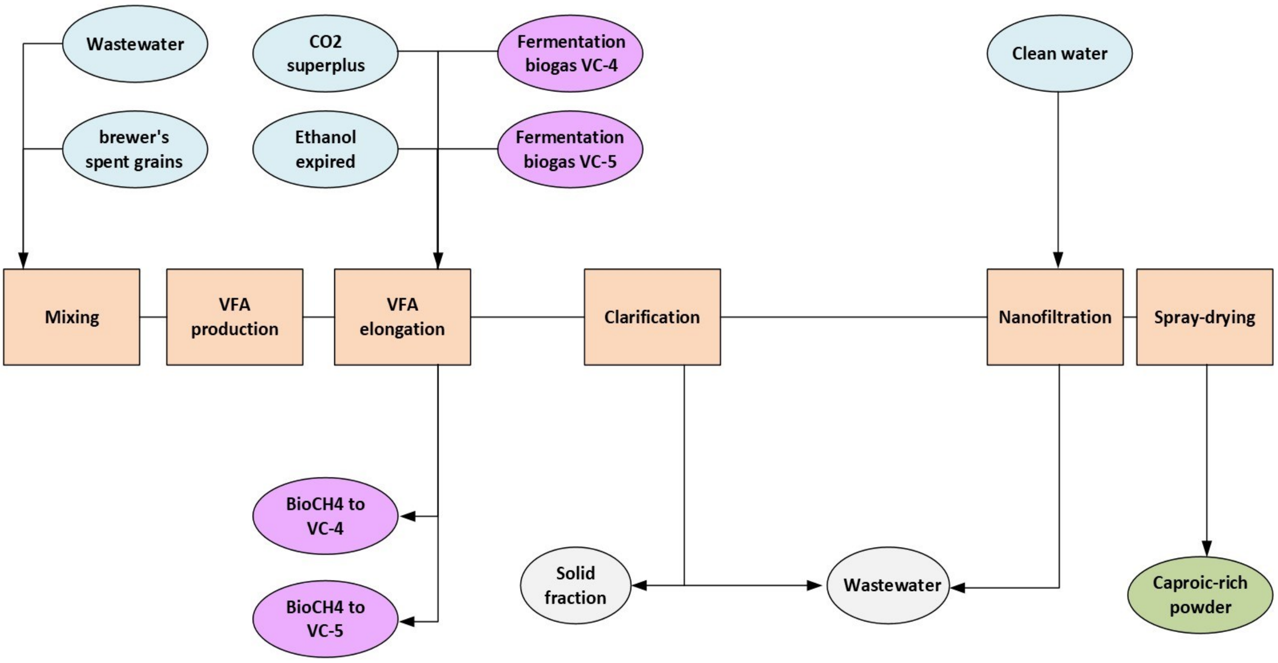

Figure 8: operational units of Caproic acid-rich powder production (VC-2) operational units

3.3.2.2 Chlorine solution production

The chlorine solution production in VC-3 can use the CO_2 fed in the absorption column from VC-4 and VC-5. In addition, the brine that is introduced into the anode of the bio-electrochemical system (BES) is a by-product of VC-4. In this value chain, a biogas stream enriched in methane is generated that can be valorised in the fermentation processes of VC-4 and VC-5.

After BES, a production of 35.6 ton/y of a diluted Cl_2 stream (0.03%) is expected. To enrich the chlorine in this stream, a nanofiltration and evaporation stage will be needed. In nanofiltration a current of rejection water will be generated that will have to be treated in the wastewater treatment plant. After the chlorine solution concentration, it is expected to produce a disinfectant concentrated in Cl_2 (11%). Figure 9 and Figure 10 show the diagrams of processes and operational units. The chlorine solution production and operational requirements of the VC-3 chlorine solution production are described in more detail in D1.4.

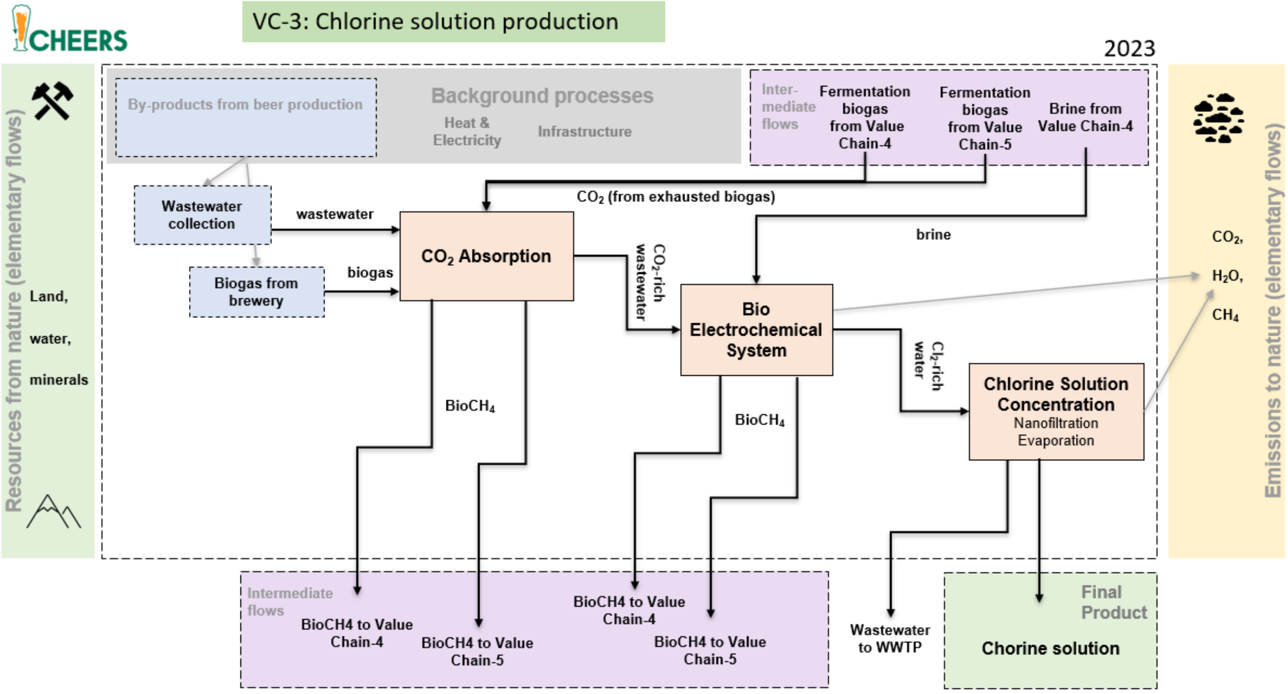

Figure 9: System model of Chlorine solution production (VC-3)

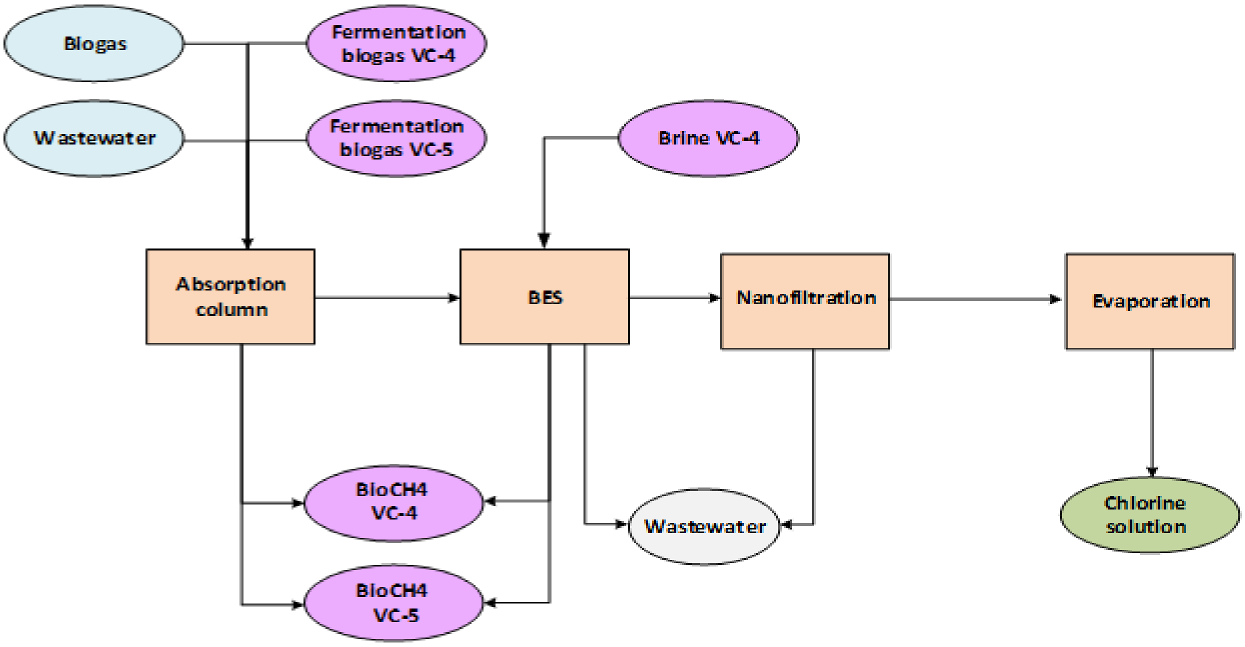

Figure 10: Flow chart of Chlorine solution production (VC-3) operational units

3.3.2.3 Ectoine production

The ectoine produced is stored inside bacteria. Therefore, a subsequent process of ectoine Bio-milking is needed in which this product is released. Among the multiple input streams, it is worth mentioning the biomethane generated in VC-2 and VC-3. In addition, in the fermentation process a biogas rich in CO_2 is generated that can be recovered in VC-2 and VC-3 (Figure 11).

A first centrifugation stage separates the bacteria with ectoine from the liquid stream. This liquid stream has an adequate concentration of NaCl (6% W/W) to be used in the BES of VC-3. Then, the solid fraction is resuspended in water and a hypoosmotic shock is carried out to release the ectoine from the bacteria.

Once the ectoine is extracted, it is necessary to apply a downstream process (DSP) to concentrate this valuable product. First, a centrifugation and ultrafiltration stage are applied to separate the biomass from the liquid stream where the ectoine is located. The solid fraction obtained in these processes has a high content of single cell protein (SCP), so it will be sent to the DSP of VC-5 in order to valorise this flow.

In the next step, electrodialysis, a solid fraction is also generated, although in this case it must be treated as waste. Acids and bases will then be added in an Exchange ion stage. At this stage, a large volume (11.68 ton/y) of acids and bases is collected and subsequently managed.

After this stage, the product obtained is dehydrated by spray-drying and then solubilized with methanol. Finally, after ultra-filtering the mixture, taking it to a crystallizer and subsequent centrifugation, ultrapure ectoine is obtained at a rate of 3.45 kg/y (Figure 12). The description of the ectoine production process is described in more detail in D1.4. Inputs to the Taylor Flow reactor are included in this document.

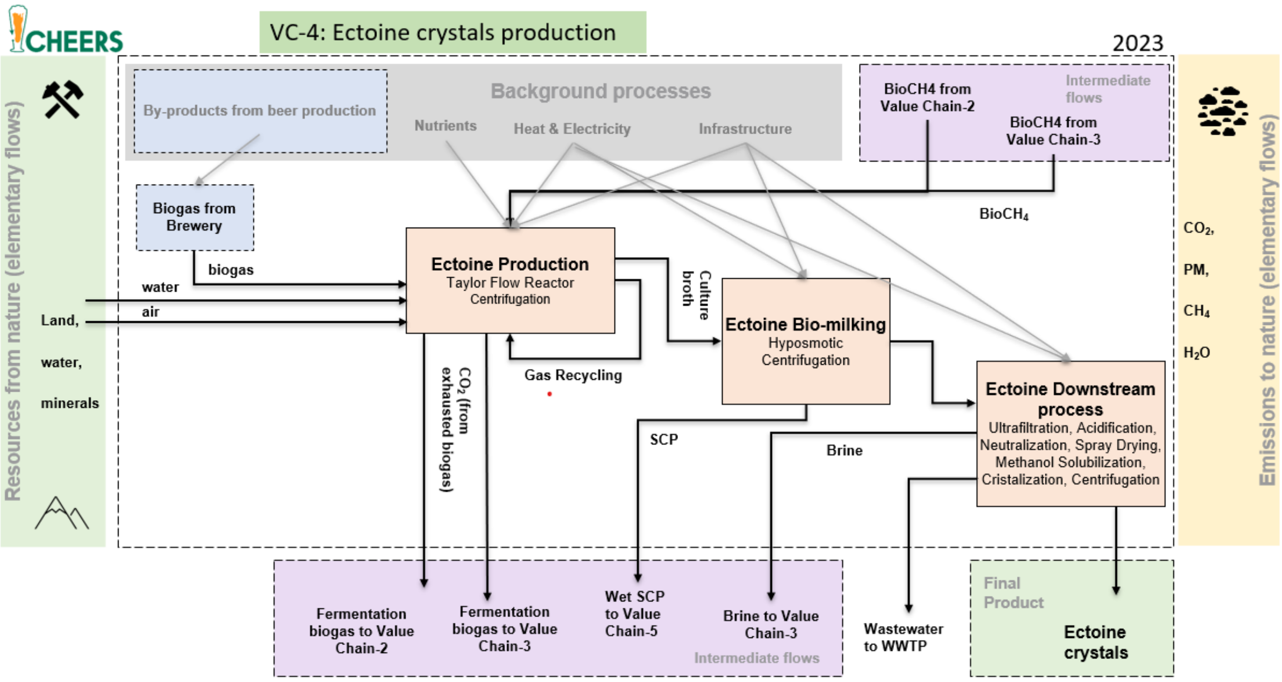

Figure 11: System model of Ectoine crystals production (VC-4)

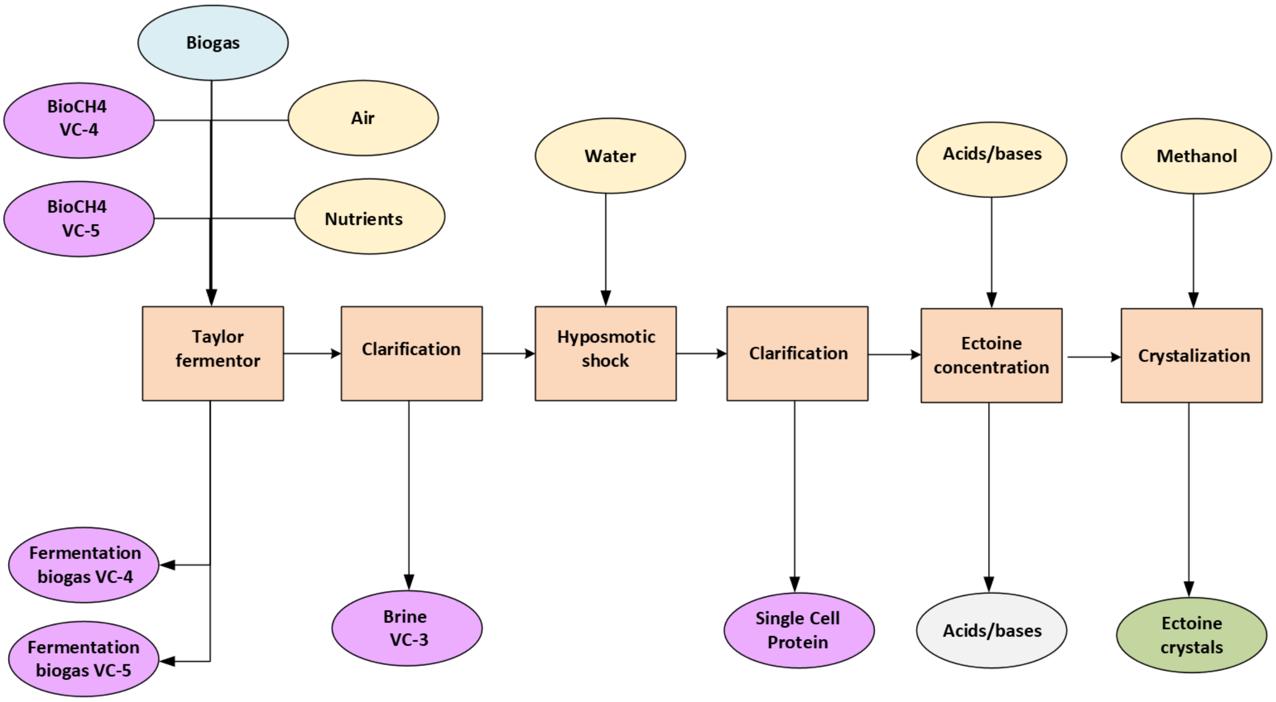

Figure 12: Flow chart Ectoine crystals production (VC-4) operational units

3.3.2.4 Single Cell Protein production

Similarly to what happened in the fermentation process of VC-4, methane-rich biogas produced in VC-2 and VC-3 can be valorised in this process and CO_2-rich biogas can be used in these same two VC as input in their biological processes (Figure 13). The protein-rich culture broth (50-70% protein content) of the U-loop fermentator is treated in the SCP extraction process to obtain the marketable product. This process will also deal with the SCP generated in ectoine DSP.

A first clarification step (centrifugation) separates the biomass with SCP from the liquid stream. This liquid stream can be recirculated to the fermenter to take advantage of unconsumed nutrients. The solid fraction will be sent to a spray-drying stage where the excess water will evaporate, and SCP powder will be generated (0.4 ton/y) (Figure 14). The SCP production process in the U-loop fermentator is described in detail in D1.4.

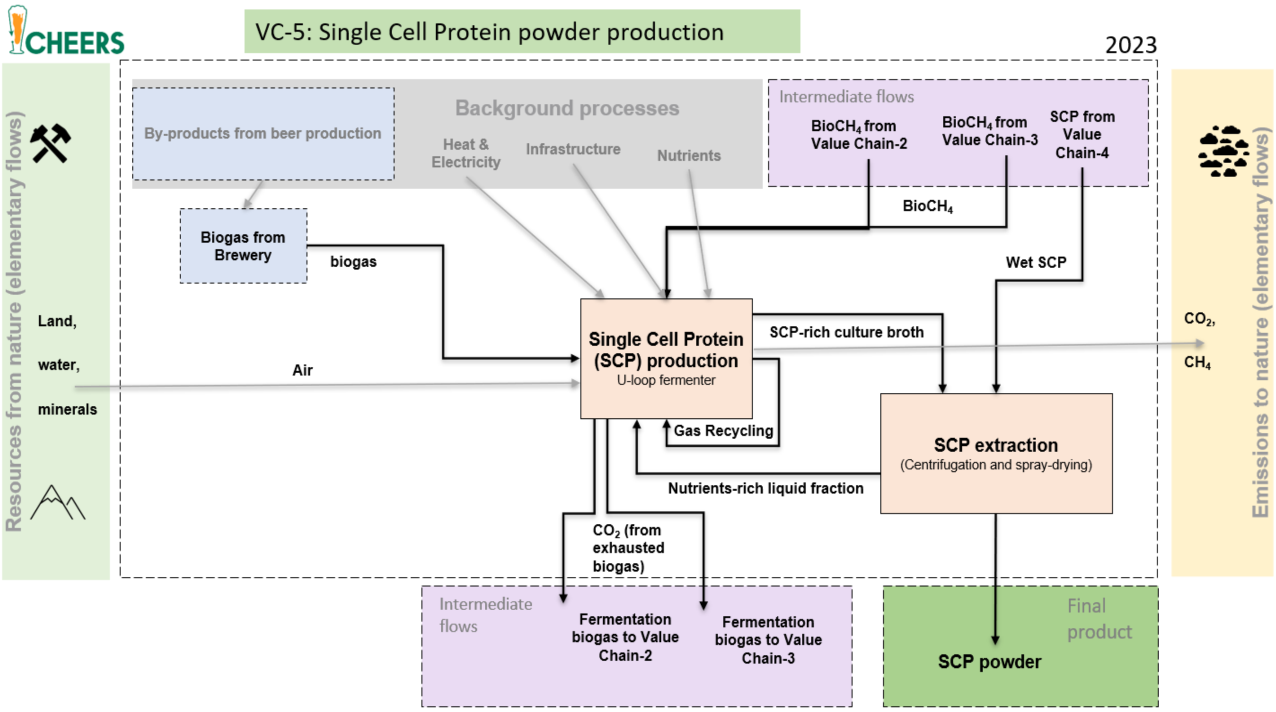

Figure 13: System model of Single Cell Protein powder production (VC-5)

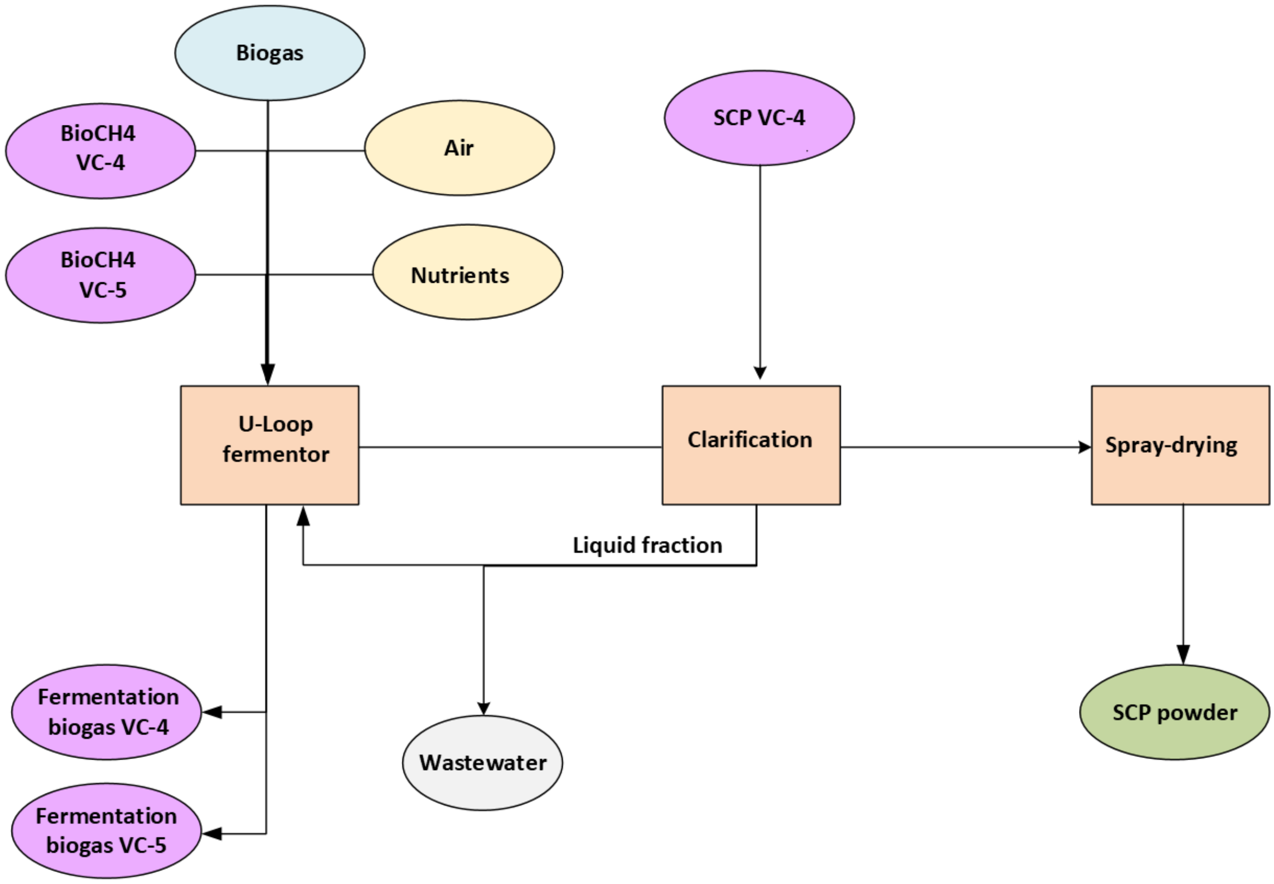

Figure 14: Flow chart Single Cell Protein powder production (VC-5) operational units

3.3.3 Geographic and Temporal Boundaries

The geographic boundaries for the TEA and LCSA of valorising by-products from the brewing sector are Spain as the main location for the for the pilot plant, and more general the operation of the CHEERS biorefinery in Europe.

However, TEA and LCSA can be influenced be different geographical und cultural issues across the European Research Areas (ERAs) as environmental impacts, consumption patterns, regulations, and resource availability vary across regions. Geographic variability affects data accuracy, and cultural preferences affects consumer choices. Regional regulations and supply chain complexities must be considered in international LCSA and TEA, and resource availability and local environmental challenges can vary widely. Different cultural values, livelihood factors, and country development also play roles in TEA and LCSA results and must be considered when extending the geographic boundaries.

Regarding the temporal boundaries the TEA and LCSA look at the current situation with the reference year 2025 and the prospective assessment covering expected developments until the year 2030 and beyond.

3.4 Data Collection

Data collection for life cycle sustainability assessment (LCSA) is relying on various data sources and databases. Regarding the data collection for the product system as described in section 3.3 the product system is divided into the foreground and background system. The foreground system is shown in the different system models in section 3.3 and will be modelled based on primary data and data projections based on results of the respective work packages. The background system relies on generic data on the connected value chains, e.g., the steel or concrete supply chains for the construction of the process and building infrastructure. It is important to note that the collection of relevant data for a life cycle sustainability assessment (LCSA) may differ depending on the analysed dimension (environmental, socio-economic and techno-economic).

The following section describes the different data collection approaches used in the TEA (Techno-Economic Assessment), E-LCA (Environmental Life Cycle Assessment) and S-LCA (Social Life Cycle Assessment) within the CHEERS project.

3.4.1 Foreground Data Collection

Foreground data collection involves gathering information directly from the CHEERS consortium, which includes collecting inventory data on inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions, waste) associated with all the processes in each life cycle stage in cooperation with the corresponding experts from the other WPs. Additionally, this primary data or primary data projects will have to be complemented by data from literature, surveys and interviews with stakeholders, including employees, experts, suppliers, and customers, in order to obtain data for missing information on process parameters, material composition, transportation distances, energy sources, and other relevant factors. In some cases, direct measurements are necessary to quantify specific parameters such as emissions from a specific process or energy consumption of a machine, requiring the use of appropriate measurement techniques and instruments to ensure accurate data collection.

3.4.2 Background Data Collection

The collected information for the foreground system will relate to generic data to establish the link to the corresponding supply chain. The background data collection will rely on publicly or commercially available databases that provide information on the connected supply chains. Established Life Cycle Inventory databases like ecoinvent (ecoinvent Centre, 2021) or industry-specific databases provide life cycle inventory data with detailed information on various life cycle stages, serving as valuable resources for data collection. Additionally, leveraging LCA software tools with built-in databases and data repositories can automate calculations and data retrieval, ensuring consistency and accuracy throughout the process.

3.4.3 Techno-Economic Assessment

The foreground data for the TEA will be collected via questionnaires from the consortium (mostly WP4 with support of WP2, WP3) and complemented with information from literature, catalogues or supplier offers as needed. If the information or data for the TEA are defined as sensitive by the partner, the corresponding deliverable will not reflect the data in its integrity (it may be included as a range or indirectly) but it will show the result reached with such information. In any case, this information will be available for reviewers who request it for detailed follow-up of the calculations.

The CHEERS biorefinery will only be operated on the pilot scale during the duration of the project. Accordingly, the information collected via the questionnaires must be translated to a prospective (ex-ante) assessment since a TEA based on actual information (ex post) will not be possible, because the CHEERS biorefinery will not be operated at scale during the project.

3.4.4 Environmental LCA

The foreground data for the E-LCA will be collected via questionnaires from the consortium (mostly WP4 with support of WP2, WP3) and complemented with information from literature and databases as needed. Based on the system models and deliverables from other WPs the corresponding questionnaires will be compiled and completed together with the respective experts from the other WPs. The CHEERS biorefinery will only be operated on the pilot scale during the duration of the project. Accordingly, the information collected via the questionnaires must be translated to a prospective (ex-ante) assessment since an environmental LCA based on actual information (ex post) will not be possible, because the CHEERS biorefinery will not be operated at scale during the project.

The background data for the E-LCA will be obtained from the ecoinvent v3.8 database (ecoinvent Centre, 2021) (or most recent). The modelling and analysis were conducted using the life cycle assessment software SimaPro v9.4 (PRé Consultants, 2022).

The results of the environmental LCA are determined by the amount and type of materials used as well as the arising emissions from the respective processes. The country where the process is operated is relevant but will not fundamentally change the results. Accordingly, the data collection for the environmental LCA will focus on material flows and emissions.

3.4.5 Social LCA

Foreground data collection for social life cycle assessment (S-LCA) involves gathering information directly from relevant stakeholders. This includes conducting surveys or interviews with workers, local communities, suppliers, and other stakeholders to obtain data on social aspects such as working conditions, employee satisfaction, labour rights, and community interactions. On-site observations could also be conducted, where relevant sites are visited to observe the work environment, employee well-being, and community interactions, noting any visible indicators of social conditions and collecting relevant data. Additionally, requesting relevant records from companies, such as employee turnover rates, training programs, safety records, grievance mechanisms, and community engagement initiatives, provides valuable insights into social practices and impacts.

The CHEERS biorefinery will only be operated on the pilot scale during the duration of the project. Accordingly, the information collected via the questionnaires must be translated to a prospective (ex-ante) assessment since a social LCA based on actual information (ex post) will not be possible, because the CHEERS biorefinery will not be operated at scale during the project.

The background data for the S-LCA will be obtained from the PSILCA v3.0 database (Maister et al., 2020) (or most recent) The modelling and analysis will be conducted using the life cycle assessment software OpenLCA (GreenDelta, 2022).

The results of the social LCA are determined by the country and sector in which the activities take place used as well as working hours and wage levels. The materials use and emissions (with exception of harmful emissions for humans) are less relevant. Country where the process is operated is relevant. Accordingly, the data collection for the social LCA will focus on the relevant sectors and countries for the CHEERS related working activities as well as their respective working conditions.

3.5 Assessment: From Screening to Full-Scale Analysis

The initial stage involves obtaining preliminary information from the D1.4 dataset developed by Genia. This dataset contains relevant data on various aspects of biorefinery conversion bioprocesses, such as the feedstock types, conversion technologies, energy inputs and outputs, economic indicators, and potential environmental impacts. This dataset serves as a valuable starting point for conducting a screening assessment to identify promising bioprocesses for further evaluation.

Using the information from the D1.4 dataset, a screening assessment is conducted. The purpose of this assessment is to identify potential biorefinery conversion bioprocesses that show promise in terms of technical and economic feasibility. It aids in the selection process and highlights hot spots for further in-depth examination in subsequent stages.

In the second stage, questionnaires are designed and distributed to all stakeholders involved in each of the five biorefinery conversion bioprocesses (mainly focusing on D4.1 of WP4 with support of WP2 and WP3). The goal is to collect more specific data and insights related to the chosen bioprocesses. The questionnaires cover topics such as process efficiency, costs, material consumption, and potential challenges.

The collected data from the questionnaires is then used to perform a first lab-scale assessment. This involves conducting detailed analysis and simulations in a laboratory setting to assess the technical and economic viability of the chosen bioprocesses. The lab-scale assessment helps in understanding the potential performance and challenges associated with each process under controlled conditions.

The information from the lab-scale assessment is further developed into a full-scale assessment. Here, the evaluation is expanded to consider different scenarios and scale-up approaches. This step is crucial as it considers real-world conditions, uncertainties, and variations that might occur when transitioning from the lab to industrial-scale production.

3.6 Prospective Scenarios and Sensitivity Analysis

In the context of the LCSA and TEA of beer by-products valorisation, we will have to rely on prospective assessments for the valorisation on an industrial scale, since the project will only operate the CHEERS biorefinery on a pilot scale. Accordingly, sensitivity analyses to assess the influence of uncertainties and variations in specific parameters on the results are necessary to test the robustness of the results. This involves systematically varying key input parameters within a reasonable range to examine their impact on the final outcomes. By conducting sensitivity analyses, valuable insights can be gained regarding the parameters that hold the greatest significance in shaping the LCA results, as well as providing an understanding of areas where data uncertainty or variability may influence the overall conclusions.

Additionally, it is important to evaluate different scenarios that include variations in key parameters or system boundaries within the LCA study. These scenarios can cover a range of factors, such as variations in the production process, raw material sourcing, energy sources, transportation distances, waste management options, or end-of-life scenarios. By comparing different scenarios, the overall environmental performance can be comprehensively assessed, enabling an understanding of the impacts resulting from these variations.

Within the context of the CHEERS project, the focus is specifically on the valorisation of by-products from one type of beer, namely lager beer. However, when examining the valorisation of by-products across various types of beer, such as lager, ale, stout, or wheat beer, it is anticipated that notable differences will arise in relation to the generated by-products and their potential applications. These differences result from variations in the brewing processes, ingredients employed, and fermentation conditions utilized in the production of different beer types. Consequently, the composition, characteristics, and quantities of the resulting by-products are expected to differ. Furthermore, these differences are likely to influence the range of potential applications for the by-products, as their suitability for specific valorisation pathways may vary depending on their origin from different beer types.

Main differences could be:

By-Product Composition: Variations in ingredients, brewing processes, and fermentation conditions result in different by-product compositions, influencing their nutritional content and characteristics.

Availability of By-Products: The quantities and availability of specific by-products vary, affecting their potential applications and valorisation pathways.

Market Demand: Consumer preferences and market demand for different types of beer impact the feasibility and viability of valorising specific by-products.

Technological Requirements: Valorising by-products may require different technologies and processes depending on their suitability for bioenergy production, food applications, or other uses.

Environmental Impacts: Environmental impacts associated with by-product valorisation differ between beer types due to variations in energy and water consumption, raw material sourcing, and waste management practices.

Conducting diverse scenarios is important to ensure the applicability of the CHEERS approach across various types of breweries. By exploring different scenarios, it becomes possible to evaluate the effectiveness and adaptability of the CHEERS approach in different contexts and settings. This involves considering variations in key parameters, system boundaries, and operational characteristics that may exist among different types of breweries. These scenarios enable a complete assessment of the CHEERS approach, considering the specific requirements, limitations, and opportunities associated with different brewery types, such as large-scale (industrial) breweries, medium-sized breweries, and small craft breweries. By conducting such scenario analyses, valuable insights can be gained regarding the feasibility, scalability, and potential challenges that may arise when implementing the CHEERS approach across a range of brewery types.

To give a better overview on the options in Europe this sensitivity analyses including other beer producing countries, namely Germany and Poland. Together with Spain they are the three biggest producers of beer in Europe (EUROSTAT, 2023).

These sensitivity analyses provide a comprehensive understanding of the environmental implications associated with different approaches to beer by-products valorisation. By evaluating the full CHEERS system, individual value chains, and the substitution of conventional feedstock, the study can capture a range of scenarios and variations.

3.7 Allocation

The CHEERS biorefinery valorises BSG and other low value side streams from beer production to produce multiple high value-added products. Accordingly, the choice for the allocation method to divide the environmental impacts between (1) the brewery and the side streams as well as (2) between the products produced in the CHEERS biorefinery will be crucial for the results of the E-LCA, the S-LCA the TEA as well as the overarching LCSA. This section will describe the different requirements and approaches for allocation for the TEA and LCSA of the CHEERS biorefinery.

3.7.1 Allocation between Life Cycles

There are three common approaches to allocate impacts between different Life Cycles in LCA, (1) cut-off, (2) avoided burden, and (3) the circular footprint formula (CFF).

Cut-off: In the cut-off allocation scenario, the side stream is treated as a waste and is not allocated any impacts. The focus is primarily on the main product, and the side stream is considered negligible in terms of environmental impacts. This approach assumes that the side stream does not have any significant impacts associated with its production or use. Therefore, the analysis focuses solely on the main product and does not consider the potential environmental implications of the side stream. An example for this allocation method would be recycled reinforcing steel. With the cut-off approach the environmental impact of the first life cycle of the primary reinforcing steel bars including the mining of the iron ore, beneficiation, steel production and others are allocated to the first use. The impacts of the recycled reinforcing steel would only include the impacts that arise due to the collection of the reinforcing steel after deconstruction as well as the remelting of the reinforcing steel as well as the production of recycled reinforcing steel bars.

Avoided burden: An alternative for the cut-off approach is the avoided burden approach. For the avoided burden approach the process that provides the feedstock (in the case of the CHEERS biorefinery this would be the brewery providing the BSG and other side streams) receives a credit for the avoided production of the feedstock materials, e.g. the saved natural gas due to the production of bio-methane from anaerobic digestion or the saved feed for insects. With this choice of allocation method, the environmental impacts of the beer production would be significantly reduced.

Circular footprint formula: The waste generated during the manufacturing, distribution, retail, use, or after use of products should be considered in the overall life cycle modelling. It is essential to model and report the waste at the respective life cycle stage where it occurs. For instance, waste generated during manufacturing should be modelled and reported in the manufacturing life cycle stage. The End-of-Life (EoL) stage of the main product typically includes waste modelling, encompassing aspects such as food waste, products left at the end of use, and primary packaging. However, for intermediate products, the End-of-Life of the product in scope should be excluded (European Commission, 2017).

To deal with multi-functionality in recycling, re-use, and energy recovery scenarios, the PEF Guide (Recommendation 2013/179/EU) requires the use of a formula known as the End-of-Life (EoL) formula, found in Annex V of the PEF Guide (European Commission, 2013). However, due to feedback and experience gathered during the pilot phase, an alternative proposal has been developed, now known as the "Circular Footprint Formula" (CFF). This CFF is used in the EF context instead of the original EoL formula. The CFF is a hybrid approach between the cut-off and avoided burden methodologies that distributed the environmental impacts more evenly between the two involved life cycles. It combines "material + energy + disposal" aspects, and it is applicated to final, intermediate, and construction products (European Commission, 2017).

It's important to note that the choice of allocation key can have a significant influence on the results and interpretation of the study. The selection should be based on a thorough understanding of the system and its specific characteristics, as well as considering stakeholder input and the goals of the assessment. Transparency and documentation of the chosen allocation method are essential to ensure the credibility and reproducibility of the results.

3.7.2 Multi-output Processes and Allocation

In life cycle assessment (LCA), when the market value of a by-product or side stream is above zero, it is considered a co-product (European Commission, 2010, p. 350). In such cases, the multifunctionality is addressed through allocation using a two-step procedure. A key step in this process is identifying the true co-producing process, which refers to the process step that has produced a product that is most similar to the by-product of side stream in a technical sense.

There are several approaches in LCA to deal with allocation for multi-output processes: (1) system expansion, (2) allocation according to physical properties, (3) allocation according to energy or exergy content, and (4) functional unit allocation or allocation according to economic value.

System expansion: This method considers the environmental impacts of both the wastewater treatment process and the avoided impacts associated with alternative waste treatment methods. It takes into account the opportunity cost of using the wastewater for caproic acid production instead of other uses (Energy/Heat production). System expansion can provide a more comprehensive assessment of the net environmental benefits or drawbacks of the conversion process.

Physical properties allocation: Allocation based on physical properties, such as volume or area, is employed in cases where these properties are relevant to the environmental impacts of the by-products.

Energy or exergy content allocation: The energy content of the by-products is used as an allocation key. It assumes that the environmental impacts are directly related to the energy content of the products.

Functional unit allocation: This approach allocates the environmental impacts based on the functional units provided by each co-product. For example, if one by-product is used as a fuel and another as a construction material, the allocation would consider their respective functional uses.

Economic value allocation: Here, the allocation is based on the economic value or market prices of the by-products. It assumes that the economic value reflects the relative environmental burdens associated with each product.

3.7.3 Allocation according to ISO-Norm 14040 /14044

The LCSA methodology for the CHEERS biorefinery will follow the requirements for allocation according to ISO Standards 14040 / 14044 (ISO, 2006, 2017). ISO 14044 is an international standard that specifically pertains to life cycle assessment (LCA). LCA is a method used to evaluate the environmental impacts of products and systems throughout their entire life cycle, from raw material extraction to disposal.

ISO 14044 emphasizes a hierarchical approach for dealing with multifunctional processes within LCA studies. Multifunctional processes are those that generate multiple products or services simultaneously. The standard recommends addressing these processes in a systematic manner to ensure accurate and reliable environmental assessments.

The first preference outlined in ISO 14044 is the subdivision of multifunctional processes. This involves separating the different functions or outputs of the process to analyse their environmental impacts individually. By doing so, a clearer understanding of the specific contributions and trade-offs associated with each product or service can be obtained.

When subdivision is not feasible, the next recommended approach in LCA is system expansion. System expansion involves expanding the boundaries of the assessment to include closely linked processes associated with the multifunctional system being evaluated. By adopting a broader perspective, the environmental impacts of the entire system can be more comprehensively assessed. In system expansion, comparable products can be substituted with by-products, leading to environmental benefits for the primary production system (Pelletier et al., 2015; Vadenbo et al., 2017). This allows for the consideration of additional products or residues in the LCA calculations without expanding the scope of the study. Substitution helps determine which products can be replaced by specific residual biomass types, indicating the potential value of these residues. However, the literature does not provide a direct connection between the system expansion approach and LCA methods for material recycling or cascading use (Olofsson & Börjesson, 2018).

Lastly, if neither subdivision nor system expansion is feasible, allocation is employed as a last resort. Allocation is the process of assigning environmental burdens or impacts to the different products or services generated by the multifunctional process. To establish a fair allocation, ISO 14044 recommends the use of an allocation key that reflects the physical causality relationship between the co-products. This key helps ensure that the environmental impacts are distributed appropriately based on the specific characteristics and contributions of each co-product.

By following this hierarchical approach, ISO 14044 aims to improve the accuracy and consistency of LCA studies involving multifunctional processes, ultimately enhancing the credibility of environmental assessments and supporting more informed decision-making in sustainable product development and resource management (ISO, 2006, 2017).

3.7.4 Allocation between Beer and Side Streams

The first choice of allocation method in the CHEERS value chains is the choice of allocation between the brewery and the side streams.

Through an extensive review of existing literature and research, it has become clear that the allocation keys for valorisation of side streams are not harmonised and consistent between different scientific studies. Therefore, selecting the allocation key for the CHEERS project requires careful consideration. The choice of allocation key should be based on scientific rigor and consistency. It is important to analyse the various allocation methodologies in terms of their theoretical foundations, applicability to the specific context of the study, and potential implications on the results. The allocation key decision should also consider the feasibility and practicality of implementation. Factors such as data availability, ease of measurement, and transparency should be considered. The selected allocation key should be well-documented, transparently communicated, and reproducible, allowing for peer review and future comparisons. In conclusion, the allocation key within the CHEERS project needs to be thoroughly researched and carefully chosen to ensure the reliability and representativeness of the study's findings. This decision will contribute to obtaining accurate and robust results, enabling informed decision-making for sustainable practices within the project's scope.

In order to provide robust results for the TEA and LCSA of the CHEERS biorefinery we will calculate the results for three different choices of allocation methods between the brewery and the valorised side-streams including (1) cut-off, (2) economic allocation, and (3) circular footprint formula. The avoided burden methodology is excluded since the valorisation of side streams is a one-off opportunity.

The cut-off allocation method is simple to calculate because the side streams of the brewery are considered as a waste and therefore are free from environmental impacts. This in turn leads to comparatively low impacts of the products from the valorisation.

Since no value is associated with the feedstocks used in the production process, they are not allocated any environmental burdens. This approach assumes that the feedstocks have a minimal environmental impact, which leads to low environmental impacts of the products that are produced in the CHEERS biorefinery. However, with this choice of allocation method the environmental impacts of the beer production would remain the same.

However, since the side streams can be valorised, they have an inherent value as feedstocks for the valorisation. Which leads us to the second allocation scenario economic allocation, in which we will divide the environmental impacts between the beer production and the side streams based on estimates for the economic value of the side streams.

With this choice of allocation method there are impacts associated with the feedstocks used in the production process, which leads to higher environmental impacts of the products that are produced in the CHEERS biorefinery and would reduce the environmental impacts of beer production. However, the prices for the feedstocks from side stream will have to be estimated since the availability of price information is limited due there being no operationalised market for this kind of feedstock.

For the third allocation scenario we will use the circular footprint formula as suggested by the EU product environmental footprint (PEF) (European Commission, 2017).

With this choice of allocation method, the environmental benefits of the valorisation of BSG and other side streams is shared between the brewery and products from the valorisation. With this choice of allocation method, the impacts of beer production will also be reduced, and a share of the impacts will be allocated to the feedstock, which will increase the impacts associated with the products produced by the CHEERS biorefinery.

3.7.5 Allocation between Products from Valorisation

The second choice of allocation method in the CHEERS value chains is the choice of allocation between the different products produced by the biorefinery.

In order to provide robust results for the TEA and LCSA of the products from the CHEERS biorefinery we will calculate the results for three different choices of allocation methods considering the impacts between the different products including (1) system subdivision, (2) system expansion and (3) economic allocation. The choice of allocation method follows the recommendation in the ISO standards 14040 and 14044 regarding allocation.

The aim of the first allocation method system, subdivision, is to divide the system as much as possible in order to avoid allocation. In the case of the CHEERS biorefinery a subdivision for the insect platform and the microbial platform is considered as feasible. However, subdivision for the four different products from the microbial platform is not possible due the interconnectedness of the processes in this platform.

The second choice of allocation method, system expansion, aims to avoid the allocation by expanding the product system with other supply chains producing equivalent products. The study is expanded to include a comprehensive assessment of the entire system without the need for allocation within the system. This approach provides a holistic view of the environmental impacts associated with the full CHEERS system and allows for a thorough evaluation of the overall sustainability performance.

The third choice of allocation method for the allocation between the products from valorisation is economic allocation. With this allocation method each of the five value chains within the CHEERS system is evaluated separately. The value chains can be defined based on the different pathways or end uses of the by-products. For example, one value chain could focus on the use of by-products as animal feed, while another could examine their utilization for bio-based production. This approach enables a detailed assessment of the environmental impacts and benefits associated with each individual value chain, providing insights into their relative contributions to the overall sustainability of the by-product's valorisation.

However, the prices for the feedstocks from side stream will have to be estimated since the availability of price information is limited due there being no operationalised market for this kind of feedstock.

3.8 Target Audience

The target audience for the TEA and LCSA for the CHEERS biorefinery are the CHEERS project consortium, stakeholders in the brewing industry as well as stakeholders in the bio-based industries and political entities. It is intended to support the 5 value chains of the CHEERS project in the ecological planning and is intended for publication.

3.8.1 Consortium

This target audience comprises environmental and sustainability professionals, researchers, and consultants. They are interested in studying the environmental impact of the CHEERS biorefinery and identifying opportunities for resource optimization and circular economy practices. The LCA results can offer valuable data and insights regarding the environmental benefits and potential trade-offs of valorising by-products in the beer industry. It is important to provide detailed information on the environmental indicators used, methodology employed, and specific findings related to energy consumption, water usage, greenhouse gas emissions, waste reduction, and other relevant metrics.

3.8.2 Breweries / Bio-based industries

This audience consists of professionals working in the brewing industry, including brewers, sustainability managers, and supply chain managers. The LCSA aims at fostering the understanding of the environmental benefits and potential cost savings associated with by-product valorisation.

The LCA results can provide insights into the environmental hotspots and opportunities for improving the sustainability performance of their operations. Key information to address would include the potential reduction in carbon emissions, resource efficiency gains, and the economic viability of implementing by-product valorisation strategies.

3.8.3 European Commission / Political entities

The third target audience are political entities in order to implement sustainable practices on a broader scale and to drive systemic changes. They shape environmental policies and regulations, making it important to include them as a target audience. The benefits of targeting political entities include informing policy development by presenting the positive environmental impacts of by-product valorisation. Demonstrating the economic benefits can encourage support for sustainable initiatives, while engaging political entities fosters collaboration among stakeholders. Additionally, showcasing environmental performance can build trust and potentially lead to preferential treatment or grants. Clear and concise communication of LCA results is vital to emphasize the environmental benefits, economic considerations, and policy implications. By demonstrating the positive impacts of by-product valorisation, breweries can encourage political entities to prioritize sustainability and facilitate wider adoption within the beer industry.

3.9 Data Quality and Uncertainty

Conducting a Life Cycle Sustainability Assessment (LCSA) of by-products valorisation is essential to evaluate the environmental, social, and economic benefits and potential trade-offs associated with such practices. However, ensuring data quality and addressing uncertainties in this specific LCSA context are necessary for generating reliable insights.

To ensure data quality, essential aspects such as accurate information on the quantity and composition of by-products (e.g., spent grains, yeast, and waste water) with consideration of their variability, detailed data on the specific processes and efficiencies of valorisation technologies (bioconversion and animal feed production), comprehensive data covering the entire supply chain, including transportation, energy consumption, and emissions associated with handling and processing by-products need to be addressed.

Additionally, technological developments in valorisation technologies over the duration of the project introduce uncertainties in their efficiency and environmental performance. Moreover, socio-economic factors, such as stakeholder acceptance and adoption of the products from the valorisation practices, introduce uncertainties in measuring the overall life cycle impacts, incorporating market demands and societal preferences. Properly identifying and addressing these uncertainties are imperative to enhance the credibility and usefulness of study.

To enhance the credibility, specific strategies should be implemented. Firstly, fostering collaboration and data sharing among all researchers and valorisation technology providers of the CHEERS project can lead to more comprehensive data collection and improved data quality. Secondly, conducting sensitivity analyses to examine the effects of varying input parameters helps identify critical uncertainties and areas for improvement. Thirdly, regularly updating the life cycle inventory with new data and technologies ensures that the LCSA remains relevant and reflective of the current state of the project. Lastly, stakeholder engagement throughout the LCSA process ensures that diverse perspectives and uncertainties are adequately considered, contributing to a more robust assessment.

4 Optimisation and Scale-up

The TEA and LCSA of CHEERS solutions will be assessed at three process capacity scales, namely with capacity for valorising the by-products of small, medium-sized, and large-scale breweries.

Optimization of CHEERS system will be focus on maximizing its economic feasibility, but at the same time minimizing negative the environmental and social impacts. The minimization of waste generation in CHEERS system is also a main objective of the optimization study despite relative waste generation is not an indicator normally considered in the LCA.

Several CHEERS configurations (by modifying the target fraction of the by-products and intermediate flows that goes to the different value chains) will be assessed by using the economic indicators (PBP, NPV) and the relative waste generation indicator. The better configurations (the one that allows a higher economic benefit but considering that the waste generated needs to be treated before disposal) will be also assessed from the environmental point of view by using a LCA methodology.

Scaling up the CHEERS system equipment and facilities from the demo scale being developed, built, and tested as part of the CHEERS project to true commercial scale.

The comparative LCSA results as well as the TEA results, apply to conventional alternatives, and recommendations for further development and scale-up of the CHEERS technologies at three levels, namely with capacity for valorising the by-products of small, medium-sized, and large-scale breweries, will be compiled in consultation with the respective partners. It will be ensured that the results and recommendations are formulated to facilitate improved decision-making, with widespread consortium and stakeholder awareness of trade-offs and uncertainties.

4.1 Scales

The TEA needs to consider the size of the brewery since the design of the equipment used in CHEERS must be in accordance with the flow rate of by-products generated to avoid oversizing the equipment. In addition, in the case of small breweries, it is possible that the ratios of by-products generated per hl of beer produced may be different from the generation in larger facilities because small breweries normally produce beer (higher alcohol content and International Bitterness Unit (IBU) which require a higher percentage of malt and/or hops or more roasted malts). This possible difference in the amounts of by-products generated (and their relationship to each other) can lead to differences in the optimum configuration of CHEERS between brewery sizes. The three scales of work to be considered are the following:

Large-scale (industrial) Brewery (beer capacity > 1 000 000 hl):

Big breweries typically have larger production volumes and greater access to resources and infrastructure. As a result, they may have more advanced and efficient systems in place for by-product valorisation. They may have dedicated facilities or partnerships with external entities to process and utilize their by-products on a larger scale. Big breweries may also have the financial capacity to invest in innovative technologies and research for further valorisation opportunities. Additionally, they may have stronger connections with suppliers and a wider distribution network, which can enable more comprehensive by-product utilization across their value chain.

Medium-sized Brewery (beer capacity < 1 000 000 hl):

Medium-sized breweries have a moderate production scale and resource availability. While they may not have the same level of resources and infrastructure as big breweries, they still have opportunities for by-product valorisation. Medium-sized breweries can explore partnerships with local farmers, animal feed producers, or biogas facilities to utilize their by-products effectively. They may also engage in community-level initiatives for by-product valorisation, such as donating spent grains to local farmers for animal feed. Collaborative efforts with other breweries or organizations within the region can help maximize the value derived from by-products.

Small Brewery (beer capacity < 50 000 hl):

Small breweries typically have limited production volumes and fewer resources compared to larger counterparts. However, they can still engage in by-product valorisation practices on a smaller scale. Small breweries often have close relationships with their local communities and can establish direct partnerships with local farmers, bakeries, or artisanal food producers to repurpose their by-products. They may also explore on-site composting or small-scale biogas production using anaerobic digestion. Collaboration with nearby breweries or shared facilities can provide cost-effective solutions for by-product utilization.

4.2 Technology maturity

The Technology Readiness Level (TRL) is a method for defining **the state of development or maturity of a technology** and its relation to the market. The European Commission decided to introduce it in its research and innovation projects since H2020.

The following definitions of TRL apply, unless otherwise specified:

- *TRL 1 — Basic principles observed*
- *TRL 2 — Technology concept formulated*
- *TRL 3 — Experimental proof of concept*
- *TRL 4 — Technology validated in a lab*
- *TRL 5 — Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies)*
- *TRL 6 — Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)*
- *TRL 7 — System prototype demonstration in an operational environment*
- *TRL 8 — System complete and qualified*
- *TRL 9 — Actual system proven in an operational environment (competitive manufacturing in the case of key enabling technologies, or in space)*

Typically, new technologies go through the various stages of the TRL scale in their life cycle (Figure 15). During the research and development phases, it is possible to have iterations among the different TRL levels. In this sense, the TRL scale also helps to evaluate the project progress (Guiding notes to use the TRL self-assessment tool, CORDIS, 2022).

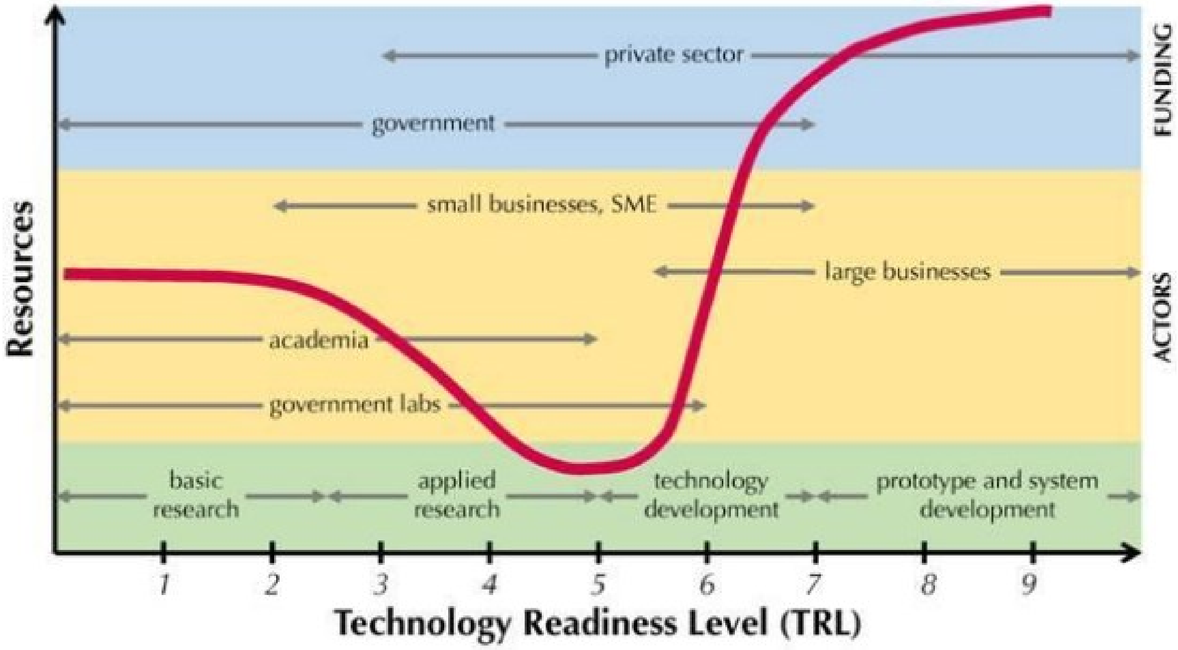

Figure 15: Availability of resources for new product development at various TRLs. The gap in the middle is sometimes referred to as "The Valley of Death" (Hensen et al., 2015).

The Horizon European portal (NCP Portal) offers a TRL self-assessment tool (developed under CORDIS, 2022) to identify the TRL of different processes or projects. Background information is summarized in the following table to assess the TRL of an industrial process (Table 4).

Table 4: Summarize of TRLs of an industrial process

TRL	Summary	Description
TRL-1	Basic principles observed	When a technology is at TRL-1, scientific research has just started, and the first results are used to be translated into future research and development.
TRL-2	Technology concept formulated	At TRL-2 basic principles have been studied and first experiments/tests are designed based on the initial findings. TRL 2 technology is still very speculative.
TRL-3	Laboratory experiments are designed to verify that the conceptual process works as expected.	When results from experiments/tests supports the initial idea, the technology is at TRL-3. Generally, both analytical and laboratory studies are required at this level to see if a technology is ready to go to the development phases. At TRL-3, a proof -of-concept model is constructed.
TRL-4	Process components are validated individually and could be integrated in an ad hoc manner at lab scale.	At TRL-4, the validation of the technology has been performed at the laboratory level, testing each component so at this point a laboratory prototype is available.
TRL-5	Integrated validation of the process to produce small outputs or short batches of the end product.	TRL-5 is a continuation of TRL-4, but the testing environment become as closer as possible to a realistic one, although still the environment is under a control mode. Reaching to this point, one can conclude that the new technology is feasible from a technological point of view.
TRL-6	Development of a pilot-scale testing plant or unit (1/100th of commercial scale) including engineering-scale equivalents of all the operations that will be required at scale.	In TRL-6, the prototype must be demonstrated in a real environment, so to confirm the engineering is feasible.
TRL-7	Successful demonstration of the continuous operation of the pilot plant/unit during a relevant timeframe.	At TRL-7 the technology requires that the working model or the prototype developed to be demonstrated in an operational environment, typically under industrial conditions and timings. Reaching to this point, one can conclude that the new technology is reliable from the technological point of view.
TRL-8	Demonstration plant is constructed (1/10th of commercial scale) and operated in continuous mode, including working outside normal parameters.	In TRL-8 technology is ready for implementation into an already existing technology or technology system.
TRL-9	Commercial plant/unit set up and running for full range of operating conditions.	Once the technology system has been proven during operations, it can be called TRL-9 and considered a commercial technology. Reaching to this point, one can conclude that the new technology is feasible from a scientific point of view.

The technology maturity analysis will be carried out at two different levels. The first will refer to the unit processes with the specifications indicated for each equipment (including elongation of VFAs, BES, and fermentation). This analysis will allow us to know the degree of difficulty to implement this technology and where the main drawbacks will be found. In addition, the degree of maturity that the technology will reach after the implementation of CHEERS will be indicated.

On the other hand, it will be necessary to know the level of maturity of the interrelation of the processes considered. That include the combination of processes and their complementarity, being the outputs of some Value Chains part of the inputs of others.

It is noteworthy to acknowledge that conducting Social Life Cycle Assessment (S-LCA) during the early stage (TRL-5) of the production process development is a highly complex undertaking. However, it is crucial to prioritize this task in order to ensure appropriate social conditions during the implementation of the process. Currently, there is a shortage of systematic and quantitative methodologies available to assist researchers in effectively applying S-LCA (Cadena et al., 2019).

5 Techno-Economic Assessment (TEA)

Understanding the TEA as *"the evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision makers in directing research and development or investments"* (Kuppens et al., 2015), this study will be carried out to determine if the technology proposed in CHEERS is profitable and if the value chains included are economically desirable. Considering this definition, sequential steps will be followed in order to achieve the degree of detail that this type of analysis requires. This methodology has been employed by previous studies (Van Dael et al., 2015).

First of all, value chains and processes will be described in order to understand the scope and boundaries of the project. The descriptions are supported by specific flowcharts of each value chain to facilitate the understanding of each of them. After the description of the value chains, the degree of detail will be increased reaching the level of unitary processes. Once this level of detail is reached, mass and energy balances will be performed. The data collection procedure for this phase will be explained in the respective sections. The sources used to obtain the economic data necessary for the calculation shall also be explained. With the disaggregated information, the economic analysis and the different sensitivity analyses proposed will be carried out, scale of the brewery and geographical location.

The economic analysis (from the modelling system to the calculation of economic indicators) will be carried out for three different work scales. Because the CHEERS system is integrated as a by-product recovery system of a brewery, different scales of beer production plants will be proposed using Spain as a base-case scenario. The initial calculation has been made for a brewery producing more than 1 000 000 hl/year as a large brewery. After this study, the capacity of the study brewery will be changed to medium-sized (between 1 000 000 and 50 000 hl/y) and small brewery (less than 50 000 hl/y). For the intermediate scale, the same costs of equipment, personnel and inputs have been maintained, changing the costs according to the formula for scaling. However, for the small brewery, it will be necessary to look for equipment more in line with the scale of work, to avoid the oversizing of the equipment and obtain acquisition and operating costs more representative. In addition, it is expected that for this scale of brewery the ratios of by-product production per hl of beer produced will be different.

5.1 Process modelling

5.1.1 Mass balance

Different sources of information will be used to obtain the necessary data. For those technologies with a high degree of maturation, the information will be obtained either based on bibliographic sources of case studies on an industrial scale or from the partner in charge of this process (by data from project, e.g., D1.4 and questionnaires). For those technologies with a lower degree of maturation, the information will be obtained from bibliography and considering the experience of the partners involved in similar processes.

Due to the input and output information being different according to the scale of work, the data to be collected will be oriented towards the effectiveness or performance of each operational unit. In this way, the information obtained can be extrapolated to other scenarios with a scale of similar magnitude. For the microbrewery scenario, the study will consider if this scale of work presents different efficiency in comparison to big and medium-size Breweries. At this scale, it is possible that the equipment employed is different and therefore so is the performance of each of them.

For the inputs, the resources necessary to produce the added-value products will be considered, as well as other resources necessary for the correct operation of the processes, such as reagents for cleaning, for example.

A flow chart of each value chain will be made at the operational unit level where the results of the mass balance are showed.

5.1.2 Energy balance

Data collection for energy balance is carried out in similar way to mass balance according to technology maturity.

To obtain the energy consumption it will be necessary to have defined the equipment used. An energy consumption performance with respect to the work capacity will be calculated, in order to be able to use the information collected from the different sources in the proposed scenarios. The technical information of the equipment will also be consulted if it is considered necessary. As it is expected that the equipment used in the microbrewery example will be different from the rest of the scenarios, it will be necessary to calculate new energy performance for this equipment.

It will also be necessary to define the number of working hours-per-day of the equipment and the annual working days in which the equipment is operational. The energy requirements will also be shown in the flow chart explained above.

5.1.3 Assets and Equipment

In order to identify the equipment required, it is necessary to increase the level of detail of the description of the processes down to the level of the operational units. Partners will be consulted to detail the different stages of operation of each value chain as well as the equipment required for each of them.

Partners will also be consulted on which equipment can be employed at the defined work scales. In this way it will be possible to know the work capacity of the equipment and thus be able to define the necessary quantity of each of them for each operational unit. For those processes that due to their high degree of innovation have not been applied on an industrial scale, information from similar processes and equipment that meets the work requirements will be used. When partners cannot provide the requested information, a bibliographic search will be used.

The flow chart that contains the energy and mass balance will also include the equipment required for each operational unit.

5.2 CAPEX

All new facilities require a capital investment to acquire the necessary new equipment. This capital expenditure, CAPEX, reflects all costs related to the acquisition of equipment. The costs of the equipment, its design, installation (direct costs) depend on the scale and its work capacity, so it will have to be considered. There may also be indirect costs associated with CAPEX installation, pipes, and design.

5.2.1 Direct Costs

The direct costs of CAPEX are those expenses that are necessary and independent of the configuration of the installation. These costs refer to the equipment, reactors and other elements necessary for the operation of the facility. The cost of the equipment will be obtained based as function of the TRL. For the most common equipment that needs fewer specific requirements, such as pumps, agitators, or blowers, catalogue or bibliographic data will be used. For specific equipment, partners will be consulted, and a bibliographic search will be carried out to obtain the necessary information.

For technology with a low TRL it will be necessary to obtain the CAPEX by modelling and subsequent scaling. Equipment costs will be brought to the same scale according to the general equation known as the six-tenth rule:

$$C_2 = C_1 \cdot \left(\frac{S_1}{S_2}\right)^n$$

Where C = equipment cost, S = scale, n = 0.7 for reactors or tanks, 1.2 for pumps and blowers, 0.5 for separators and 1.0 for other equipment, as conventionally done in the literature (Debergh & Van Dael, 2022). All data will be converted into € 2023 units using currency exchange rates from European Central Bank and the Chemical Engineering Plant Cost Index (CEPCI) as appropriate.

5.2.2 Indirect Costs

Indirect costs are related to those tasks necessary for the installation of the equipment. These costs are variable since they depend on several criteria, such as design, location, and scale. These costs include piping, instrumentation, controls, electrical, buildings, design & engineering, and offsite costs. The indirect costs are calculated taking into account the direct costs by means of the Lang Factor (LF) in the formula for the total capital investment:

$$TCI = \sum_i (EC_i \cdot LF)$$

Where TCI is the total capital investment and EC is equipment cost. A value of 5 LF is selected according to (Peters et al., 2003). The lifetime of each equipment will be estimated based on the information offered by the partners.

5.3 OPEX

Unlike CAPEX, operational expenditures, OPEX, are costs or benefits that must be accounted for annually, as it refers to the permanent costs for the operation of the system and the benefits obtained after the operation of the system. Within the expenses included, fixed and variable costs can be differentiated. Fixed costs usually include the salary of the people assigned to the maintenance and operation of this equipment, and maintenance costs, among others. The variable costs include the purchase of raw material that may be needed in some processes, also consumables (such as enzymes, cleaning reagents, and nutritional supplements) and Utilities (electricity, fuels, and water), for example. Benefits can include all final products with market value that are generated within the CHEERS system.

On the other hand, due to the depreciation of the value of money, the economic variation of the costs of each item will be recalculated annually according to an adjusted discount rate with inflation rate.

5.3.1 Fixed Costs

All equipment employed must undergo continuous maintenance. This maintenance involves an economic cost that must be taken into account. Maintenance costs are estimated as 3.5% over the TCI (Pérez et al., 2022). Labour costs were calculated considering the task necessary for each value chain. The average salary in Madrid (14.5 € person/h) was used for the estimation of direct labour costs in the base-case scenario (Worlddata.info, 2021).

In addition to the salary of the workers who perform the daily tasks, it is necessary to allocate part of the salary costs to management and supervision also, to conduct follow-up analysis in the laboratory to ensure the correct functioning of the processes. These costs are assumed as 25% of the labour cost for management and supervision and 10% for the laboratory (Debergh & Van Dael, 2022).

The cost of maintenance and repair of the equipment depends on the equipment installed, therefore, this annual cost is estimated as 2.5 %TCI/year (Debergh & Van Dael, 2022). Similarly, the cost of Insuring the installation will depend on all the installed capital, so its annual cost is estimated at 1% of the TCI (Debergh & Van Dael, 2022).

5.3.2 Variable Costs

In addition to the by-products of the brewery and other streams that come from beer production, other materials will also be needed as substrate, mainly nutrients and supplements. The required quantity of these raw materials will be calculated based on the mass balance of D1.4. Consortium partners will be asked to share what type of raw material is used and what the purchase cost is. In this same round of consultation, they will be asked about other consumables that are not used, as substrates, but that are necessary both for production processes and in maintenance and cleaning (enzymes, acids, and basis).

Energy consumption will also be obtained from the information in D1.4 and detailed with partners when a higher level of detail is required. A Bibliographical approach will also be used to calculate the average consumption of this equipment if detailed information cannot be obtained. For energy costs national sources will be consulted, in this case, Spain, as the brewery of the study is in Valencia.

Energy requirements for pumps are calculated according to the following equation, where P_{pump} represents the power in kW, Q stands for the volumetric flow expressed in $m^3 \cdot s^{-1}$, ΔP is the pressure drop in kPa, and 0.7 is the electrical efficiency of pumps and compressors:

$$P_{pump} = \frac{Q \cdot \Delta P}{0.7}$$

Energy requirements for blowers and compressors are calculated according to the following equations, where P_{blower} represents the power in kW, P_{is} stands for the isentropic power in kW, 0.7 is the electrical blower efficiency, γ is the adiabatic coefficient, T_{out} refers to the gas isentropic outlet temperature, T_{in} represents the gas inlet temperature, P_m is the gas molecular weight, and Q stands for the inlet volumetric flow:

$$P_{blower} = \frac{P_{is}}{0.7}$$

$$P_{is} = 2.31 \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{T_{out} - T_{in}}{P_m} \cdot Q$$

It will proceed in a similar way for water consumption and costs, where it is required. Bibliographic information and technical information of the equipment (depending on whether it exists and is required) will be used to calculate the fuel consumption. The cost of these fuels will also be extracted from national sources.

5.3.3 Revenues

Intermediate flows can be generated that are not valuable but required a previous treatment before disposal. Mass balance and D1.4 will be used to identify and quantify these currents. For wastewater and solid fractions generated in the different stages of concentration and extraction of the final products, the average treatment and management costs calculated by EPSAR, the sanitation entity of Valencia (Spain), will be applied. For the rest of the costs of remediation of the other streams, national references will also be used when possible, or failing that, bibliographic data referencing the same geographical area.

The market value of the main final products will be obtained from the CHEERS Grant Agreement. For other currents that are recovery and that can be marketed, their sale price will be obtained by consulting different bibliographic sources.

5.4 Economic indicators

In order to determine the viability or not of CHEERS, the Net Present Value (NPV) must be calculated:

$$NPV = \sum_{t=0}^{n} \frac{V_t}{(1+k)^t} - I_0$$

This indicator corresponds to the present value of the financial flows of an investment. The higher this indicator, the more profitable the investment. If the result is less than zero, this project will not be profitable.

To be able to apply this formula, the expected duration of this project (n) must be fixed before. In this case, V_t corresponds to the balance of costs and benefits of each year. CAPEX, the initial acquisition costs, are included in I_o. Discount rate, *k*, must be defined also. The discount rate converts the value of the future profit to the present value. For the calculation of the discount rate, the following equation will be used based on the interest rate, since the interest rate is the inverse of the discount rate:

$$k = \frac{i}{1+i}$$

The interest rate will be obtained from Bank of Spain. The value of the discount rate that causes the NPV to be zero is called the Internal rate of return (IRR). Bigger differences between IRR and discount rate suggests that the project is more likely to be feasible.

It will also be necessary to consider the expected inflation (g) throughout the project, since the value of inflation modifies the value of V_t of each year, but will also the discount rate need to be adjusted (k'):

$$k' = k + g + (k \cdot g)$$

Inflation rate will remain fixed for the entire calculation period and will be taken from the Bank of Spain's consumer price index. Linear depreciation will be applied for the entire period considered.

Once this information is obtained, the **amortization period** can be calculated. That is, the time that has to elapse until the initial investment is returned and the project begins to offer benefits. This calculation can be performed as the first year necessary to obtain a positive NPV.

In a simpler way, the **payback period (PBP)** can be calculated to obtain an estimate of the time needed to recover investment expenses and start making net profits from the installation. This calculation requires CAPEX and the expected annual net balance sheet:

$$Payback\ period = \frac{\text{Initial investment}}{\text{Recovery year cash flow}}$$

5.5 Sensibility and Risk Analysis Methodology

Once the economic analysis has been carried out, the most influential variables of the cost-benefit analysis will be identified. In this way, the results obtained under different scenarios can be validated and used to provide a reliable error margin. A geographic sensitivity analysis will be carried out for this purpose, using Spain as a base-case scenario. For this analysis, the economic variables that are subject to greater variability between countries have been modified, such as the cost of electricity, water, the average salary or equipment cost acquisition (Pérez et al., 2020). Energy and water industrial selling prices were obtained from national resources. For the sensibility analysis we will employ Germany and Poland as ubication of the CHEERS systems.

In addition, as indicated in chapter 4: Optimisation and Scale-up, different CHEERS configurations (by modifying the target fraction of the by-products and intermediate flows that contribute to the different value chains) will be studied to obtain those configurations that maximize the economic benefit but at the same time minimize the generation of waste and the environmental impact.

In the risk analysis, the robustness of the CHEERS system will be evaluated in different adverse situations. This analysis aims to know if the set of processes is still viable even in unfavourable situations or if some processes need special attention due to their influence on the viability of the project. To do this, we will analyse how the failure of a value chain affects the rest of the process. In addition, the effect of increased maintenance costs and replacement of parts will also be studied, to simulate a scenario where an extra effort is required to ensure the correct functioning of CHEERS system.

6 Life Cycle Sustainability Assessment (LCSA)

As mentioned before, CHEERS aims to harness the untapped potential of side streams in beer production by developing five competitive and innovative bio-based products. Among these products is the utilization of brewer's spent grain as feed for insects, specifically mealworms (Tenebrio molitor larvae), to produce protein flour for protein-rich shakes targeted at health-conscious consumers. Additionally, microbiological processes are employed to maximize the use of carbon dioxide from beer fermentation and methane from anaerobic wastewater digestion. These processes yield four additional products: single cell protein (SCP) for pet food ingredients and caproic-rich mixture of volatile fatty acids (VFAs) for animal feed, chlorine for disinfectants, and ectoine for cosmetic applications.

To evaluate the environmental, social and economic implications of these novel products, a life cycle sustainability assessment (LCSA) methodology will be employed in this study.

This chapter will provide a comprehensive overview of the specific LCSA methods selected for the analysis. These methods allow for the holistic evaluation of the environmental, social, and economic dimensions of the studied products. By employing robust assessment frameworks, the study aims to quantify and compare the life cycle sustainability performance of the bio-based products developed within the CHEERS project.

The selected LCSA methods will address a range of impact categories, including climate change, resource depletion, biodiversity, and primary energy demand. By applying these methods, the study will assess the environmental impacts associated with the production of products develop within the CHEERS project, comparing them with alternative utilization approaches and conventional production methods.

Moreover, the chapter will delve into the social dimensions of the studied products, examining potential financial gains derived from utilizing by-products for new goods instead of incurring costs for waste treatment. Social implications, such as job creation and community engagement, will also be considered within the LCSA framework.

The chapter aims to provide a comprehensive understanding of the life cycle sustainability assessment methods employed in the study, highlighting their relevance and suitability for evaluating the environmental, social, and economic aspects of the innovative bio-based products developed within the CHEERS project. By employing assessment methodologies, this research seeks to contribute to the advancement of sustainable production practices and decision-making processes in the brewing industry and waste utilization in general.

6.1 Environmental Life Cycle Assessment (E-LCA)

An Environmental Life Cycle Assessment (E-LCA) is a systematic approach for evaluating the environmental impact of a product, process, or service throughout its entire life cycle, from raw material extraction to production, use, and disposal. E-LCA typically consists of several distinct phases.

In the Goal and Scope Definition phase, the purpose, boundaries, and metrics for comparison are established, along with the identification of relevant environmental impacts. The Life Cycle Inventory (LCI) phase entails gathering comprehensive data on inputs and outputs throughout the entire life cycle, while the Life Cycle Impact Assessment (LCIA) analyses this data to quantify environmental impacts using impact assessment methods like global warming potential. Finally, the interpretation phase involves identifying key impact contributors, assessing data uncertainties, comparing different options, and drawing conclusions to inform decision-making.

6.1.1 Impact Assessment Methods

In the impact assessment of a E-LCA, various methods are utilized to evaluate different environmental impacts. For the CHEERS project's E-LCA, the methods employed include global warming potential (GWP100a) based on IPCC guidelines (IPCC, 2021), which focuses on quantifying the potential for global warming; and the total environmental impact using the method of ecological scarcity (ESM) (Frischknecht et al., 2021), which assesses overall environmental impact considering multiple indicators. Additionally, the assessment includes cumulative energy demand (CED) (Hischier et al., 2010) and environmental footprint (EF 3.1) recommendation (Fazio et al., 2018) to assess energy consumption and overall environmental pressures associated with the project, respectively. For the impact assessment, the methods listed in Table 5 are considered in the study.

Table 5: Impact assessment methods

Method	What is being considered?	unit
IPCC (IPCC, 2021)	Global Warming Potential (GWP100a)	kg CO_2-eq
Method of Ecological Scarcity (ESM) (Frischknecht et al., 2021)	Total Environmental Impact	Eco Points (EP)
(Hischier et al., 2010)	Cumulative Energy Demand (CED)	MJ-eq
Midpoint impact assessment methods for the environmental footprint according to PEF (Fazio et al., 2018)	Depletion of the Ozone Layer, Human Toxicity, Particulate Matter (PM), Ionizing Radiation, Photochemical Ozone Formation, Acidification, Terrestrial Eutrophication, Aquatic Eutrophication, Freshwater Ecotoxicity, Land Use	Different

6.1.1.1 Global Warming Potential

As an initial step in the impact assessment, the environmental indicator "global warming potential" is calculated using the IPCC 2021 GWP100 method (IPCC, 2021). This method enables the determination of greenhouse gas emissions and their respective global warming potentials over a 100-year timeframe. The emissions of greenhouse gases are converted into kilograms of carbon dioxide equivalent (kg CO_2-eq), utilizing the characterization factor specific to each gas, and then summed. This value represents the potential of a product, also known as its CO_2 balance or CO_2 footprint. A higher balance indicates a greater contribution of the product to climate change.

The IPCC 2021 GWP100 method is an update to the 2013 IPCC method developed by the Intergovernmental Panel on Climate Change (IPCC). It incorporates IPCC climate change factors with a time horizon of 100 years. The results can be calculated cumulatively as GWP100 (select Damage assessment in your results) or per category, including GWP100 - fossil, GWP100 - biogenic, and GWP100 - land transformation.

It is important to note that the IPCC characterization factors employed in this method consider the direct global warming potential of air emissions and do not account for several factors, such as the indirect formation of nitrous oxide from nitrogen emissions, radiative forcing from emissions of substances like NO_x, water, sulphate in the lower stratosphere and upper troposphere, a range of indirect effects indicated by the IPCC, and the indirect effects of carbon monoxide emissions. Additionally, normalization and weighting are not included in this method (IPCC, 2021).

6.1.1.2 Ecological Scarcity Method

The second impact assessment method chosen is the ecological scarcity method (ESM), which evaluates the total environmental impact. This method takes into account various environmental impacts, including air emissions, surface water emissions, groundwater emissions, soil emissions, resource use, and waste generation. These impacts are normalized and weighted based on the objectives of Swiss environmental policy, employing a "distance-to-target" approach. In this approach, current emission values are compared to Swiss environmental targets.

The greater the deviation of emission values from the targets, the higher the corresponding eco-factor. The eco-factor is then multiplied by the life cycle inventory results, resulting in a single score expressed in eco points (EP) (Hischier et al., 2010).

The allocation of environmental impact points makes it possible to compare different environmental impacts among each other. The ecological scarcity method is regularly revised and adapted to changing environmental goals. The method does not follow the guidelines for assessment in life cycle assessments according to ISO 14040, as it applies a weighting according to Switzerland's political environmental goals. However, it can be used as a complementary analysis to indicators that fulfil the requirements in ISO 14040 (Frischknecht et al., 2021).

6.1.1.3 Cumulative Energy Eemand

The cumulative energy demand (CED) method used in this analysis is based on the methodology published by ecoinvent version 1.01, with additional enhancements by PRé to incorporate energy resources available in the SimaPro database. The CED calculation considers the higher heating values of fuels and incorporates extra substances from the Ecoinvent database version 2.0.

CED is characterized by dividing energy resources into five impact categories: non-renewable fossil, non-renewable nuclear, renewable biomass, renewable wind, solar, geothermal, and renewable water. Normalization is not included in this method. To obtain the cumulative energy demand, each impact category is given an equal weighting factor of 1, indicating equal importance in assessing energy demand (Frischknecht et al., 2007; Hischier et al., 2010).

6.1.1.4 Environmental Footprint 3.1 (adapted)

The environmental footprint (EF) 3.1 method, developed by the European Commission, is a comprehensive impact assessment framework designed for use within the Environmental Footprint (EF) initiative. This methodology serves as a standardized approach to assess the environmental performance of products and organizations.

EF 3.1 is the latest version of the method and is recommended for application in Product Environmental Footprint Category Rules (PEFCRs), Organisation Environmental Footprint Sector Rules (OEFSRs), as well as Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) studies conducted during the EF Transition Phase. One notable update in EF 3.1 compared to the previous version, EF 3.0, is the inclusion of revised impact categories. These revised categories encompass climate change, acidification, photochemical ozone formation, human toxicity, and ecotoxicity. These updates align with current scientific knowledge and reflect the evolving environmental priorities.

The EF 3.1 methodology employs life cycle assessment (LCA) principles and methodologies to collect and analyse data on inputs, processes, and outputs throughout the product life cycle. It considers both direct and indirect environmental impacts, aiming to provide a comprehensive evaluation of the environmental footprint associated with a product or system. Characterization factors and impact assessment models are utilized within EF 3.1 to convert the collected data into impact scores or indicators. These indicators allow for quantitative representation of the environmental performance of the assessed product or system, facilitating comparison and analysis.

This methodology has been specifically designed for the EF initiative and is intended to enhance transparency, comparability, and informed decision-making. By adopting EF 3.1, researchers and practitioners can conduct rigorous and standardized environmental assessments, promoting sustainable practices across various sectors and industries (Fazio et al., 2018; Hauschild et al., 2011).

The environmental footprint according to PEF in Table 6 includes a collection of 12 models for impact assessment as recommended by the Joint Research Council of the European Commission for calculating the Environmental Footprint (EF) for the Product Environmental Footprint (PEF) (Fazio et al., 2018).

Table 6: Impact categories of the Environmental Footprint according to Fazio et al. (2018)

Impact Category	Model	Unit	Source	Further Information
Ozone depletion	Steady-state ozone-depleting potential	kg CFC-11eq	(World Meteorological Organization (WMO), 2014)	Evaluates the potential for reducing ozone concentration in the stratosphere.
Human toxicity, cancer and non-cancer effects	USEtox 2.1 model	CTUh	(Rosenbaum et al., 2008)	Two aspects: Both cancer and non-cancer effects are assessed using the Comparative Toxic Unit for Human Health (CTUh).
Particulate matter/Respiratory inorganics	PM model recommended by UNEP	Disease incidences	(Fantke et al., 2016)	Change in mortality due to PM emissions, expressed in deaths per kilogram of PM2.5 emissions.
Ionising radiation, human health	Human health effect model	kBq U^{235}	(Frischknecht et al., 2000)	The impacts on human health are considered.
Photochemical ozone formation	LOTOS-EUROS	kg NMVOC eq	(Goedkoop et al., 2009; van Zelm et al., 2008)	Increase in tropospheric ozone concentration due to emissions.
Acidification	Accumulated Exeedance	mol H+ eq	(Posch et al., 2008; Seppälä et al., 2006)	Evaluates the impact of acidifying substances on soil and water.
Eutrophication, terrestrial	Accumulated Exeedance	mol N eq	(Posch et al., 2008; Seppälä et al., 2006)	Evaluates the impact of nutrients in sensitive terrestrial ecosystems.
Eutrophication, aquatic freshwater and aquatic marine	EUTREND mode	kg P eq, kg N eq	(Goedkoop et al., 2009)	Two aspects: Evaluates nutrients in freshwater (phosphorus as the limiting nutrient) and in marine waters (nitrogen).
Ecotoxicity freshwater	USEtox 2.1 model	CTUe	(Rosenbaum et al., 2008)	Toxic effects on aquatic freshwater species.
Land use	LANCA -Soil quality index	Dimensionless, aggregated index of: kg biotic production/ (m^2 *a) kg soil/ (m^2 *a) m^3 water/ (m^2 *a) m^3 g.water/ (m^2*a)	(Bos et al., 2016)	The LANCA model considers various indicators for a range of soil properties. It assesses the impacts due to land use: erosion resistance, mechanical filtering, physical-chemical filtering, groundwater recharge, and biotic production.

6.1.2 Life Cycle Biodiversity Impact

The CHEERS project wants to put a special focus on the evaluation of the biodiversity impact. Biodiversity is considered in addition to other environmental impacts analysed in the E-LCA. According to the proposal, CHEERS aims to contribute to biodiversity preservation through the establishment of farms for edible insects. By increasing food availability and reducing the need for land-clearing, pesticides, and intensive agriculture, these farms help alleviate pressure on ecosystems and promote biodiversity conservation. Moreover, the project recognizes that the reduction of greenhouse gas (GHG) emissions plays a crucial role in preserving biodiversity on a global scale.

Natural processes involving the decomposition of organic matter produce CO_2 and CH_4, and the diverse microorganisms in nature have the potential to transform these GHGs into various chemicals, bio-based products, and new biomass feedstocks. This untapped biodiversity can be harnessed by CHEERS for the benefit of different industrial sectors, including cosmetics, animal feed, food, and chemicals, among others.

Biodiversity is a complex issue that is not defined in detail and can be measured in different ways. DeLong (1996) provides the following definition:

"Biodiversity is a state or attribute of a site or area and specifically refers to the ***variety within and among living organisms****, assemblages of living organisms, biotic communities, and biotic processes, whether naturally occurring or modified by humans. Biodiversity can be* ***measured*** *in terms of genetic diversity and the identity and* ***number of different types of species****, assemblages of species, biotic communities, and biotic processes, and the amount (e.g., abundance, biomass, cover, rate) and structure of each. It can be observed and measured at any* ***spatial scale*** *ranging from microsites and habitat patches to the entire biosphere."*

Based on that definition, the following aspects must be defined for a biodiversity impact assessment:

- Aspect of biodiversity measured, e.g. number of species
- Spatial scale of biodiversity

The **geographic boundaries** must be defined as well because the effect of activities affecting biodiversity are highly site, habitat, and ecosystem specific. We focus the analysis on the site of Mahou San Miguel in Spain since data can be collected in sufficient detail. In addition, a more general analysis of two different sites is planned in Germany and Poland.

The impact on biodiversity reflects the **damage that occurs in an area of protection** -in this case biodiversity - and are therefore called "Endpoint-Indicators". They are opposed to the direct measurement of negative impact on the environment called "Midpoint-Indicators", as an example climate change or eco-toxicity.

Certain **environmental impacts on the midpoint level** that are typically being considered in the environmental LCA also influence biodiversity, as an example eco-toxicity or climate change.

Other aspects, for example the introduction of new species (invasive neobiota), is typically not considered within existing methods. The direct exploitation of species is also a potential threat to biodiversity. To our current knowledge, there is no overlap of direct exploitation within the CHEERS concept.

The commonly measured and probably most relevant aspect influencing biodiversity is **land use** and land transformation. Within this project, it is expected that the area needed to obtain the agricultural products used in beer production and to produce the five innovative products as well as for the conventional production these products to be relevant. The direct land use caused by the production site can be included as well.

6.1.2.1 Land Use Intensity-Specific Global Characterization Factors

In their 2018 study, Chaudhary & Brooks focused on biodiversity impact assessment and specifically highlighted the concept of increased spatialization. They emphasized the importance of considering the spatial distribution of ecosystems and their vulnerability when assessing the impact of biodiversity. The researchers also emphasized the need to differentiate between different types of land use and the intensity of their usage, as these factors can significantly affect biodiversity.

Chaudhary & Brooks (2018) employed a methodology that involved utilizing the countryside Species-Area Relationship (SAR) (Figure 16) model to derive updated characterization factors (CFs) for projecting potential species losses resulting from different land use types and management intensities. They focused on five broad land use types and considered three intensity levels to account for variations in management practices.

Covering 804 terrestrial ecoregions, the study incorporated recent global land use intensity maps and the International Union for Conservation of Nature (IUCN) habitat classification scheme to parameterize the SAR model accurately. By calculating CFs for each combination of land use type and intensity level, the researchers quantified the biodiversity impact associated with specific land use practices. Furthermore, they conducted a case study comparing CFs for different forest management regimes in India to demonstrate the improved applicability of the updated CFs. The analysis also considered uncertainties, and the updated CFs showed smaller uncertainty intervals, enhancing the precision in estimating biodiversity impacts. Overall, the methodology provided more accurate estimates of potential species losses and increased the practical applicability of biodiversity impact assessments in life cycle analyses. The UNEP-SETAC life cycle initiative recommended the utilization of the countryside species–area relationship (SAR) model for calculating CFs to assess the biodiversity impact associated with land use throughout a product's life cycle.

The study limited its examination of land use types to forestry and agriculture, and other sectors were not yet considered in their assessment. This suggests that the study's findings and conclusions may not fully capture the potential impact of biodiversity loss or conservation efforts in sectors outside of forestry and agriculture.

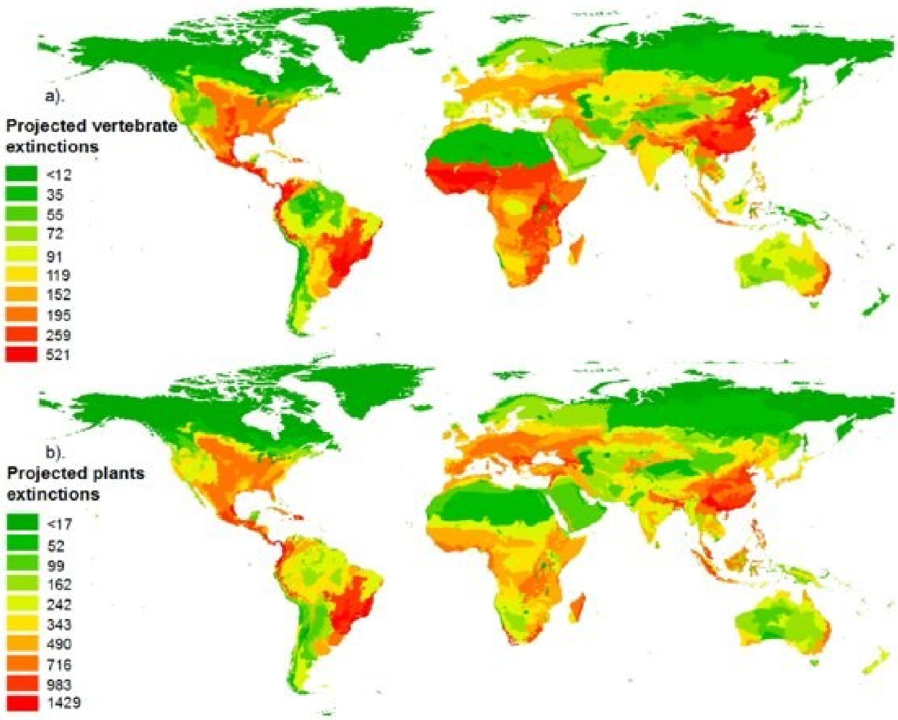

Figure 16: a) Projected species loss per ecoregion calculated using countryside SAR for four vertebrate taxa combined (mammals + birds + amphibians + reptiles). (b) Projected species loss for plants (Chaudhary & Brooks, 2018)

6.1.2.2 LC-Impact Approach

The LC-Impact approach, as outlined by Verones et al. (2020), focuses on deriving characterization factors (CFs) at the damage level for 11 impact categories, with 8 specifically addressing ecosystem quality. These impact categories are associated with three Areas of Protection (AoP): human health, natural resources, and ecosystem quality (Figure 17). Spatial differentiation is incorporated into 7 of the 11 impact categories, considering various spatial scales. The ecosystem quality category considers a vulnerability factor, and value choices are applicable within the approach, particularly regarding the time horizon and the level of scientific evidence. This involves the utilization of four sets of CFs that correspond to different levels of scientific evidence. Overall, the LC-Impact approach provides a comprehensive framework for assessing the impacts of different activities and products on various aspects of the environment, incorporating spatial differentiation, and accommodating value choices in terms of time horizon and scientific evidence.

An endpoint approach is implemented to evaluate the impact on the disappearance of species resulting from various environmental factors. This endpoint approach considers impact categories such as climate change, ozone formation, acidification, marine and freshwater eutrophication, ecotoxicity, water stress, and land stress. It provides a comprehensive assessment of the potential loss of species due to these environmental stressors. The approach is implemented in SimaPro. It considers different aspects that can influence biodiversity, allowing for a more holistic evaluation of the impacts associated with the studied activities or products. By incorporating both the LC-Impact approach and the endpoint approach, a more comprehensive understanding of the environmental impacts, particularly in relation to biodiversity loss, can be achieved.

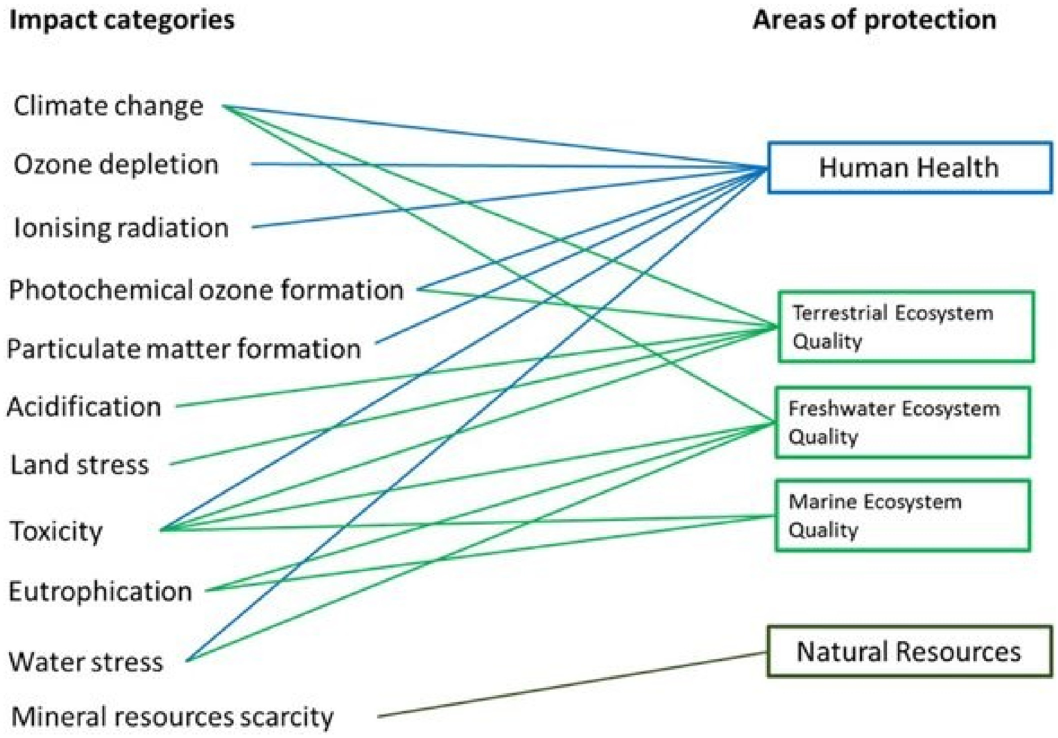

Figure 17: Overview of the broad impact categories and Areas of Protection (AoP) covered so far in LC-IMPACT. The colour of the lines indicates to which AoP the impact categories are related. Within ecosystem quality, three different ecosystems types are distinguished (Verones et al., 2019 in Verones et al., 2020)

6.2 Social Life Cycle Assessment (S-LCA)

S-LCA is a method that evaluates the social impacts of products and services over their entire life cycle (from raw material extraction to the final stage). For this purpose, both quantitative and qualitative data are combined in the modelling to obtain information on the social aspects. A S-LCA provides information on social and socio-economic aspects for decision-making, with the intention of improving the social performance of an organization; it is based on a combination of methods, models, and data.

Consideration of different data sources is important for S-LCA to compare information and identify possible similarities and differences. The appearance of contradictions when using different data sources is very likely. On the one hand, one's own perception (subjectivity) plays a role in qualitative data, and on the other hand, sensitive information is involved. For example, a company's own data on social hotspots is generally less reliable than publicly available data from non-governmental organizations (NGOs), but there are also false reports from NGOs. Some information is only available from a single source anyway, such as the manufacturing company, because not every company has been investigated by independent organizations. Information from employees can also be very valuable and helpful in identifying vulnerabilities, but employee perceptions are subjective and shaped by individual experiences and personal characteristics. Consequently, the data sources for the S-LCA should include recognized NGOs, governmental organization, literature, participating companies and employees (UNEP, 2020).

In CHEERS, the S-LCA approach is aligned with the method of the "Guideline for Social Life Cycle Assessment of Products and Organizations 2020" from the United Nations Environment Programme (UNEP) (UNEP, 2020) and can either be conducted using the Product Social Impact Life Cycle Assessment (PSILCA) method, and be modelled and presented in the OpenLCA software (GreenDelta, 2022; Maister et al., 2020), the Product Social Impact Assessment (PSIA) method of PRé Sustainability (Goedkoop, M.J. et al., 2020b, 2020a) or follow the approach of the Social Footprint method (Weidema, 2018).

6.2.1 Product Social Impact Life Cycle Assessment (PSILCA)

PSILCA is a database directly adapted to the needs of S-LCA and developed following the UNEP/SETAC guidelines. It contains data for 25 subcategories and 88 qualitative, quantitative, and semi-quantitative indicators on social and environmental risks, opportunities, and positive impacts for 5 stakeholder groups (Table 7). Approximately 15 000 country-specific industries and products in 189 countries are included. To provide insights into global supply chains, PSILCA uses a multi-regional input/output (MRIO) database, based on the Eora framework. Sources and survey dates are also documented (Maister et al., 2020).

Table 7: One example of unit of measurement to analyse impact of one indicator for one particular subcategory within one stakeholder group (UNEP, 2021).

Stakeholder	Subcategory	Indicator	Unit of measurement
Workers	Child labour	Children in employment	% of children ages 7 - 14
Local community	Local employment	Workforce hired locally	% of local employees
Society	Corruption	Carries out a programme	Written document
Consumer	Transparency	Report	Publication of a report
Value chain actors	Fair competition	Statement	Written document

One way to calculate the social impacts in an S-LCA, the "Social Impact Weighting Method" could be used. Since social impact assessment is still being researched and no universally recognized method has been developed thus far, the "Social Impact Weighting Method" is rather rudimentary. This method aggregates the indicators and provides a result at the level of each respective subcategory. The reference unit used is "Medium Risk Hours," which allows for presenting and comparing the results (Eisfeldt, 2017). Table 8 illustrates the impact factor that is applied based on the corresponding risk level, enabling the estimation of "Medium Risk Hours."

Table 8: Impact factors for the subcategories to calculate reference unit "Medium Risk Hours" (Eisfeldt, 2017)

Risk level	Factor
Very low risk	0.01
Low risk	0.1
Medium risk	1
High risk	10
Very high risk	100
No risk	0
No data	0.1

6.2.2 Product Social Impact Assessment (PSIA)

The PSIA methodology is unique in its focus on assessing the social impacts of individual products and services, rather than the overall impact of a company. It shares strong connections with the E-LCA methodology. However, there are fundamental differences between social and environmental life-cycle approaches.

From 2013 to 2020, a group of proactive companies collaborated in a roundtable format to establish consensus on how to assess the positive and negative social impacts throughout the life cycle of products and services. This publication represents the fifth iteration of the Handbook, with each iteration incorporating several changes and improvements compared to the previous versions. The roundtable members have gained valuable experience by applying the methodology in case studies and internal procedures. Additionally, the roundtable engages with other initiatives and approaches related to social metrics, such as fruitful collaborations with the WBCSD (Chemical Working Group and Social and Human Protocol) and the Social LC Alliance.

The development of the PSIA methodology as a joint effort stem from the shared understanding among member companies of the importance of consensus on methodology. Rather than competing on methodologies, companies aim to compete based on the results achieved. This conviction forms the foundation of the Product Social Metrics Roundtable, where member companies actively contribute their insights to reach a consensus.

The initial inspiration for the PSIA methodology in 2013 was the UNEP/SETAC document "Guidelines for Social Cycle Assessment of Products" (2009), developed by a group of experts, along with other similar publications. One significant distinction from the UNEP/SETAC Guidelines is our emphasis on practicality and business applicability. The formation of this roundtable was driven by the recognition among companies of the necessity for a social impact assessment methodology that aligns with business needs. Throughout the roundtable discussions, the emphasis was placed on real-life cases, knowledge sharing, and practical experiences to thoroughly assess the feasibility and effectiveness of the method (Goedkoop, M.J. et al., 2020b).

In the PSIA methodology, information related to each social aspect, structured by performance indicators, is evaluated using a scale. This scale allows to compare the data against a benchmark, typically an international standard or convention. If the assessment method is customized for a specific study, the reference points can be established as targets for improvement. The referencing stage plays a crucial role in interpreting the results and facilitating informed decision-making.

PSIA is designed to consider both positive and negative impacts of the product or service, employing a 5-point scale. Each position on the scale represents a performance reference point with a score ranging from -2 to +2. A score of -2 indicates unacceptable performance, while +2 represents ideal performance (Goedkoop, M.J. et al., 2020b). Table 9 illustrates a reference scale, which can be adapted for each social topic.

Table 9: Generic scale to assess social performance (Goedkoop, M.J. et al., 2020b)

Scale	Description
+2	best in class, continuous improvement
+1	beyond generally acceptable situation, continuous improvement
0	generally acceptable situation
-1	unacceptable situation but improving
-2	unacceptable situation, no improvement

6.2.3 Social Footprint Method

The method of Weidema (2018) combines a top-down approach using input-output data to prioritise data collection efforts on processes with high value added or a high number of work hours. It incorporates a streamlined impact assessment that reduces the need for detailed impact pathway descriptions and inventory data. Instead, the method focuses on the macro-scale impacts of income redistribution and productivity impacts of missing governance, which are considered nonproduction-specific impacts.

These impacts are unrelated to enterprise-specific actions and technology choices, making them quantifiable using national statistics without the need for detailed technology- or enterprise-specific data. The method allows for further refinement and detail in areas of specific interest for a particular product or project.

It is demonstrated that non-production-specific impacts create most social and economic impacts. The importance of income inequality in the impact assessment is highlighted. A novel approach is applied to combine impacts on productivity and impacts on human well-being, revealing the greater influence of inequality on well-being compared to interventions solely affecting consumption levels.

The method enables comprehensive assessments of social footprints for products with reduced efforts compared to existing approaches. The potential credits for positive action are found to be significantly higher in countries with missing governance, providing a compelling argument for locating activities in such countries, provided that enterprises can pursue an active strategy to create shared value.

A novel approach is applied to combine impacts on productivity and impacts on human wellbeing. It is demonstrated that inequality implies that an intervention altering the amount of quality-adjusted life years (QALY) for a population group consistently results in a larger change in wellbeing compared to an intervention of the same monetary value that solely affects the level of consumption for the same population group (Weidema, 2018).

6.3 Integrated Assessment (TEA, E- & S-LCA)

Upon completing the LCSA for the innovative bio-based products developed within the CHEERS project, we will need to integrate the results into a comprehensive framework that addresses the environmental, social, and economic dimensions. To this end, we will, we explore three distinct options for integrating the LCSA results, each offering unique perspectives and insights, which are summarised below:

Option 1: TEA with environmental externalities & social externalities

This approach involves integrating the results of TEA with the environmental and social externalities identified in the LCSA. TEA serves as the foundation, providing insights into the economic viability and costs of the studied products. The identified environmental and social externalities derived from the LCSA are then incorporated as additional factors that complement the economic assessment, and it is all expressed in a monetary value added.

By considering environmental externalities such as carbon emissions, resource depletion, and biodiversity impacts, alongside social externalities like community well-being, health, and job creation, this integrated approach offers a comprehensive understanding of the products' overall sustainability performance. This option facilitates a holistic evaluation, enabling for a broader spectrum of impacts beyond the financial realm.

Option 2: TEA as basis, social impacts based on (minimal) wellbeing, environmental impacts as limitations for the solution space

In this option, TEA remains the basis for the integration, providing essential economic insights. Social impacts, instead of being quantified in detail, are qualitatively evaluated based on minimal wellbeing considerations. By focusing on key indicators related to the well-being of stakeholders and communities affected by the studied products, decision-makers can assess the social implications more intuitively.

Meanwhile, environmental impacts serve as constraints or limitations for the solution space. The results from E-LCA guide decision-makers in identifying environmentally sustainable choices and avoiding potential adverse effects. This option facilitates an approach where social considerations are streamlined while ensuring that the solutions align with strict environmental and planetary boundaries.

Option 3: Independent analysis of TEA, E-LCA, and S-LCA, Integration of results with a qualitative approach

In this option, the TEA, E-LCA, and S-LCA are conducted independently, with each providing valuable insights into the economic, environmental, and social dimensions, respectively. The results are then integrated through a qualitative approach, such as expert judgment or multi-criteria analysis.

The strengths of each assessment method can be drawn independently, considering their individual perspectives, uncertainties, and limitations, while recognizing the interconnections among the three dimensions. This approach allows for a more distinct understanding of the products' sustainability performance, considering a wide range of factors and perspectives.

Each integration option offers a distinct approach to incorporate the results of the LCSA into the decision-making process for the innovative bio-based products developed within the CHEERS project. By carefully considering the trade-offs and strengths of each option, the project can effectively communicate the products' life cycle sustainability performance, supporting more informed, holistic, and sustainable decisions within the brewing industry.

For the final results, we will focus on one integration method. However, we will need to explore the different options in more detail before the final selection of the integration method.

7 Conclusion and Outlook

The aim of the CHEERS biorefinery is to valorise the by-products of the brewery industry into higher value-added products. In this deliverable, a comprehensive approach to assess the positive and negative impacts of the CHEERS bio-based system has been outlined. The proposed methodological TEA & LCSA approach aims to the assessment of the environmental, social, economic, and biodiversity impacts of the CHEERS system as subsequent processes for the valorisation of the by-products generated in breweries to produce new bio-based products. By integrating LCA, S-LCA, TEA, and life cycle biodiversity assessments, a holistic assessment of the system can be achieved.

This methodology report describes the methodological framework for LCSA and TEA. This includes a description of the goal and scope of both assessments, the functional unit applied for the production system, a detailed description of the production system with system models including their boundaries and potential data sources for data collection. Furthermore, approaches for allocation between beer and side streams as well as between the different products from the CHEERS biorefinery as well as data quality and uncertainty are discussed, the target audiences are defined and data quality concerns are outlined.

In addition, the selected indicators for the TEA and LCSA are described in the chapters 5 and 6 covering a wide range of economic, environmental, and social indicators covering the whole life cycle of the CHEERS biorefinery. This includes environmental indicators like greenhouse gas emissions, cumulative energy demand and biodiversity impact, social indicators like working conditions, corruption, and inequality as well as economic indicators like net present value and payback period.

After the compilation of this methodological report on the TEA and LCSA we identified 3 main challenges for the assessment: (1) high dependence of the results on the allocation choices, (2) scaling the input data from pilot scale to actual industrial scale and (3) integration of the results from the economic, social and environmental dimensions. However, this deliverable also outlines the strategies on how to tackle these challenges with scenario techniques, sensitivity analysis, prospective assessments as well as an initial screening assessment in order to identify the most relevant hotspots in the analysed value chains.

This report is the basis to perform a full-scale TEA and LCSA, integrating and evaluating environmental, social, economic, and biodiversity aspects with a holistic view of the impacts of the CHEERS biorefinery. By integrating various assessment tools and aspects into the LCSA and TEA framework, we aim to develop a comprehensive understanding of the complex interactions between by-product valorisation and sustainability.

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CHEERS

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