BIO4AFRICA

Diversifying revenue in rural Africa through circular, sustainable and replicable biobased solutions and business models

Research and Innovation Action (RIA)
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D5.3: Results of life cycle assessments per pilot case - initial version

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Acronyms

Acronym	Formal Title
AC	Acidification
AS/NZS	Standards Australia and Standards New Zealand
CBOs	Community-based Organizations
CC	Climate Change
C-LCC	Conventional Life Cycle Costing
DLG	District Local Governments
EcF	Ecotoxicity-freshwater
EF	Environmental Footprint
E-LCC	Environmental Life Cycle Costing
EoL	End of Life
Eq.	Equivalents
EuF	Eutrophication-freshwater
EuM	Eutrophication-marine
EuT	Eutrophication-terrestrial
FAOSTAT	Food and Agriculture Statistics
FU	Functional Unit
H2020	Horizon 2020
HTP	Human Toxicity Potential, cancer
HTP-NC	Human Toxicity Potential, non-cancer
IEC	International Electrotechnical Commission
IP S-LCIA	Impact Pathway Assessment

IR-HH	Ionizing Radiation-Human Health
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPC	Liquid Protein Concentrate
LU	Land Use
NCV	Net Calorific Value
NFASS	National Food and Agricultural Statistics System
NGOs	Non-Governmental Organizations
NPV	Net Present Value
ODP	Ozone Depletion Potential
PE	Polyethylene
PEF	Product Environmental Footprint
PM	Particulate Matter
POCP-HH	Photochemical Oxidant Formation Potential-Human Health
PSILCA	Product Social Impact Assessment
R&D	Research and Development
RS S-LCIA	Reference Scale Assessment
RUf	Resource Use-fossil fuels
RUmm	Resource Use-minerals and metals
S0	Scenario 0

S1	Scenario 1
S2	Scenario 2
S3	Scenario 3
SDG	Sustainable Development Goals
SETAC	Society of Environmental Toxicology and Chemistry
SHDB	Social Hotspot Database
S-LCA	Social Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
S-LCI	Social Life cycle Inventory Analysis
S-LCIA	Social Life Cycle Impact Assessment
SO-LCA	Social organizational LCA
UN	United Nations
UNEP	United Nations Environment Programme
USD	United States Dollar
WP	Work Package
WU	Water Use
ZARDI	Zonal Agricultural Research and Development Institute

Executive Summary

The Bio4Africa project (H2020, no.101000762) aims at promoting small-scale technologies for cascading local biomass and providing diversified revenue in areas of rural Africa. In the framework of Task 5.4 of the project, a holistic sustainability assessment addressing the life cycle environmental, economic, and social impacts associated to the technologies examined within the Bio4Africa project is foreseen to take place, through targeted environmental Life Cycle Assessments (LCA), Life Cycle Costing (LCC) and Social LCA (S-LCA) studies. The current Deliverable (D5.3), is the first version of the deliverable foreseen in the framework of this Task, while the final version of the deliverable (D5.6) is foreseen to be concluded on M44.

In this Deliverable, a complete LCA of the environmental impacts associated to the implementation of one pilot case is carried out, i.e., the Green biorefinery pilot at Uganda, as by the time of the assessment, the availability of data for carrying out the LCA for the other Bio4Africa pilots as well as for carrying out the LCC and S-LCA for all pilots, was not sufficient. The current deliverable also presents the goal and scope of the LCC and S-LCA study for the pilot of Uganda. Deliverable 5.6, on the other hand, will include the LCA, LCC and S-LCA studies for all technologies implemented within the Bio4Africa project.

Considering the main characteristics of the Green biorefinery pilot, it was decided to focus the assessment on two LCA perspectives. The first perspective examines the life cycle impacts of the Green biorefinery products that are intended to be used as animal feed. This perspective refers to a Cradle-to-Gate approach, the system boundaries of which include the cultivation of feedstock and the Green biorefinery unit. The results of this LCA perspective can be compared to the respective impacts associated to conventional animal feed products (e.g., soybean), in terms of protein content. Additionally, under this perspective different scenarios are considered in the cultivation of the Green biorefinery feedstock with respect to the nutrient sources used for fertilization. These scenarios are intended to examine the benefits of employing nutrient inputs of natural origin (i.e., manure, nitrogen-binding legumes), compared to chemical fertilizers. The second perspective goes beyond the Green biorefinery level, including the use of the produced animal feed by local farmers in livestock farming, up to the consumption of the livestock products (meat, milk, eggs) by the final consumers. This approach extends the system boundaries of the assessment to also consider the benefits of increased and more stable food availability to the local population, that is aimed to be achieved through this pilot. The first perspective is assessed in the current deliverable, while the second perspective will be assessed in the final version of the Deliverable (D5.6).

The LCA study is conducted according to the main LCA stages prescribed in the ISO 14040:2006 and ISO 14044:2006 standards, i.e., Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, Interpretation. The methodology for carrying out the LCC study is based on the SETAC guidelines on Life Cycle Costing. An environmental LCC approach is selected to focus on the same stages of the value chain, as the LCA. To assess the life cycle costs of the system under study, the individual costs over the entire life cycle of the system are aggregated, using the Net Present Value method. The methodology for carrying out the S-LCA study is based on the UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products and Organizations. The methodology foresees the identification of the relevant stakeholder groups (workers, local community, society, and value chain actors) and impact indicators. For each stakeholder group, a set of impact indicators will be identified based on a three-step approach including: i. screening of relevant published material, ii. use of social impact databases and iii. consultation with local key actors. The Reference Scale Approach for Life Cycle Impact Assessment is selected for assessing the social performance and risks of the studied system.

The results of the LCA study highlight the eight most important impact associated to the Green biorefinery in Uganda, with the top three impact categories being the impact categories of Climate Change, Resource Use-minerals and metals and Resource Use-Fossil Fuels. In terms of the most impactful life cycle stages and processes of the Green biorefinery system, the cultivation life cycle stage was found to have the most significant environmental impact in the selected impact categories, amounting to an average contribution of 77%. The respective average contribution of the Green biorefinery and the transportation life cycle stages in the selected impact categories was 16% and 7%, respectively. As for the absolute characterization values of the three most impactful categories, the production of 1 ton of crude protein

for the Green biorefinery system results in the emission of 1703 kg CO_2 eq. (CC), while it creates a material resource demand (RUmm) of 0,024 kg Sb-eq. and a respective fossil fuel energy demand of 20037 MJ. As for the assessment of the impact of different fertilization scenarios, the results of the LCA study indicated that the environmental footprint of the current (baseline) fertilization practice of applying a mix of chemical fertilizers and manure (S0) is better compared to the application of chemical fertilizers alone (S1). More specifically, S1 leads to a 104% average increase of the characterization values of all eight selected impact categories in relation to S0. S2 (chemical fertilizers and legumes for nutrient supply) and S3 (chemical fertilizers and legumes, manure as nutrient supply), on the other hand, lead to an average reduction of the characterization values of all eight selected impact categories equal of -27% and -49% in relation to S0, respectively, highlighting the improving potential of the application of manure along with the cultivation of nitrogen-binding legumes.

At the same time, the comparison of the production of crude protein from the Green biorefinery system against the respective production of crude protein from conventional soybean animal feed reveals an overall better environmental footprint for the former. In more detail, the single weighted impacts for the soybean system reveals a score of 0,47, in contrast to the respective score of the Green biorefinery system (0,21). The better overall performance of the latter can be attributed to its superiority in all five most significant impact categories of the soybean system (Climate Change, Eutrophication-marine, Land Use Ecotoxicity-freshwater, Eutrophication-marine), and specifically to the lower impacts observed in the cultivation and transportation life cycle stages of the Green biorefinery system. This is a reasonable finding, considering the significant contribution of the land use change-related emissions to most impact categories for the soybean system, as well as the transportation needs for importing soybean animal feed in Ugandan markets.

1. Introduction

The Bio4Africa project (no.101000762) is a Horizon 2020 Research and Innovation Action project aiming at diversifying revenue in rural Africa through circular, sustainable and replicable biobased solutions and business models. It offers simple and small-scale technologies (Green biorefinery, pyrolysis, hydrothermal carbonization, briquetting, pelletizing, bio-composites, and bioplastics production technologies) for cascading biomass into value-added products. Some of the main value-added products that result from the implementation of these technologies are animal feeds, fertilizers, pollutant absorbents, construction materials, packaging, solid fuel for cooking and catalysts for biogas production. These products could potentially provide a diversified income to local farmers and communities, while their production and testing is currently under way in various testing sites in four African pilot countries (Uganda, Senegal, Ivory Coast, Ghana). An overview of the small-scale technologies implemented per country is presented in Table 1.

Table 1: Technologies tested and implemented per pilot country within the Bio4Africa project

Pilot Country	Technologies
Uganda 	Green biorefinery
	Hydrothermal Carbonization
	Densification
Ghana 	Green biorefinery
	Pyrolysis
	Densification
Cote D'Ivoire 	Pyrolysis
	Densification
	Bioplastics/Biocomposites
Senegal 	Pyrolysis
	Hydrothermal Carbonization
	Densification
	Bioplastics/Biocomposites

The implementation of the Bio4Africa project is divided into 9 work packages (WP), each one of which is further divided into certain Tasks. The present deliverable is foreseen under WP5 "Development and assessment of circular, replicable and sustainable business models" and in particular Task 5.4 "Life cycle assessment of agronomic, environmental, social and economic sustainability". Task 5.4 foresees a holistic sustainability assessment of the Bio4Africa technologies. Each pillar of the sustainability (environmental protection, economic well-being, social equity) of the technologies is evaluated through targeted LCA, LCC and S-LCA studies, respectively.

The environmental LCA studies are conducted according to the global ISO 14040 and 14044 studies and include the stages of i. Goal and scope definition of the studies, ii. The collection of the life cycle inventories iii. The life cycle impact assessment, and iv. The interpretation of the LCA results. The LCA studies provide accurate estimations of the environmental impacts of the implementation of the technologies in relation to important impact categories, such as Climate Change, Eutrophication, etc., while they allow comparisons between the environmental performance of the technologies and the respective performance of conventional technologies and products. In this way, any environmental superiority of the implemented technologies against current practices is highlighted and the respective business cases are reinforced.

Respectively, the LCC and S-LCA studies within the Bio4Africa project aim at assessing the life cycle costs and social life cycle impacts of the respective technologies, as to obtain a holistic view of the socio-economic impacts implied for both the farmers and other potential implementing parties of the technologies, as well as for other stakeholders and the local society in general. In general, the LCC study is based on the collection of different types of costs (e.g., capital, variable, fixed, disposal costs) and their aggregation for estimating the total cost of implementing the technology over its lifetime. This information could be potentially valuable for farmers, local entrepreneurs, investors, and other stakeholders. The S-LCA, on the other side, is more focused on estimating the social impact hotspots of implementing the technologies of the project. Although it involves the use of economic data for its completion, it is orientated at estimating social well-being, human rights, equality, and other important social issues. This social study involves the use of data both from secondary sources (databases, literature, etc.) as well as the use of primary on-site data for collecting the view of local engaged stakeholders.

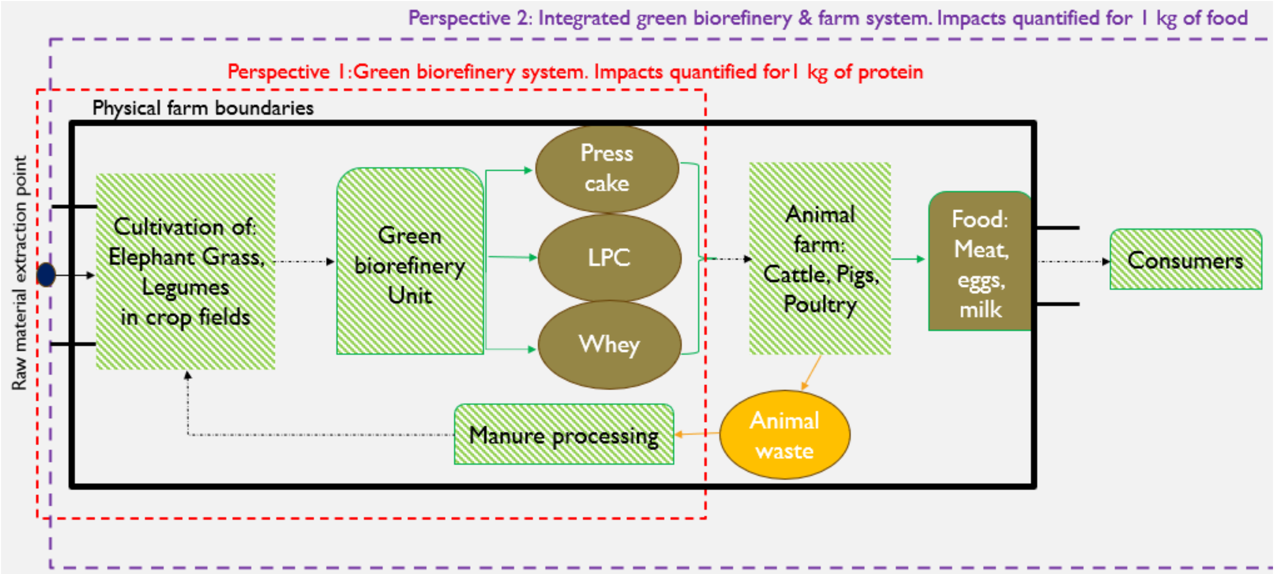
The current Deliverable (D5.3), is the first version of the deliverable foreseen in the framework of this Task, while the final version of the deliverable (D5.6) is foreseen to be concluded on M44. In this Deliverable, a complete LCA of the environmental impacts associated to the implementation of one pilot case is carried out, i.e., the Green biorefinery pilot at Uganda, as by the time of the assessment, the availability of data for carrying out the LCA for the other Bio4Africa pilots, as well as for carrying out the LCC and S-LCA for all pilots, was not sufficient. The current deliverable also presents the goal and scope of the LCC and S-LCA study for the pilot of Uganda.

Considering the main characteristics of the Green biorefinery pilot, it was decided to focus the assessment on two LCA perspectives.

- **Perspective 1:** The first perspective examines the life cycle impacts of the Green biorefinery products that are intended to be used as animal feed. This perspective refers to a Cradle-to-Gate approach, the system boundaries of which include the cultivation of feedstock and the Green biorefinery unit. The results of this LCA perspective can be compared to the respective impacts associated to conventional animal feed products (e.g., soybean), in terms of protein content. Additionally, under this perspective different scenarios are considered in the cultivation of the feedstock with respect to the nutrient sources used for fertilization. These scenarios are intended to examine the benefits of employing nutrient inputs of natural origin (i.e., manure, nitrogen-binding legumes), compared to chemical fertilizers.
- **Perspective 2:** The second perspective goes beyond the Green biorefinery level, including the use of the produced animal feed by local farmers in livestock farming, up to the consumption of the livestock products (meat, milk, eggs) by the final consumers. This approach extends the system boundaries of the assessment to also consider the benefits of increased and more stable food availability to the local population, that is aimed to be achieved through this pilot. The first perspective is assessed in the current deliverable, while the second perspective will be assessed in the final version of the Deliverable (D5.6).

An overview of these perspectives is provided in **Figure 1**.

Figure 1: Overview of the perspectives studied for the case of Green biorefinery in Uganda



The two perspectives considered for the LCA studies in Deliverables 5.3 and 5.6, respectively, are representative of the future conditions of the Green biorefinery system operation.

Perspective 1 included in the current Deliverable 5.3, considers a fully mechanized cultivation stage in terms of performing the different agricultural processes for producing the necessary feedstock, while a processing capacity of 1000 kg of fresh feedstock per hour is considered for the Green biorefinery stage. The same conditions will apply also in the second perspective that will be examined in Deliverable 5.6, with certain additions in terms of further optimizations considered. Firstly, a near-zero transportation need will apply, since the Green biorefinery pilot is intended to be located within the boundaries of the farms producing the feedstock for minimizing the respective environmental impacts and applicable costs. Additionally, further optimizations may apply, such as a solar electricity supply in the Green biorefinery pilot.

The structure of the Deliverable 5.3 is as follows: Section 2 provides an overview of the methodology, methodological tools and relevant standards employed for the implementation of the LCA, LCC and S-LCA studies. In Section 3, the Green biorefinery pilot at Uganda is presented, along with a description of the applied Green biorefinery technology and the associated benefits for the wider system. Section 4 describes the application of the LCA, LCC and S-LCA methodologies for the Ugandan Green biorefinery pilot and provides a detailed overview of the main steps towards the implementation of the assessments (LCA, LCC, S-LCA) performed within the deliverable. Finally, Section 5 includes the main conclusions resulting from the employed study, in terms of the main findings and limitations to be considered in Deliverable 5.6 (Results of life cycle assessments per pilot case – final version).

2. Methodology, Methodological tools & Relevant Standards

In order to perform the sustainability assessment of the Green biorefinery in Uganda the methodologies of LCA, LCC and S-LCA were employed. The collection of the necessary data for the realization of the studies was performed through the development of data collection templates and their distribution to the partners responsible for the implementation of the pilot (GRASSA, KRC). Additionally, several data validation and clarification meetings were organized and realized, to ensure the validity of the collected information. Section 2 provides an overview of the methodologies, methodological tools and relevant standards used for performing the LCA, LCC and S-LCA studies. In more detail Section 2.1 present the methodologies and relevant standards for carrying out the LCA (Section 2.1.1), LCC (Section 2.1.2), and S-LCA (Section 2.1.3), included in D5.3, while Section 2.2 presents the methodological tools (software & databases) employed for the completion of the respective studies.

2.1 Methodology & Relevant Standards

2.1.1 Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) technique is one of the most widely used methods for assessing the environmental impacts of a large variety of natural, human, and technical activities. Between other utilities, LCA can be used for the assessment of the environmental burdens associated with different socio-economic activities, or for identifying their respective impact hotspots to assist the implementation of optimization measures with respect to the protection of the environment. Additionally, LCA can support comparative assessments of different products, processes, and technologies in an environmental impact context, thereby pointing to the most burden-free alternatives among a set of different options. Due to these utilities, the LCA technique can facilitate multiple decision-making processes, such as business management, political policy support, or even consumer decisions in some cases, when LCA studies are prerequisites for obtaining certain ecolabels and certifications at a product and process level, respectively.
To ensure the scientific robustness, standardization, and the validity of the results of LCA studies, the latter are guided by the ISO 14040:2006 and ISO 14040:2006 global standards of the International Standardization Organization (ISO). Depending on the purpose of the study and the specific geographical context of the respective products and processes that are evaluated through LCA, additional documents, standards and platforms may apply influence in the specifics of the relevant studies.
The implementation of LCA studies that are in accordance with the relevant main guiding standards (ISO 14040:2006 and ISO 14044:2006 standard) is divided into 4 main phases, namely the a. Goal and scope Definition phase, b. The inventory analysis phase, c. The impact assessment phase, and d. the interpretation phase. Each of the four phases of an LCA study is described below as in the guiding standards of ISO 14040:2006 and ISO 14044:2006.

A. *Goal and scope definition:* In this first phase of an LCA study, the intended purposes of performing the study, as well as the details of the product/process/technology system(s) to be assessed in regard with their environmental impacts through the LCA lens are respectively declared. In the Goal phase of the LCA study, the LCA practitioner(s) state the intended applications and audiences of the study, the reasons for carrying out the study, as well any intentions of performing comparative assertions intended for disclosure to the public. The Scope definition phase on the other hand, is divided into multiple sub-phases, that include the definition of the product system to be examined through the LCA study as well as their respective system boundaries and functional units. Other steps included in the goal definition phase are the registration of the data requirements for performing the LCA study, and the related assumptions and limitations in this aspect.

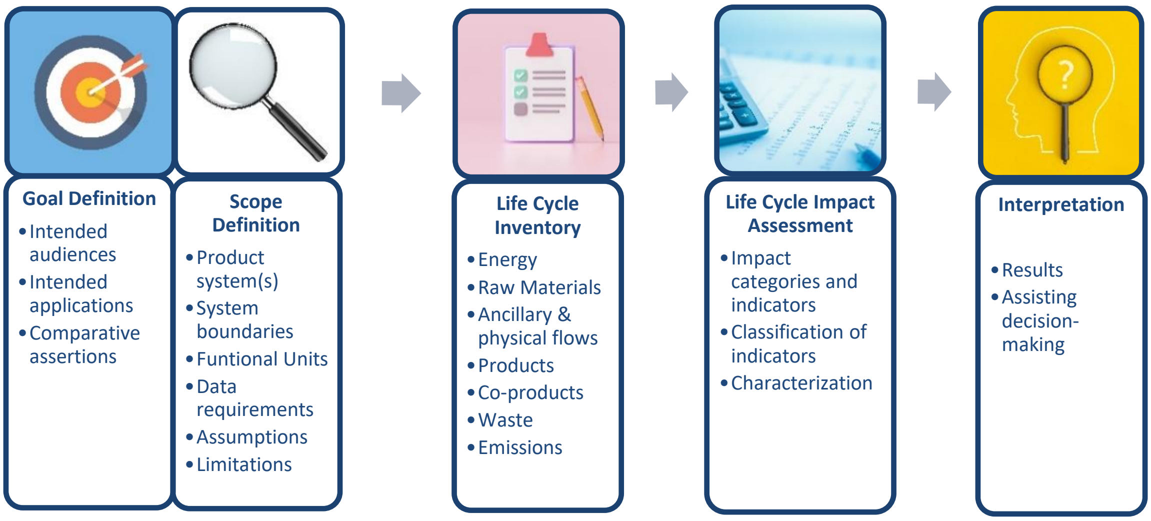
B. *Life Cycle Inventory (LCI) analysis*: In the second phase of an LCA study, the data regarding the inputs and the outputs of the system under LCA study are collected, quantified, and calculated. This iterative process focuses on the collection of data including (but not limited to) the energy sources, raw material consumption, ancillary and physical flows on the input side, as well as the products, co-products, waste, and emissions, on the output side. The LCI phase also involves the collection of information that allow the allocation of inputs to the products and co-products of a product system, as well as the validation of the collected data and their relating to the reference flow of the functional unit.

C. *Life Cycle Impact Assessment (LCIA)*: In the third phase of an LCA study, the data from the LCI phase are classified to specific environmental impact categories and related indicators, while the selection of appropriate characterization models enables the quantification and the calculation of the latter, by assigning specific characterization factors to the LCI dataset of the LCA study. The "classification" and "characterization" sub-phases of the LCIA phase, along with the selection of appropriate impact categories and related category indicators to be quantified and calculated according to the goal and scope of the study, are obligatory actions within the LCIA phase according to the respective ISO standards. In particular, the characterization phase refers to the selection of the selection of the model that allows the quantification of the environmental impacts of the system, as well as to the quantification of the impacts itself. There are additional optional stages within the LCIA of the studies, such as the normalization and weighting phases, which enable the calculation of the selected category indicators relative to reference information, and the aggregation of the results according to specific numerical values, respectively. The LCIA can be accompanied by comprehensive data quality analyses, for assessing the reliability of the extracted LCIA results.

D. *Life Cycle Interpretation*: In the fourth and final phase, the results from the LCI and LCIA phases are presented according to the goal and scope of the study in an understandable and comprehensive way. The interpretation phase often provides the commissioner(s) of the LCA study with valuable recommendations and conclusions, ultimately supporting and assisting in this way their decision-making duties.

Figure 2 collectively illustrates the four phases of LCA.

Figure 2: The four phases of Life Cycle Assessment



2.1.2 Life Cycle Costing (LCC)

As mentioned previously in Chapter 2.1.1, the Life Cycle Assessment (LCA) method is an essential tool to evaluate the environmental impact of products or services, including several factors such as CO_2 emissions, energy consumption, and raw materials. To achieve a more comprehensive evaluation, it is essential to consider additional factors, such as the complete system cost. This is where the Life Cycle Costing (LCC) method becomes critical.

Life Cycle Costing (LCC) is a method that calculates all the costs associated with the life cycle of a product or a service. LCC can be a tool or part of a comprehensive strategy for sustainable development, aligned with environmental Life Cycle Assessment (LCA). Guidelines and standards for the implementation of LCC include the SETAC Guidelines on Environmental Life Cycle Costing (Hunkeler et al. 2008) The guideline aims to provide a consistent approach to combining costs and environmental aspects. ISO 15686-5:2017, focusing on buildings and constructed assets. The ISO 15686-5 relates to the construction sector but offers a helpful structure for analysing life cycle cost (LCC) that can be applied in four main stages: investment and planning, design and construction, operational stage, and disposal or end-of-life stage. It is worth noting that there is no specific standard or guideline that all researchers use in their approach, such as ISO 14040-44 on LCA. To comprehend the methodology of Life Cycle Costing (LCC), the research team depended on the two previously mentioned standards and guidelines.

LCC types

According to Hunkeler et al. (2008) LCC analysis is categorized into Conventional LCC, Environmental LCC, and Societal LCC.

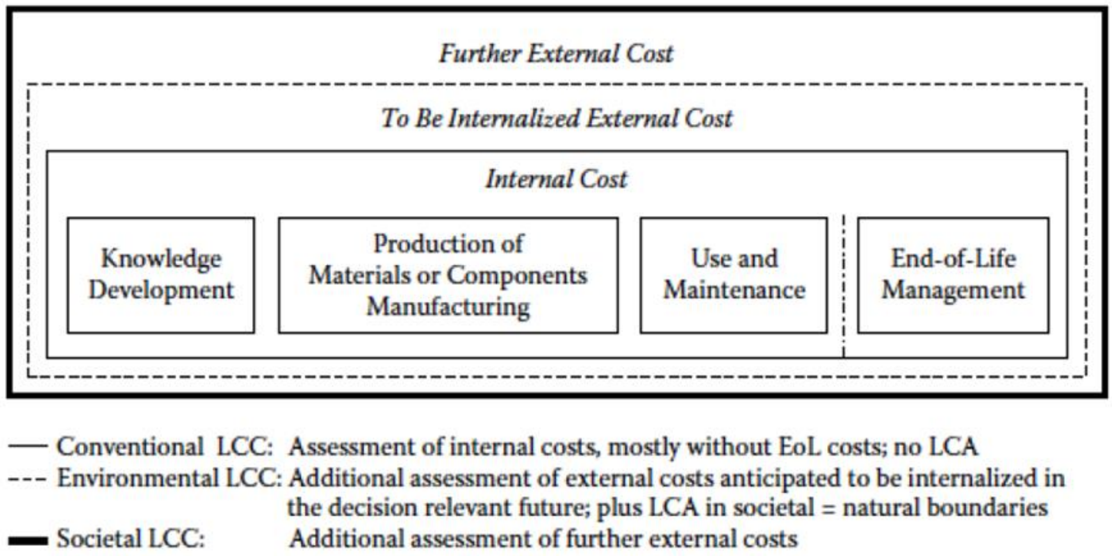
Conventional LCC is the widespread method, focusing exclusively on the economic aspect. C-LCC is a useful tool to aid in decision making for purchasing expensive capital equipment and long-life products (Hunkeler et al., 2008). C-LCC is performed from the viewpoint of a single actor, usually the user of the product or solution. For instance, when buying a vehicle, the driver would assess multiple options based on economic factors. In such cases, the focus is on the acquisition cost, taxes, fuel expenses, expected maintenance cost, and may also consider end-of-life expenses or returns.

Environmental LCC is consistent with ISO standards 14040 and 14044 regarding Life Cycle Assessment (LCA) as it considers the functional unit's perspective and considers the entire life cycle, including all participants in the value chain or life cycle. The purpose of eLCC is to support LCA by covering the economic dimension and identifying hot spots in terms of both cost and environmental impacts. In addition to the internal costs incurred by participants in the life cycle, eLCC may also include external costs. External costs are costs that are already expressed in monetary units because they are expected to be internalized in the future and will remain so. (Hunkeler et al. 2008)

Societal LCC helps decision-making at the societal level by quantifying environmental impacts in monetary terms. This includes assigning a monetary value to selected external costs. To achieve this, LCA impact results are translated into monetary units by estimating the cost of damages using various monetisation methods.

The table and figure below show the differences between these three types.

Figure 3: Types of life cycle costing (Hunkeler et al., 2008)



LCC cost categories

Understanding the life cycle costs of a product or a service is crucial for economic management and strategic planning. The cost of a product or service at each stage, from acquisition to disposal, belongs to a different cost category that affects budget and resource management differently. Below are the detailed descriptions of these cost categories.

This stage aims to determine the costs over the entire lifespan of the unit. Since there are several cost factors, the study narrowed to the following:

1. Capital costs: Mainly acquisitions of land, equipment, and other capital investments.

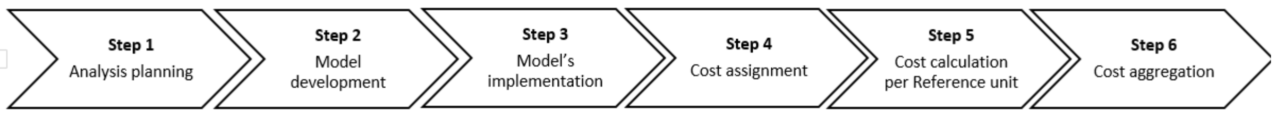
2. Variable costs: Costs for obtaining raw materials, energy, and other goods of variable nature
3. Fixed costs: Costs of rents, personnel, taxes, and other fixed responsibilities
4. End-of-life costs: Costs of disposal and treatment of waste

Life Cycle Costing – Implementation procedure

In addition, Hunkeler et al (2008) describe a detailed six-step process for collecting information and calculating cost data in LCC. This approach involves a six-step process that can be customized for each unit process or subsystem within a product system model, making it easier to aggregate life cycle costs for the production, use, and end-of-life phases. The six steps are as follows:

1. **Identification of subsystems or unit processes**: This step involves identifying specific subsystems or unit processes within the product system that might result in varying costs or revenues. Here, the term “costs” is used to express both costs and revenues.
2. **Assignment of costs to product flows**: In this stage, costs or prices are assigned to the product flows of the identified unit processes or subsystems (from step 1), using the output of the process as a reference unit (e.g., the cost per 1 kg of an intermediate product).
3. **Identification of additional cost effects**: This involves identifying any additional cost or price effects of the unit processes or subsystems that differ between the alternatives studied. This includes other operating costs like investments, tooling, and labor.
4. **Assignment of costs to additional operating costs**: Costs or prices are then assigned to the additional operating costs identified in step 3, again using the process output as the reference unit.
5. **Calculation of costs per unit processor or subsystem**: The costs per reference unit from steps 2 and 4 are multiplied by the absolute quantities of the process outputs. This calculation provides the costs for the reference flows of the complete production system.
6. **Aggregation of costs and prices over the life cycle**: Finally, all the costs and prices (viewed as outflows from the same perspective) of all unit processes or subsystems from step 5 are aggregated over the entire life cycle of the product.

Figure 4: Graphic representation of the six stages of Life Cycle Costing (Hunkeler et al., 2008)



To calculate the costs associated with the life cycle of a product (Step 5 & 6: Calculating the cost per process or subsystem unit = life cycle phase, cost summation) the following equation is used (Hunkeler et al., 2008)

$$LCC = \sum_{life\ cycle\ phase\ 1}^{Life\ cycle\ phase} \sum_{process\ 1}^{process\ i} (\mu i \times \sum_{cost\ el.1}^{cost\ el.p} \sum_{flow\ 1}^{flow} amount\ q \times costs\ p)$$

Where:

i = process -specific variable
p = cost category – specific variable
q =process flow- specific variable (can be either input or output)
μ = process scaling factor related to the product system
n = life cycle phase- specific variable

Life cycle cost analysis is an approach used to determine the total economic costs incurred over the life cycle of a product, such as system operation in the present study. LCC provide the opportunity to assess costs over an extended period. Typically, the present value (NPV) method is employed for LCC calculations, which involves converting future cash flows to their current values.

$$\boldsymbol{NPV} = \sum_{\boldsymbol{t=1}}^{\boldsymbol{T}} \frac{\boldsymbol{Ct}}{(\boldsymbol{1}+\boldsymbol{d})^{\boldsymbol{t}}}$$

Where:
NPV= the present value of LCC
t: represents time measured in years
T: Time Horizon of the investment
Ct= net cash inflow-outflows during a single period t
d= discount rate

The real discount rate considers the time value of money, which means that money in the future is worth less than money in the present. On the other hand, the inflation rate indicates how much prices are expected to increase over time. The discount rate is calculated based on the inflation rate and interest rate, using the following formula:

$$d = \frac{1+r}{1+i} - 1$$

Where:
d = discount rate
i = inflation rate
r = interest rate.

The integrated LCC formula was applied to collect the total costs from production to disposal costs associated with the operation of system. When considering a particular stage in the life cycle (t), the total cost at current period (Ct) is determined by adding the several components of the Life Cycle Cost (LCC) model.

$$Ct = C_i + CV_{(t)} + C_F + C_{EOL}$$

where:
C_i =is the initial investment, which is a one-time upfront cost.
$CV_{(t)}$ =represents variable costs that can change over time based on operation or production levels at time *t*.
C_F =represents fixed costs, which are constant over time regardless of the level of output.

C_{EOL} =represents end-of-life costs, which could include decommissioning, disposal, or salvage value at the end of the life cycle.

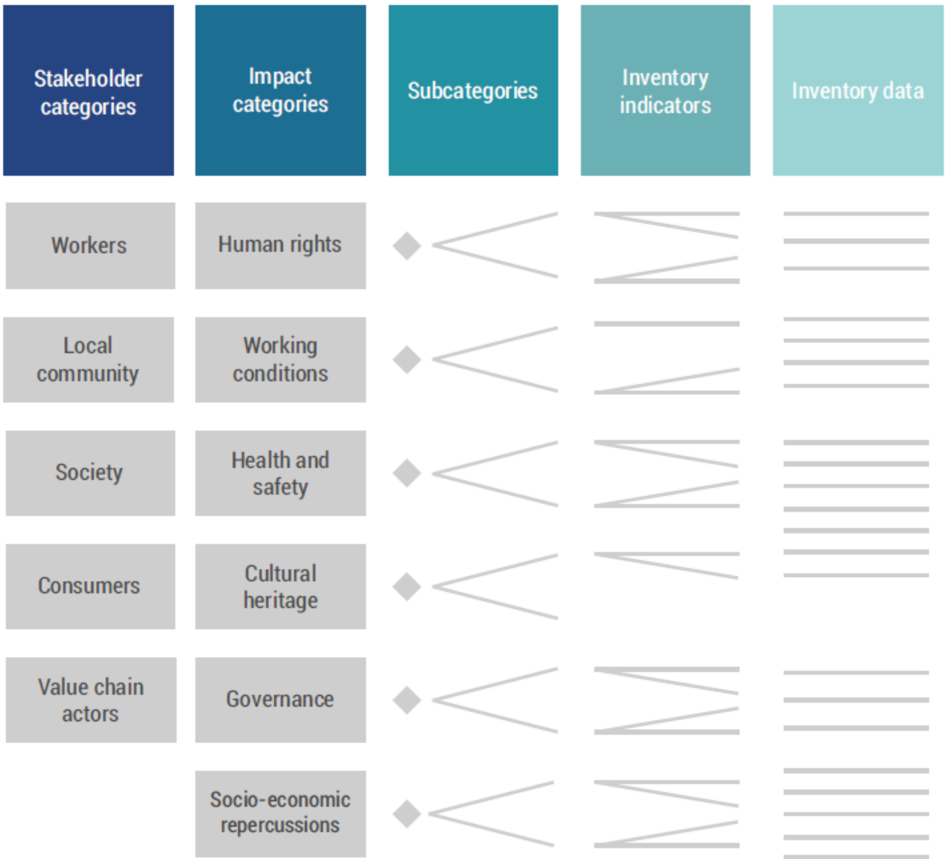
Sensitivity analysis

In the context of the LCC studies of the Bio4Africa project, sensitivity analysis studies will take place when the necessary data is available. It is a method used to assess how changes in baseline scenario affect decision-making. This technique involves exploring a range of uncertainties, ensuring alignment with the baseline scenario, and focuses on identifying the most influential inputs on the LCC outcome. Assumptions such as changes in discount rates, the chosen period for analysis, maintenance, repair, and replacement cycles play a significant role in the analysis.

2.1.3 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment (S-LCA) is a relatively new methodology for the socio-economic assessment of products and organizations. S-LCA provides information on social and socio-economic aspects for decision making, in the prospect of improving the performance of organizations and ultimately the wellbeing of the associated stakeholders (Benoît-Norris et al., 2020). Guidelines for S-LCA have been developed in 2009 by the UNEP/SETAC Life Cycle Initiative and updated in 2020. The 2020 Guidelines for Social Life Cycle Assessment of Products and Organizations (hereinafter referred to as S-LCA Guidelines) provide a roadmap and a knowledge base to help stakeholders in the assessment of social and socio-economic impacts of products' life cycles, their related value chains, and organizations. This means that S-LCA focuses not only on the process that produces a product, but also at the social aspects related to all the associated processes, both upstream and downstream. The S-LCA Guidelines provide additional information and consensus-based guidance for each step of the S-LCA, expand the framework to cover new methodological and practical developments such as social organizational LCA (SO-LCA) and present the strengths and challenges to handle various concerns linked to the social sustainability of products and organizations, for instance to support measuring and assessing progress towards the UN Sustainable Development Goals (SDG).
S-LCA assesses social impacts in relation to various stakeholder groups, who will potentially be affected through the life cycle of products and services. The S-LCA Guidelines consider 6 stakeholder categories: Workers, Local community, Society, Value chain actors, Consumers and Children. However, depending on the study system boundaries and sector specificities, it is possible to add, exclude, differentiate, or define new stakeholder categories. The stakeholder groups are divided into subcategories which are assessed by means of inventory indicators. These indicators are classified though impact categories and subcategories, which may include one or more indicators and are directly related to a specific stakeholder group (**Figure 5**).

Figure 5: S-LCA assessment system (Benoît-Norris et al., 2020)



The S-LCA methodology is in line with the LCA and the respective ISO Framework 14040 and 14044 (ISO, 2016)[1], therefore it comprises of the same four phases: i. Goal and scope definition, ii. (Social) Life cycle Inventory Analysis (S-LCI), iii. (Social) Life Cycle Impact Assessment (S-LCIA), and iv. Interpretation. According to (Benoît-Norris et al., 2020), these four phases are described as follows:

a. ***Goal and scope:*** This first phase aims to specify the purpose and the object of the study and determine the methodological framework. It is considered a key phase of a S-LCA, which will have a significant impact on the conduction of the study and the results. In this phase the system boundaries, functional unit and the cutoff criteria should be described, as well as the methodological pathways regarding the selection of stakeholder groups and impact subcategories together with the impact assessment method.
b. ***Social Life Cycle Inventory (S-LCI):*** Data for all unit processes within the system boundaries should be identified and collected, as well as the social inventory indicators to be evaluated. This part is

[1] The ISO/DIS 14075 "Environmental management - Principles and framework for social life cycle assessment" is currently under development (https://www.iso.org/standard/61118.html).

strongly influenced by the type of S-LCIA used. For each considered product system, data is normalized for a given output process. Input/output flows can then be linked through an activity variable, which reflects the relative significance of each unit process in the whole system. Activity variables allow describing the most intensive activities in a unit process and could therefore prioritize data collection and quantify the considered social inventory indicators. The most common activity variable is "worker-hours" which refers to the number of worker-hours necessary to complete a production activity unit/process. The two main S-LCA databases available are the Product Social Impact Assessment (PSILCA) and the Social Hotspot Database (SHDB). Both databases use the "worker-hour" activity variable and can be used to build the targeted S-LCA model.

c. ***Social Life Cycle Impact Assessment (S-LCIA):*** This phase aims at the calculation and understanding of the potential social impacts of a system through its life cycle. The term "potential" is important as it reflects on the likely presence of the social impact, supported by a range of hypotheses and thus limitations. S-LCIA approaches are classified into two main groups:
    - Reference Scale Assessment ("Type I" or RS S-LCIA) assesses the social performance or social risk
    - Impact Pathway Assessment ("Type II" or IP S-LCIA) assess the consequential social impacts through characterizing the cause-effect chain.

d. ***Interpretation of results:*** It consists of reviewing all the previous phases and conducting a thorough analysis of S-LCA results and covers among others the materiality assessment and the final conclusions, limitations, and recommendations on actions to take at the production site or regarding the supply chain. A materiality assessment is a process to select the most significant social issues regarding their impact on stakeholders or relevance to the business.

2.2 Methodological Tools

2.2.1 LCA modelling software

OpenLCA

OpenLCA is a free sustainability assessment software developed by GreenDelta. It is used for performing the LCA study included in the current deliverable, along with the EcoInvent database.

SIMAPRO

Simapro is a commercially available LCA tool developed by PRé Sustainability, used for performing the S-LCA study that is partially included (Goal & Scope definition) in this Deliverable. The software will be used along with the SHDB database for conducting the S-LCA of the Green biorefinery case in Uganda, along with the SHDB database. The complete S-LCA and the results of the study derived from Simapro will be included in Deliverable 5.6.

2.2.2 Databases

EcoInvent

The EcoInvent database is a commercially available database for simulating real-life processes and product systems in a LCA context. It includes over 18000 datasets able to model a diverse set of socioeconomic processes that range from everyday human activities to more complex agricultural and industrial productive systems. The EcoInvent is used in the OpenLCA software for the provision of the datasets necessary for conducting the LCA study of the Green biorefinery pilot in Uganda.

Social Hotspot Database (SHDB)

The Social Hotspots Database[1] (SHDB) is a tool that provides a comprehensive approach to assessing social issues in supply chains. It was launched in 2009 to provide transparent access to information about working conditions and other social impacts in global supply chains and through a risk mapping tool, and a license in combination with LCA software (such as OpenLCA and SimaPro), provides full access to information on social risks in 244 countries and territories and 57 sectors to supply chain managers, academics, policy-makers, development organizations, investors etc., through visualization and analysis tools. The SHDB is used in the Simapro software for the provision of the datasets necessary for conducting the S-LCA study of the Green biorefinery pilot in Uganda.

3. The Green biorefinery pilot case of Uganda

Section 3 aims at familiarizing the readers of the deliverable with the technology of the Green biorefinery, currently applied as an integral task of the Bio4Africa project in Uganda. Sub-section 3.1 presents the basic technological steps and processes of the Green biorefinery, while sub-sections 3.2 and 3.3 describe the Green biorefinery products and some important sustainability considerations related to the implementation of the technology, respectively. In Sub-section 3.4, specific details for the application of the Green biorefinery technology in Uganda are provided.

The presentation of the applied technology is considered common practice within LCA reports and LCA related deliverables, since it provides fundamental information in regard with the systems that are modelled within the scope of the LCA, LCC and S-LCA studies (Section 4). This practice is essential for ensuring the robustness of such studies since it ensures the avoidance of asymmetries in the inclusion of information between the real-life and the modelled system(s). In this way, the full disclosure of the occurring inputs, outputs and processes of the real-life system is facilitated, as is the accurate estimation of their respective environmental, economic, and societal impacts.

The information included in this section is mostly extracted by the deliverable titled "D2.3: Design and installation of biorefinery", authored by GRASSA, which is the technology provider partner for the case of the Green biorefinery application in Uganda.

3.1 Technology Overview

GRASSA is a Netherlands-based company providing the technology of small-scale Green biorefinery for the pilot cases of Uganda and Ghana within the pilot trials of the Bio4Africa project. The former case constitutes the main object of this deliverable through the lens of LCA, LCC, and S-LCA assessments. In Uganda, Grassa works closely with the local partner KRC for the optimization of the procedures involved in the operation of the small-scale Green biorefinery unit that was constructed as a main pilot site of the Bio4Africa project in 2022.

[1] http://www.socialhotspot.org/

The technology of Green biorefinery exploits fundamental mechanical and biochemical principles and relevant procedures for transforming green leafy biomass to value-added products, such as animal feeds. The process begins with the collection of fresh leaves, grass, and other green agricultural residues as feedstock, which is transported to the small-scale Green biorefinery facility and washed thoroughly for avoiding damages and contamination of the Green biorefinery equipment. As an experienced Green biorefinery expert company, Grassa points out the importance of the freshness of the feedstock input for avoiding the disintegration of the protein content of the biomass that takes place in instances of long-distance transport routes. The feedstock is advanced to the extruder, which presses the input and results in two fractions of output:

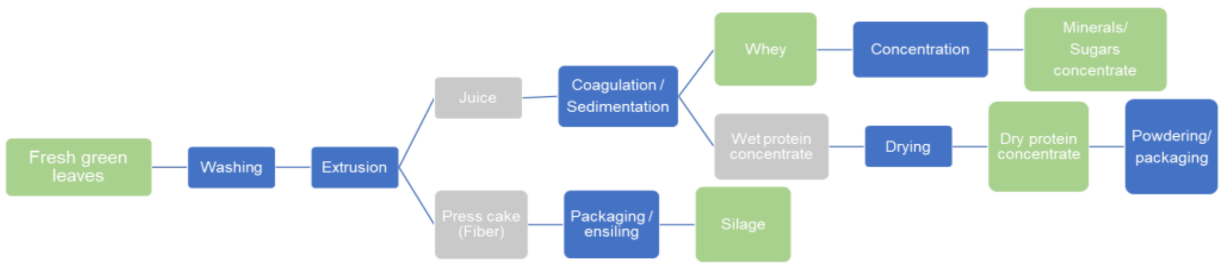
1. The press cake, a fibrous mass of relatively low water content and a high protein concentration.
2. The juice, a high protein concentration liquid that is advanced for further processing with biochemical means.

The press cake is then packaged and ensiled, while the juice gets through a series of sedimentation/coagulation processes from which two fractions result as an output:

1. The whey, which gets concentrated and results in a concentrate rich in high minerals and sugars.
2. The wet protein concentrate, which results in dry protein concentrate protein powder through a series of drying, powdering, and packaging processes.

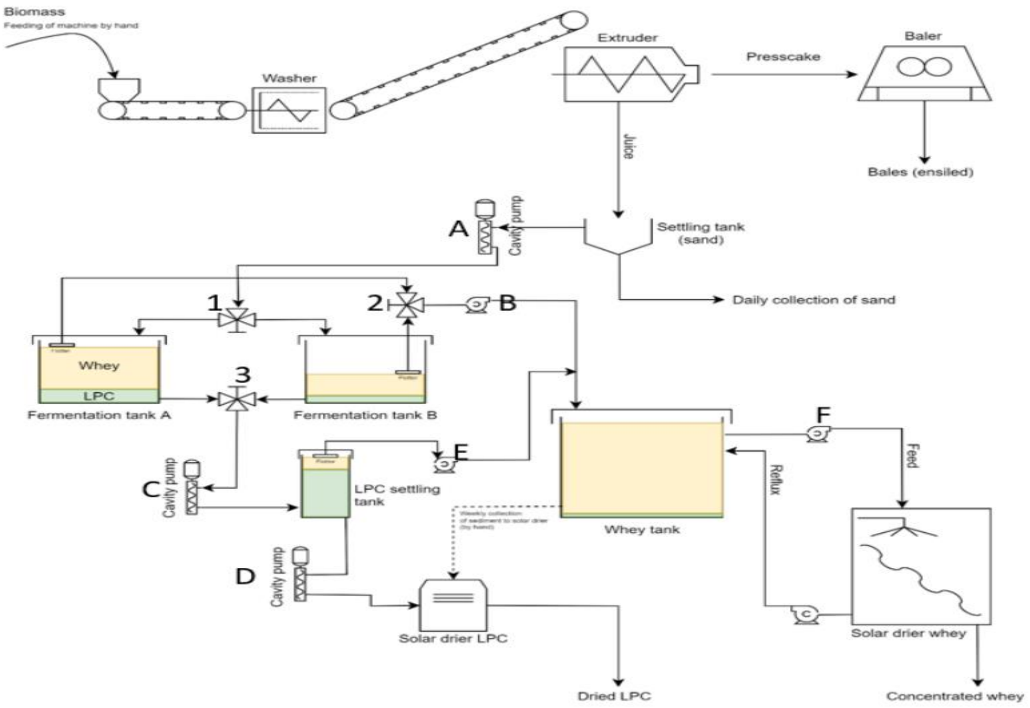
Figure 6 provides a high-level illustration of the Green biorefinery processes, from the point of collection of fresh green leaves from cultivation fields to the point of the extraction of value-added products (whey concentrate, dry protein concentrate, press cake) through the Green biorefinery process:

Figure 6: High-level illustration of the Green biorefinery process (Van Doorn et al., 2022)



For a better understanding of the Life Cycle Inventory of the Ugandan Green biorefinery pilot case that is going to be presented and analyzed in later sections of the deliverable, a more in-depth view of the overall system is important. As mentioned earlier, the system begins at cultivation fields, that provide locally available protein-rich green leaves and grass, such as elephant grass, Napier, Pakchong, nitrogen-binding legumes and leftovers of other cultivations. After transporting them to the small-scale Green biorefinery unit, the biomass is advanced through a conveyor belt to a washing cage where dirt, sand, metals, and other potentially harmful for the equipment and the quality of the extracted protein materials are removed. Through a second conveyor belt, the biomass is transported to the extruder, which uses a combination of pressing and squeezing processes for opening the plant cells and releasing the juice. The solid fibrous fraction (press cake) and the juice are separated, with the former being advanced to a baler for being packaged with plastic and ensiling, and the latter being deposited to settling tanks for further removal of sand. The resulting liquid is then advanced to fermentation tanks, where a combination of sedimentation/coagulation with lactic acid bacteria processes take place for separating the whey from the liquid protein concentrate (LPC). These two fractions are further advanced to two separate tanks (LPC settling tank, Whey tank), where further separation of these two takes place. Both LPC and whey are then sent for drying; The LPC in a passive solar energy drying house, and the whey in a specially designed solar energy evaporator where it is periodically sprayed for removal of excess humidity. As for the final products, the dry protein concentrate is packed in air-tight bags before getting powdered (for certain applications) and stored in a dark room, while the whey is stored in the UV-light enforced whey tank for avoiding microbial contamination. It should be noted that the liquid flows within the Green biorefinery unit are transported to different stages of the procedure by installing and using appropriate pumps. A small-scale Green biorefinery flow diagram is provided by GRASSA and illustrated below.

Figure 7: In depth view of the small-scale Green biorefinery, as planned for the case of Uganda (Van Doorn et al., 2022)



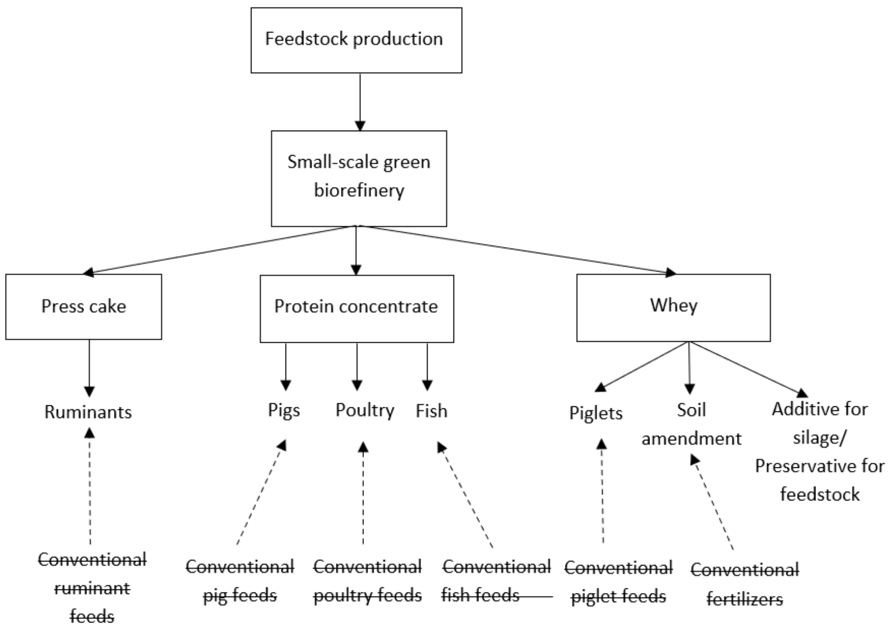
The respective products are then ready for transport for their relevant agri-food applications, as described in section 3.2.

3.2 Products

The main products resulting from the technology of Green biorefinery are animal feeds (press cake silage, protein concentrate and whey). These products can serve as protein-rich animal feeds, fertilizers and even as an additive/preservative for certain applications.

In more detail, the press cake is a fibrous protein-rich silage destined for consumption by ruminants, such as cow, sheep, and goats. The dry protein concentrate, on the other hand, is a suitable feed for poultry, pig, and fish breeding (in the form of powder). Lastly, whey can serve as feed for piglets, soil amendment, additive for silage or even as a preservative for feedstocks in cases of long logistic distances. All these products have a significant potential not only to improve certain local agri-food and sustainability aspects, but also to partially/totally substitute conventional counterpart products that are currently used for the abovementioned applications and are produced through business-as-usual linear operational procedures (Figure 8). The circularity and sustainability-related aspects of both the processes and products involved in the small-scale Green biorefinery technology are further analyzed in Section 3.3.

Figure 8: Products of small-scale Green biorefinery and their potential in substituting conventional agrifood products



3.3 Sustainability Considerations

The implementation of the small-scale Green biorefinery technology in the respective pilot areas of the Bio4Africa can represent an important driver for the establishment of local sustainability. In the environmental domain, the optimized use of the technology is associated with lower emissions, high efficiency and closed loops of minerals and materials, while at an economic and social context, the Green biorefinery might potentially bring multiple benefits, such as the diversification of the income of local communities, the creation of jobs, and the animal food security of the areas of implementation, among other benefits.

For the domain of sustainability, the establishment of small-scale Green biorefinery units is associated with significant environmental benefits. In an efficiency context, elephant grass (as a main feedstock of the Green biorefinery) provides approximately twice the amount of protein included in soy per hectare, leading to more efficient land use for animal feed purposes. Additionally, GRASSA highlights the fact that the production of both press cake and protein concentrate through Green biorefinery makes the grass protein available for both ruminants and monogastric, formerly available only for ruminants. By producing the protein concentrate and given the higher protein conversion factor of protein for monogastrics, the agricultural yield of food grade proteins of the overall system can be potentially increased by 50%. In addition, the increased efficiency of the system obviously leads to less emissions and pollution associated with land use, as well as to the closing of nutrient and mineral loops due to a more optimal use of green biomass.

In more detail for the control of emissions and associated pollution, GRASSA points out the need for the minimization of feedstock logistic distances as a prerequisite for preserving the integrity of the protein included in the biomass. This necessity leads to the recommendation of GRASSA of installing the unit in proximity with feedstock source(s), which ultimately results in less logistic-related emissions that add to the reduction of emissions achieved by higher efficiency. Additionally, the production of animal feeds, fertilizers and other products could potentially lead to reduced demand for primary counterpart products, with the latter being often associated with high emissions within the lifecycle of primary agri-food processes and products.

As for the closing of the material, nutrient and mineral loops, GRASSA intends to valorize the animal waste from ruminants as fertilizer manure for the feedstock cultivation phase, ultimately leading to the reduction of the associated emissions and waste production. This upcycling strategy is intended to be combined with other similar circular strategies, such as the use of thermal energy and biochar from nearby pyrolysis/HTC units for operational purposes and soil amending, respectively. The abovementioned combinations result in the establishment of micro- and meso-level circular synergies within the agri-food systems of the local areas. These small-scale circular ecosystems are characterized by closed nutrient loops and facilitate an improved lifecycle environmental footprint of the Green biorefinery system, from the point of feedstock cultivation to the point of the final production of value-added goods. Overall, with the establishment of manure valorization strategies the mineral and nutrient cycle closes at a farm level.

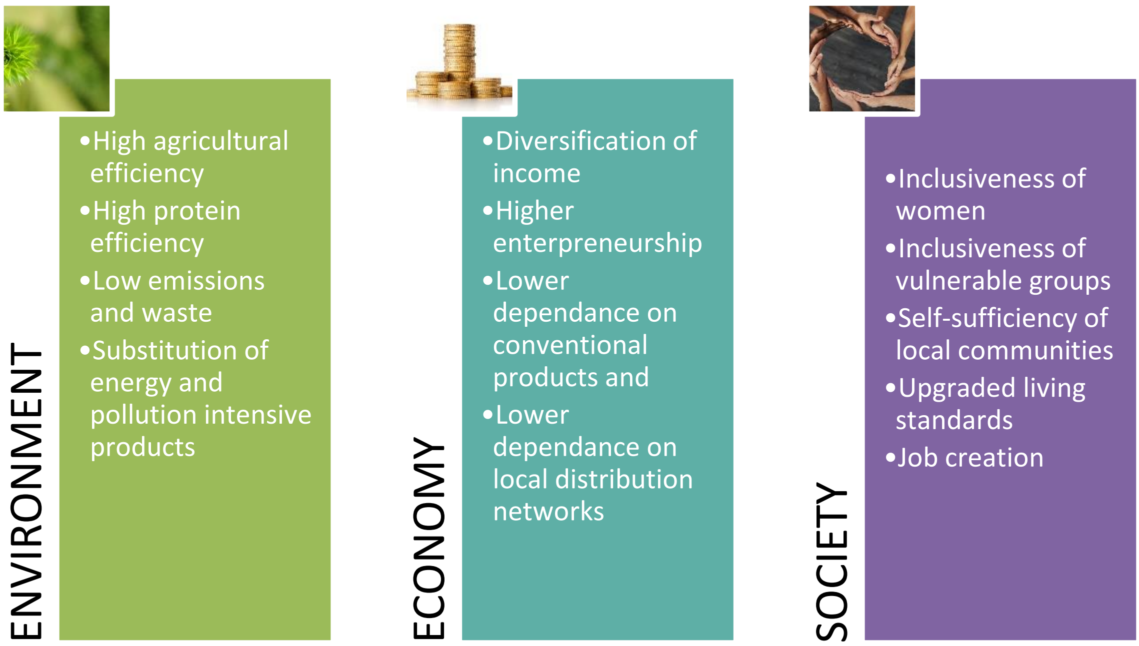
Besides the environmental benefits, the technology of Green biorefinery is a promising strategy for improving the economic prosperity and social well-being of the pilot areas. In regard with the economic pillar, the most obvious influence of the technology in the local economic prosperity relates to the overarching goal of the Bio4Africa project, being the diversification of the income of African farmers and communities. Due to the small scale and the relevant simplicity of the technology, locals are allowed to produce themselves basic agricultural goods, thereby reducing their dependance on the availability of large-scale production and logistical routes. This is especially important in an African context, where lack of the latter is frequently observed, compromising the ability of local primary sector stakeholders to adequately perform their agricultural-related economic activities. At the same time, the use of the Green biorefinery products by farmers not only releases the part of their income previously dedicated to the purchase of primary counterpart products, but also offers them opportunities for additional income by selling the products to interested buyers. It should be mentioned that the installation and operation of the small-scale Green biorefinery unit is a labor-intensive procedure that has potential for opening job positions for local people.

Therefore, despite the possible substitution of conventional products from respective Green biorefinery outputs, the local job potential seems to not being jeopardized, but rather redistributed to more decentralized job positions.

As for the social domain, some benefits of the implementation of the Green biorefinery system to the social wellbeing and equality of the local societies are strongly connected to the economic offerings of the technology. The improvement of the economic position of locals due to the production of the Green biorefinery products, as explained above, could bring an upgrade of their living standards, stimulate the entrepreneurship of individuals that will be tempted by the agronomic and economic benefits of the technology, and boost the overall self-sufficiency of local communities. Besides the social improvements related to the economic benefits of the Green biorefinery, an improvement of the social and economic status of local women and other potentially vulnerable groups is expected. This is partly due to the strong orientation of the Bio4Africa project in the inclusion of these groups to the respective project activities. The high inclusion of vulnerable groups could potentially boost the overall equality of local communities both at a general as well as at a gender context, and potentially act as the starting point for the widespread establishment of progressive and modern mindsets among both youths and the older generation of African communities.

The sustainability-related benefits of the Green biorefinery technology are summarized in **Figure 9**.

Figure 9: Overview of the expected sustainability-related benefits from implementing Green biorefinery



Although the Green biorefinery seems to be a very promising strategy that will contribute to the overall sustainability of the implementation areas, there is a need to verify and support the sustainability claims of the technology through scientifically recognized methods, such as the Life Cycle Assessment methodology.

The LCA, LCC and S-LCA studies of this deliverable will highlight potential environmental, economic, and social benefits, and identify any impact hotspots with room for improvement. At an initial stage, this process will take place for the Green biorefinery unit of Uganda, the specifics of which are presented in sub-section 3.4.

3.4 Application of the technology in the pilot case of Uganda

The application of the Green biorefinery technology in Uganda represents the main study area for the LCA, LCC and S-LCA studies of Deliverable 5.3. KRC with GRASSA installed the small-scale Green biorefinery unit during 2021-2022, despite of the significant challenges posed by global health and geopolitical crises that took place from the beginning of the project in 2021. The installation of the unit took place in the Boma area of Fort Portal in western Uganda, selected due to its relevant proximity to the cultivation fields of the feedstocks that are currently grown by KRC and the Uganda National Agriculture Research Centre in the agricultural premises of the Rwebitaba Zonal Agricultural Research and Development Institute. In the future, the Green biorefinery unit is intended to be installed between the feedstock cultivation fields, in order to both minimize the logistic distances and the relevant environmental and economic impacts, as well as to preserve the protein content of the feedstock. Additional initial obstacles in the installation of the unit were posed by the hilly terrain of the pilot area, the challenging weather conditions that are prevalent during the rainy season in Uganda, as well as the lack of adequate roads for the transportation of heavy machinery used for the construction and operation of the small-scale Green biorefinery unit. The broader geographical area of both the Green biorefinery unit and the feedstock cultivation fields is presented in Figure 10.

Figure 10: Geographical area of the small-scale Green biorefinery unit in Boma, Fort Portal UG (blue pin) and the feedstock cultivation fields in Rwebitaba ZARDI (red pin)[1]

[1] https://earth.google.com/web, accessed on 15/10/2023

The setup of the small-scale Green biorefinery unit in Uganda is as described in sub-section 3.1. Some additional spaces were designed to support the main activities of Green biorefinery technology, such as laboratory, office, and storage spaces. The initial capacity of the unit has a processing capacity of 200 kg of fresh green leaves per hour, while there is room for capacity increase up to 1000 kg/hr. The current processing capacity of the unit stands at 400 kg of feedstock per hour. Albeit the unit is operational and is currently producing the desired Green biorefinery products (press cake, whey, protein concentrate), it is still submitted to fine-tuning and optimization modifications (Calibration and re-testing of the extruder, processing capacity improvements, design of the when concentrator, adjustment of the solar drier, completion of the laboratory and the storage facility).

For the feedstock cultivation phase, KRC has completed the testing for selecting the 3 most promising leguminous crops in terms of protein and moisture content, among a large sample of such protein-rich plants (Kalliandra, Tithuania, Blabla, Alfalfa, Mucuna beans, Butterfly Pea-Clitoria Ternatea, Lablab, Apios Americana), while the use of local Napier elephant grass as feedstock should be taken for granted. The selected leguminous crops are currently grown by KRC at the Rwebitaba ZARDI. For the purposes of feedstock transportation from the field to the unit KRC bought a 4-ton capacity refrigerated truck, for ensuring the integrity of the protein of the feedstock in cases of longer transportation routes. Additionally, as at the time of authoring this Deliverable the Green biorefinery process was already operational, it should be noted that 6 farmers are providing the Green biorefinery unit with feedstock, with another 10 part-time fieldworkers working in the harvesting of the biomass.

The full operation of the Green biorefinery unit under optimal conditions, along with the animal feed (and other) trials within the Tasks of WP4, will reveal the full range of the sustainability-related impacts of the system, through LCA/LCC/ S-LCA studies in this deliverable. As a result, the process of the identification of the most promising Green biorefinery business models to be followed and replicated in the tasks of WP5 (and other WPs) will be significantly reinforced.

The future optimal conditions of the Green biorefinery system applicable for the LCA study included in the current Deliverable 5.3 are summarized in the **Table 2**. They are presented per life cycle stage and examined perspective, and in contrast to the current (still optimized) conditions.

Table 2: Technologies tested and implemented per pilot country within the Bio4Africa project

Life cycle stage	Current conditions	Future Conditions related to Perspective 1 (Deliverable 5.3)	Future Conditions related to Perspective 2 (Deliverable 5.6)
Feedstock cultivation	• Mix of manual labour and mechanized agricultural processes	• Fully mechanized agricultural processes	• Fully mechanized agricultural processes
Green biorefinery	• 400 kg per hour feedstock processing capacity	• 1000 kg per hour feedstock processing capacity	• 1000 kg per hour feedstock processing capacity

Life cycle stage	Current conditions	Future Conditions related to Perspective 1 (Deliverable 5.3)	Future Conditions related to Perspective 2 (Deliverable 5.6)
	• Use of Ugandan electricity mix (Section 4.1.2)	• Use of Ugandan electricity mix (Section 4.1.2)	• Use of Ugandan electricity mix (Section 4.1.2) and solar self-generated electricity
Transportation	Feedstock and manure transported to a 10 km distance	Feedstock and manure transported to a 10 km distance	Near zero transportation needs, since the Green biorefinery unit is planned to be located within the farms

4. Sustainability assessment in the Ugandan pilot

Section 4 presents the LCA (Section 4.1), LCC (Section 4.2), and S-LCA (Section 4.3) studies that took place for the case of the Green biorefinery pilot in Uganda. In more detail, Section 4.1 analytically presents the employed LCA study and presents the Goal & Scope definition (Section 4.1.1), the LCI of the study (Section 4.1.2), the LCIA of the study (Section 4.1.3) and the interpretation of the LCA results (Section 4.1.4). Similarly, Section 4.2.1 includes the Goal & Scope definition of the LCC, while Sections 4.2.2 describes the type of the requested information for the compilation of the LCC Inventory. Finally, Section 4.3 presents the S-LCA study, in terms of Goal and Scope definition (Section 4.3.1).

4.1 Life Cycle Assessment for the Green biorefinery pilot case in Uganda

4.1.1 Goal and Scope definition

Goal Definition

A. Reasons for carrying out the study/Intended applications

The primary reason for conducting this LCA study is the calculation of the environmental footprint of the implementation of the pilot, as part of a comprehensive sustainability assessment at all three domains of sustainability (environment, economy, and society). The results of the LCA, along with the results of the respective LCC (Section 4.2) and S-LCA studies (Section 4.3) will provide the overall sustainability profile of the implementation of the Bio4Africa Green biorefinery pilot of Uganda. An additional reason of conducting the LCA study is the estimation of the environmental footprint of four (4) different fertilization and cultivation scenarios in the stage of the cultivation of the feedstock (Table 3).

Table 3: Fertilization and cultivation scenarios to be assessed by LCA

Fertilization and cultivation scenarios in the Life cycle stage of Cultivation			
Scenario	Abbreviation	Fertilizers	Feedstock outcome
Baseline scenario 0	S0	Mix of chemical fertilizers and manure	Fresh leaves
Scenario 1	S1	Chemical fertilizers only	Fresh leaves
Scenario 2	S2	Chemical fertilizers only	Fresh leaves, legumes
Scenario 3	S3	Chemical fertilizers, manure	Fresh leaves, legumes

Moreover, the LCA study of this deliverable aims at the identification of the respective environmental impact hotspots of within the different lifecycle stages of the abovementioned pilot, which allows the consideration of potential interventions in the life cycle stages of the implementation of the pilot for the improvement of its environmental footprint. DreVen (LCA), GRASSA (technology provider) and KRC (local partner) will discuss the LCIA results and conclude to potential improving interventions, if applicable.
Finally, the results of this LCA study reveal the difference in the environmental impacts of the production of Green biorefinery-derived crude protein with the respective impacts of crude protein derived from conventional soybean animal feeds (Perspective 1).

B. Intended audience(s)

According to the declared reasons and applications of the study, the LCA study included in the deliverable concern the following groups of audiences:

- The technology provider (GRASSA)
- The local partner (KRC)
- The European Union, as the main funding institution of the Bio4Africa project
- The European Commission, as the main reviewing mechanism of the Bio4Africa project
- The scientific community
- The Ugandan Government
- Governmental or NGO environmental protection agencies
- Communities
- Farmers
- Businesses
- Potential entrepreneurs
- Funding institutions

C. Comparative assertions

The LCA study included in this deliverable is partially intended for comparing the environmental impacts of the implementation of the Green biorefinery technology products with the respective impacts of counterpart products at a later stage of the Bio4Africa project. This intention does not stem from commercial competitive purposes, but purely from a scientific research point of view. Therefore, no external review (besides the review procedure prescribed by the project’s Grant/Consortium Agreements) will be necessary for the Deliverables 5.3 and 5.6, according to ISO 14040:2006 and ISO 14040:2006.

Scope Definition

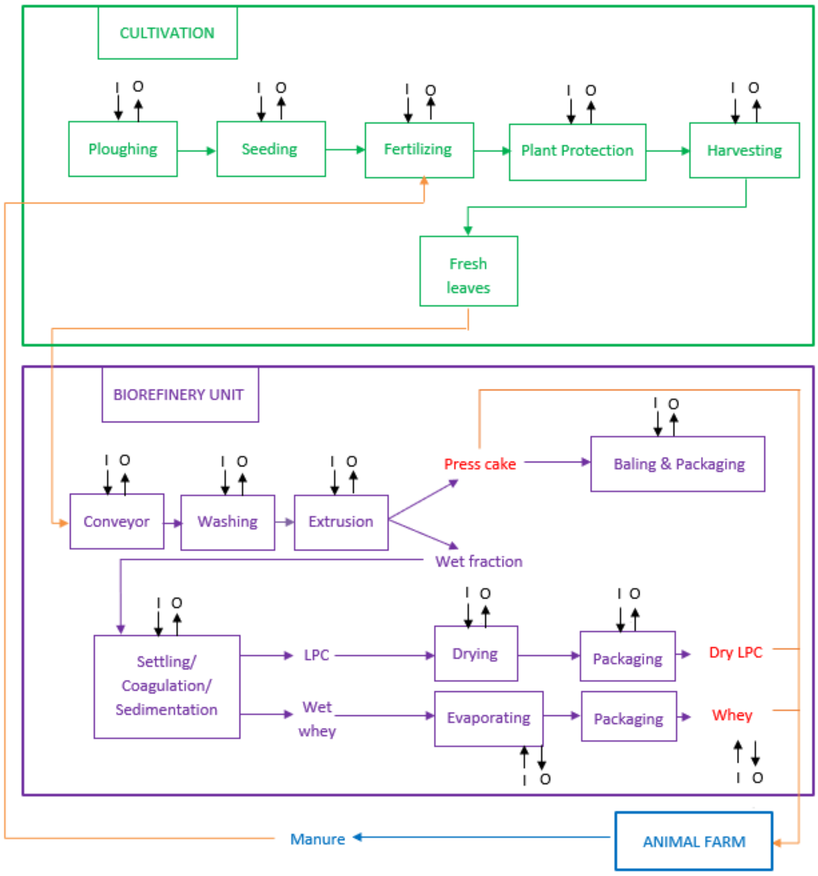
A. Product system details, functions, and processes

The product study under study performs the fundamental process of the production of crude protein, included in the three main Green biorefinery products (press cake, dry LPC, whey). This production is performed through the operation of the Green biorefinery unit, which processes the feedstock of the cultivated elephant grass fresh leaves at a capacity of 1000 kg/h. The cultivation of the fresh leaves’ feedstock as one of the main life cycle stages of the produced crude protein, includes the fully mechanized processes of land preparation, in terms of ploughing and seeding the cultivation land, the application of soil amendments, the protection of the grass and of course, the harvesting of the feedstock. The latter is then transported to the Green biorefinery unit, from which the crude protein results as an end-product.

The Green biorefinery stage includes a series of processing actions, which begin with the transportation of the feedstock in a tray and its washing for removing sand, dirt, and other potentially harmful debris. The leaves are then extruded using a press, from which two fractions are formed, the dry fraction (press cake) and the wet fraction. The wet fraction is further processed to produce dry LPC and the whey result, as end-products. The former is baled and packaged with wrapping foil, while the latter is fermented through a series of settling, coagulation, and sedimentation phases. The respective products of the wet fraction are then dried and packaged.

Next, a flow diagram of the product system examined within the current study is presented (**Figure 11**).

Figure 11: Flow diagram of the product system for the Green biorefinery pilot in Uganda



Moreover, the Green biorefinery product system includes the life cycle stage of the intermediate transportations (orange arrows), as well as all background processes related to the production of the necessary inputs and outputs (black arrows), as depicted in Figure 11. Regarding the latter, they usually involve the production and the transportation of the necessary inputs (raw materials, energy, resources, equipment, infrastructure, other) on-site, while the output processes mostly include the transportation and management of waste as well the release of emissions.

Finally, the product system under study includes the process of the production of manure from animals that are fed with the Green biorefinery product (blue arrows), and the use of the latter as a fertilizer in the cultivation land. However, as manure is considered a waste of the livestock system, it enters our system "burden-free", i.e., with zero upstream impacts. An aggregated overview of the system processes and functions is also included in the "System Boundaries" sub-section, in which the boundaries of the overall system under LCA study are introduced.

B. Functional Unit

The term "Functional Unit" (F.U.) refers to the quantitative reference to which the inputs and outputs as well as their quantities are related. According to the information deriving by the calculations performed on the primary data provided by GRASSA, the following F.U. definition of the Green biorefinery product system is provided:

The functional unit (F.U.) of this study is 1 ton of crude protein. In the Green biorefinery system, the functional unit derives from the production 0,91 tons of dry LPC, 4,49 tons of whey and 7,71 tons of press cake (13,11 tons of total product), that include 0,31 tons, 0,1 tons and 0,59 tons of crude protein, respectively. The three products result from processing 25,64 tons of elephant grass fresh leaves as feedstock input at the Green biorefinery unit during an operation timeframe of 25,64 hours. This quantity of fresh leaves is cultivated in 1,03 hectares of land during a 1-year period.

C. System Boundaries

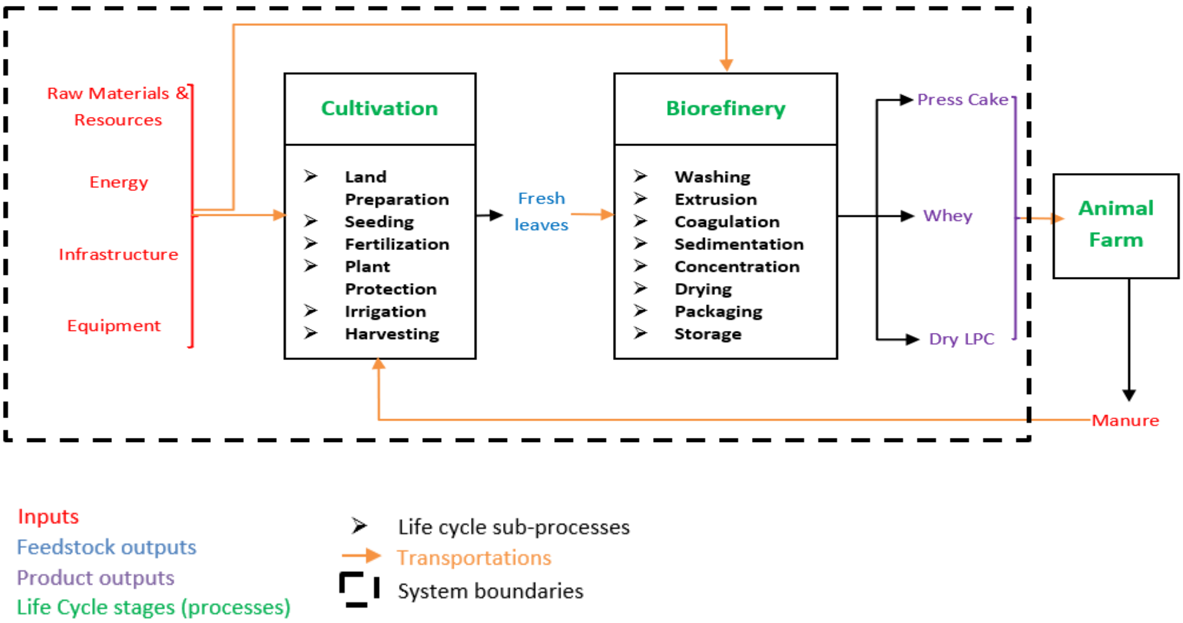
The system boundaries of an LCA study delimit the life cycle stages, processes and related inputs and outputs that are considered (or not) for the study. There are different types of LCA boundaries, which usually begin at the point of extraction of resources from nature (Cradle) and conclude to the outer limit of the production site (Gate), or to the point of discarding or alternative treatment of the product after its use, including the management of waste and emissions (Grave).

For this LCA study, the system boundaries (Figure 12) begin at the point of extraction of raw materials from nature and conclude at the gate of the Ugandan Green biorefinery unit after the production of the relevant outputs (press cake, dry LPC, whey). The main lifecycle stages of the examined product system are:

I. The cultivation of the fresh leaves' feedstock
II. The Green biorefinery unit operation
III. The various transportations of logistic nature between the different life cycle stages.

Moreover, the system boundaries include the production of all necessary inputs and outputs that participate within these life cycle stages. Finally, the use of manure, produced from the animals fed with the Green biorefinery products, is taken into consideration as a "burden-free" nutrient input to the cultivation life cycle stage. This allows the creation of different fertilization scenarios, the impacts of which on the overall system performance will be thoroughly examined.

Figure 12: System boundaries of the LCA study on the Green biorefinery plant (Uganda pilot)



D. Allocation

Allocation is considered necessary in cases where a system has more than one function or product, while the aim is to study the impacts of one or some of them. Although the product system under study (i.e., the Green biorefinery in Uganda) produces three products, no allocation was considered necessary, since the F.U. of the study refers to the total crude protein produced from the three products (press cake, dry LPC, whey).

E. Selected Impact Categories

The goal and scope of this LCA study foresee a broad assessment of the environmental impacts associated to the Ugandan Green biorefinery pilot and as a result, an appropriate LCIA candidate method for this study should optimally provide a wide range of environmental impact categories. At the same time, one of the most comprehensive methods for holistically assessing the environmental impacts of products and processes through LCA is represented by the Environmental Footprint (EF) LCIA method, which is recommended by the EC (European Commission, 2021a). This method, offers a total of 16 midpoint impact categories, including climate change, human health, resource use and eutrophication, among other impact categories. As it will be presented in more detail in Section 4.3., for this LCA study the EF 3.1 method is employed. The full list of the EF v3.1 impact categories, indicators and measurement units are listed in **Table 7**, located in Section 4.1.3. For selecting the most important EF impact categories (of the 16 in total) for the specific product system to be examined in more depth in the LCIA phase, the Product Environmental Footprint (European Commission, 2021b) recommendation was considered. In particular, the PEF recommends the selection of those impact categories that the aggregated weighted impact results sum to approximately 80% of the total impact. The method is presented in detail in the relevant section of the deliverable (Section 4.1.3).

F. Cut-off criteria

A 1% cut-off criterion was applied for excluding processes the impact of which contributes less than 1% of the total impact per selected impact category.

G. Type and Format of LCA Report

Not applicable for the LCA study of this deliverable.

4.1.2 Life Cycle Inventory

Assumptions

Due to the presence of certain data gaps about the specificities and the inventory of the system under study, literature-sourced and/or logical assumptions have been employed. Before presenting the detailed LCI of the Green biorefinery product system, it is useful to present and discuss the assumptions that were deployed for each life cycle stage of the system under study.

a) Cultivation

1. Elephant grass removes carbon from the atmosphere during its growth phase. However, carbon sequestration from the atmosphere is not considered in this study since the valorization of the grass feedstock is intended to produce animal feed products. In simpler terms, the carbon included in the animal feed will return to nature at some point of the supply chain in different forms and natural sinks during its downstream course, and as a result, it gets fully balanced.

2. For most of the processes of the overall system that include diesel energy consumption, readily available datasets provided by EcoInvent are used. Exception is the case of "Baling and Packaging (press cake)" in the stage of Green biorefinery, where data for the used machine were available, and therefore the dataset has been adjusted to include the availability of this information. In this case, the mass consumption of diesel is calculated by using the respective energy consumption for this process estimated by GRASSA and transforming it into diesel mass consumption by taking into consideration the net calorific value of diesel fuel (43 MJ/kg) (Eurostat, 2020). The relevant emission outputs provided by the "diesel, burned in agricultural machine", were adjusted to reflect the ratio of diesel mass to energy production (0,0222 kg of diesel per 1 MJ of energy) and emissions of the abovementioned provider. Therefore, every diesel combustion related emission of this dataset has been multiplied by the following factor and added as outputs of these two processes.
3. For the abovementioned process, for which no readily available datasets of the EcoInvent were used, the losses of energy during diesel combustion were also considered. In more detail, the estimated mass diesel quantity (and their energy output) was considered to represent the final useful work, and a 66.6% loss of energy (Taymaz, 2006) was added to their values.
4. The soil emissions related to the tire abrasions of agricultural machines, the respective emission outputs were provided by the "diesel, burned in agricultural machine" provider of EcoInvent, in terms of the same flow and quantity.
5. For the processes of "Ploughing" and "Baling", datasets that represent the manufacturing of the respective agricultural machines were used in quantities provided by supplier websites. For instance, the weight of the baling machine was provided by sourcing the weight of the specific machine from the supplier's[1] website.
6. Regarding the "Seeding" process of the Cultivation stage, a need of 135 seeds per square meter of land was assumed (Lopez et al., 2022). Additionally, the weight of the seeds was assumed to be 0,005 kg per 100 seeds[2].

b) Green biorefinery

1. For estimating the kg of PE tanks in the settling/coagulation/sedimentation stage, an analogy of 1,5 kg of material per 50 L tank capacity is assumed, according to GRASSA insights in regard with other PE-related inputs.
2. Regarding cleaning procedures of the Green biorefinery equipment, GRASSA pointed to a need for 50 L of sodium hypochlorite solution (4% v/v) per year. For further dilution of this amount of sodium hypochlorite solution, the insights of McGlynn (2004) allowed the estimation of the relevant water needs to be added in the solution. According to this study, a concentration of 200 ppm of sodium chloride is considered both safe and adequate for disinfection when cleaning food processing equipment.

[1] https://www.ritchiespecs.com/model/new-holland-br7060-rotor-baler, accessed on 11/11/2023

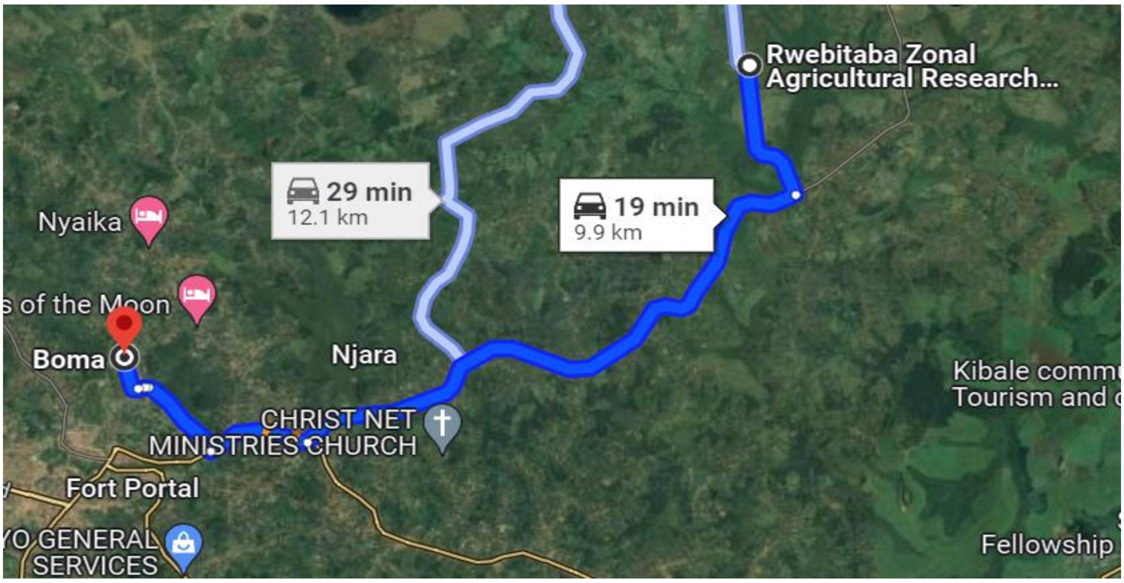
[2] (https://gettreesfast.com/shop, accessed on 12/11/2023)

3. For rinsing residues of the cleaning solutions (sodium chloride, sodium hypochlorite) after cleaning, a need of 5L of water per kg of cleaning solution used is assumed.
4. Assumptions regarding the "Baling" process are analyzed in the sub-section of the "Cultivation" life cycle stage above.

c) Transportation

1. This life cycle stage represents the transportation needs of feedstock and manure per scenario. Therefore, their quantities are related to the relevant needs foreseen in the description of each fertilization scenario.
2. The transportation of feedstock (included in all scenarios) is assumed to take place in two-way routes between the cultivation area (Rwebitaba ZARDI) and the Green biorefinery unit, located in the Boma area of Fort Portal. According to google maps, this distance is approximately 9.9 km (Figure 13).
3. The assumed vehicle is a Euro 3, 3,5-7,5 ton-capacity truck, to accurately represent the 4-ton capacity truck purchased by KRC (Van Doorn et al., 2022). An empty load return route was also considered. In general, for transporting the necessary quantity of feedstock to the Green biorefinery unit, 7 two-way routes with a feedstock load of 3,663 tons are assumed. (7*3,663 = 25,64 tons).
4. The transportation of manure (included in S0 and S3) is assumed to take place between the Green biorefinery unit and a cattle farm located 10 km from the latter. Due to the low weight of the manure, only one two-way route is necessary.

Figure 13: Fastest route from Rwebitaba ZARDI (cultivation area) to the Green biorefinery unit (Boma, Fort Portal)[1]



[1] https://www.google.com/maps, accessed on 30/11/2023

d) Equipment, machines, and infrastructure-related assumptions for all life cycle stages

1. All metal machinery and equipment of an unknown metal composition, they were assumed to be manufactured with 100% stainless-steel. Additionally, the impacts related to the metal working for transforming the semi-ready stainless steel into the final product were also considered.
2. The impacts related to the manufacturing/construction of equipment, machine and infrastructure inputs were considered, as shown in Section 4.1.1. For adjusting their respective impacts in the timeframe of the functional unit, an expected steady production of 117 tons of crude protein per year in the lifetime of the machine was assumed. Every quantity of these input flows was divided by the expected steady production of crude protein multiplied by the expected lifetime. It is worth mentioning that this tactic was used only for inputs that were manually included in the respective datasets of the LCA. For readily available datasets that represent processes of the overall system, their default lifetime for the included equipment was used. The following expected lifetime per equipment/machine/infrastructure flows were extracted (**Table 4**), mostly by the valuable insights of GRASSA.

Table 4: Expected LT of infrastructure, machine and equipment flows

Input flow (equipment, machine, infrastructure)	Expected lifetime (years)
Building	20
Ploughing vehicle	10
Baling machine	5
Conveyor belt	10
Greenhouse	10
Metal sheets (whey drying)	10
Extruder	10
Washing tray	5
All pumps	10
PE tanks (settling/coagulation/sedimentation)	10

3. For maintenance of equipment items (when applicable), each maintenance is assumed to carry 10% of the environmental impacts of the production of the respective equipment item.

Life cycle inventory

The collection of the LCI data for the overall system took place in a modular fashion, in terms of sourcing information per main life cycle stage considered (feedstock cultivation, Green biorefinery, transportation) and the respective processes of each life cycle stage. The data collection procedure took place with the development of an inventory template file from DreVen Greece, which was then shared to the technology provider partner (GRASSA). The latter compiled the relevant information in the file and was sent back to DreVen Greece. An initial validation meeting between the two partners took place in November. According to the collected information and the scenarios to be examined, 4 different LCI were developed in total based on the 4 different fertilization scenarios presented in section 4.1.1; the first LCI is about the currently applied fertilization scheme to the pilot cultivation stage (baseline scenario, S0), which is based on the use of a chemical fertilizer and manure mix. The LCI of the S0 scenario is presented below (Table 5). The LCIs of the S1, S2 and S3 related to the differences between the S0 on the fertilization and transportation stage are provided in Annex I.

Table 5: LCI of the production of 1 ton of crude protein in the Ugandan Green biorefinery pilot, S0

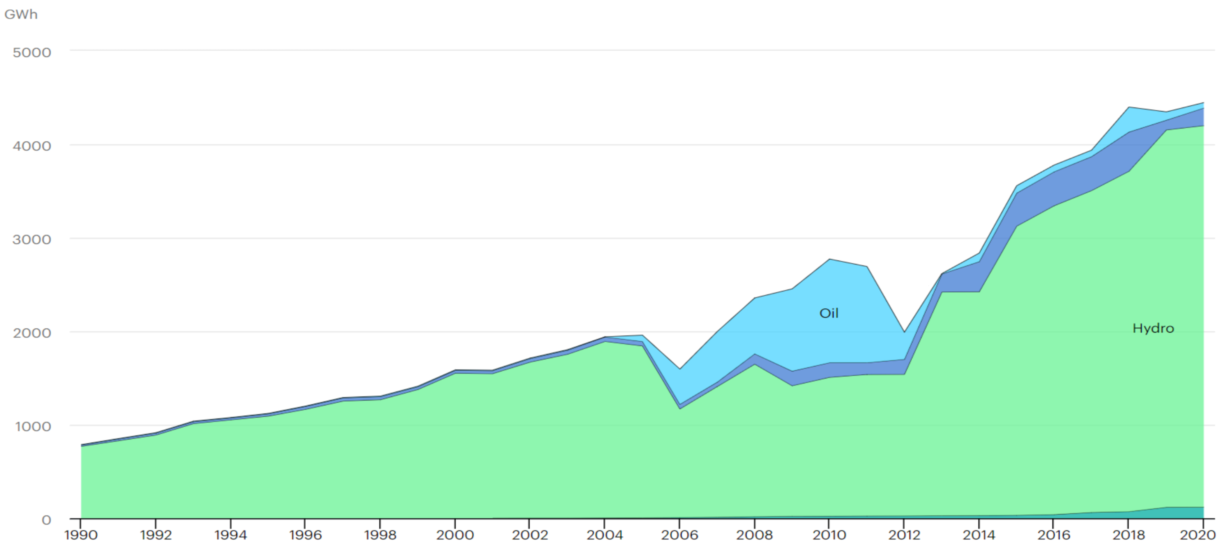
Inventory of producing 1 ton of crude protein in the Green biorefinery system, under the following conditions: • Fully mechanized agricultural processes • Processing capacity of the Green biorefinery unit: 1000 kg/h				
Life Cycle Stage	**Life Cycle Stage Process**	**Flow Category**	**Flow(s)**	**Quantity per F.U. (as described in Section 4.1.1, page 23)**
Cultivation	**Ploughing**	**Inputs**	Agricultural machinery	2,09 kg
			Diesel	23,96 kg
		Outputs	Diesel combustion emissions	See "Assumptions", Section 4.1.2
			Tyre abrasion soil emissions	See "Assumptions", Section 4.1.2
Cultivation	**Seeding**	**Inputs**	Elephant grass seeds	34,69 kg
			Sowing	0,52 m^2
		Outputs	-	-
Cultivation	**Fertilizing**	**Inputs**	Fertilizing, by broadcaster	1,03 ha
			Chemical Fertilizer (N)	61,80 kg
			Chemical Fertilizer (P)	10,30 kg
			Chemical Fertilizer (K)	72,10 kg
			Manure	144,20 kg

Inventory of producing 1 ton of crude protein in the Green biorefinery system, under the following conditions: • Fully mechanized agricultural processes • Processing capacity of the Green biorefinery unit: 1000 kg/h				
Life Cycle Stage	**Life Cycle Stage Process**	**Flow Category**	**Flow(s)**	**Quantity per F.U. (as described in Section 4.1.1, page 23)**
		Outputs	-	-
Cultivation	**Plant protection**	**Inputs**	Hoeing	2,06 ha
		Outputs	-	-
Cultivation	**Harvesting**	**Inputs**	Harvesting, by harvester	1,03 ha
		Outputs	-	-
Green biorefinery	**Conveyor**	**Inputs**	Conveyor belt (production)	0,004 m
			Conveyor belt (maintenance)	0,0002 m
			Electricity (medium voltage)	23,08 KWh
		Outputs	-	-
Green biorefinery	**Feedstock Washing**	**Inputs**	Washing tray (production)	0,012 kg
		Outputs	-	-
Green biorefinery	**Extrusion**	**Inputs**	Extruder (production)	6,15 kg
			Extruder (maintenance)	0,55 kg
			Electricity (medium voltage)	461,54 KWh
		Outputs	-	-
Green biorefinery	**Baling & Packaging (press cake)**	**Inputs**	Baling machine	4,99 kg
			Electricity (medium voltage)	19,66 KWh
			Wrapping foil (low density PE)	3,85 kg
		Outputs	-	-
Green biorefinery	**Settling/ Coagulation/ Sedimentation**	**Inputs**	PE tank 1	0,077 kg
			PE tank 2	0,077 kg
			PE tank 3	0,077 kg

Inventory of producing 1 ton of crude protein in the Green biorefinery system, under the following conditions: • Fully mechanized agricultural processes • Processing capacity of the Green biorefinery unit: 1000 kg/h				
Life Cycle Stage	**Life Cycle Stage Process**	**Flow Category**	**Flow(s)**	**Quantity per F.U. (as described in Section 4.1.1, page 23)**
		Outputs	-	-
Green biorefinery	**Drying (LPC)**	**Inputs**	Drying greenhouse	1,71 m^2
		Outputs	-	-
Green biorefinery	**Evaporation (Whey)**	**Inputs**	Corrugated metal sheet	0,85 m^2
		Outputs	-	-
Green biorefinery	**Infrastructure (general purposes)**	**Inputs**	Building	0,17 m^2
		Outputs	-	-
Green biorefinery	**Cleaning**	**Inputs**	Sodium Chloride solution (4 v/v%)	0,54 kg
			Bleach solution (4 v/v%)	0,57 kg
			Tap water	515 kg
		Outputs	Wastewater	430 kg
Green biorefinery	**Pumping**	**Inputs**	Pumps (production)	0,005 Items
			Pumps (maintenance)	0,0005 Items
			Electricity (medium voltage)	23,08 KWh
Transportation	**Transportation (feedstock)**	**Inputs**	transport, freight, lorry 3.5-7.5 metric ton, EURO3	253,91 t * km
		Outputs	-	-
Transportation	**Transportation (manure)**	**Inputs**	Transport, freight, lorry, unspecified	1,45 t * km
		Outputs	-	-

Additionally, it should be noted that a dataset for representing the current mix of electricity consumed in the Ugandan Green biorefinery was manually constructed, for accurately reflecting the impacts related to this input flow of the Green biorefinery. As the national public electricity corporation of Uganda does not provide data regarding the residual electricity mix that is consumed within the country, and for this reason, alternative information sources were sought. The electricity mix was created based on the information provided by the International Energy Agency (IEA)[1]. The electricity generation mix of Uganda for 2020. According to this source, the electricity generation mix of Uganda in 2020 constituted mainly by hydroelectricity (4081 GWh), followed by biofuel (188 GWh), solar (118 GWh) and oil (58 GWh) generated electricity (**Figure 14**), totaling up to an electricity production of 4445 GWh for 2020.

Figure 14: Electricity generation mix of Uganda (IEA)



This electricity generation mix was adjusted to reflect the imports and exports of electricity, according to information collected by the Globaleconomy website[2] for year 2021. In this year, Uganda exported around 200 GWh of electricity to neighboring countries while it imported 20 GWh of electricity, mainly from Kenya. This import/export balance was assumed to be valid for 2020, while the whole information set was considered representative of the current electricity situation in Uganda.

According to the abovementioned information and assumptions, the calculations of **Table 6** the creation of the dataset for representing the electricity mix of the Ugandan Green biorefinery.

[1] https://www.iea.org/countries/uganda, accessed on 17/11/2023

[2] https://www.theglobaleconomy.com/Uganda/electricity_exports/ (accessed on 17/11/2023)

Table 6: Ugandan electricity generation mix and electricity consumption mix (sourced from IEA & Global economy)

Electricity source	Electrical energy produced (GWh)	Electrical energy consumed (after imports and exports	Electricity energy consumed (adjusted with import/export balance, per KWh of total electricity consumed)
Hydro	4081	3897	0,914
Oil	58	55	0,013
Solar	118	113	0,026
Biofuel	188	180	0,042
Total production	4445		
Imports		20 (Kenya)	0,005
Exports	200		
Internal consumption		4265	1

Finally, it should be noted that the abovementioned quantities of electricity refer to the production of high voltage electricity and include energy losses during the transformation of high voltage electricity to medium voltage. For calculating the latter, as well as for considering the emissions related to the Ugandan transmission network, information in that regard for the respective high voltage electricity production of neighboring Tanzania was collected through the relevant EcoInvent dataset. Specifically, both the amount of energy losses in Tanzania (0,015 KWh per 1 KWh) and the size of the Tanzanian transmission network were assumed to be representative for the case of Uganda.
The cultivation of the elephant grass feedstock, the processing phase of the latter through the technology of Green biorefinery, the various transportation needs as well as the electricity situation of Uganda, were simulated in the OpenLCA software and the EcoInvent dataset. The latter provided adequately representative datasets for modelling the product system under study, and offered the ability of creating datasets manually, such as in the case of electricity.

4.1.3 Life Cycle Impact Assessment

EF 3.1 LCIA Method

For calculating the environmental impacts of the Ugandan Green biorefinery pilot of the Bio4Africa project, the EF 3.1 LCIA method is employed. The complete list of the included impact categories (with abbreviations), as well as their respective underlying LCIA methods, characterization units and normalization/weighting factors are presented in **Table 7** (Andreassi Bassi et al.).

Table 7: The EF 3.1 method (Andreassi Bassi et al.)

EF impact category	Method	Abbreviation	Characterization Unit	Normalization Factor	Weighting Factor
Climate Change, total	Bern model - Global warming potential (GWP) over a 100-year time horizon based on IPCC 2021 (Forster et al., 2021).	CC	kg CO2 eq.	7550	0,2106
Ozone depletion	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon (WMO 2014 + integrations)	ODP	kg CFC-11 eq.	0,0523	0,0631
Human toxicity, cancer	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)	HTP	CTUh	1,73E-5	0,0213
Human toxicity, non-cancer	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)	HTP-NC	CTUh	1,29E-4	0,0184
Particulate matter	PM model (Fantke et al., 2016 in UNEP 2016)	PM	Disease incidence	5,95E-4	0,0896
Ionising radiation, human health	Human health effect model as developed by Dreicer et al. (1995) and published in Frischknecht et al. (2000).	IR-HH	kBq U235 eq.	4220	0,0501
Photochemical ozone formation, human health	LOTOS-EUROS model (Van Zelm et al., 2008) as applied in ReCiPe 2008.	POCP-HH	kg NMVOC eq.	40,9	0,0478
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	AC	mol H+ eq.	55,6	0,062
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	EuT	mol N eq.	177	0,0371
Eutrophication, freshwater	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008.	EuF	kg P eq.	1,61	0,028

EF impact category	Method	Abbreviation	Characterization Unit	Normalization Factor	Weighting Factor
Eutrophication, marine	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008.	EuM	kg N eq.	19,5	0,0296
Ecotoxicity, freshwater	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), adapted as in Saouter et al. (2018)	EcF	CTUe	56700	0,0192
Land use	Soil quality index based on LANCA model (De Laurentiis et al. 2019) and on the LANCA CF version 2.5 (Horn and Maier, 2018)	LU	Dimensionless (pt)	819000	0,0794
Water use	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP 2016)	WU	m3 water eq. of deprived water	11500	0,0851
Resource use, minerals and metals	van Oers et al., 2002 as in CML 2002 method, v.4.8	RUmm	kg Sb eq.	0,0636	0,0755
Resource use, fossil fuels	van Oers et al., 2002 as in CML 2002 method, v.4.8	RUf	MJ	65000	0,0832

Characterization of EF 3.1 impact categories

The characterization results of the EF 3.1 impact categories of the crude protein production system in the Ugandan Green biorefinery pilot of the Bio4Africa project are presented in **Table 8**:

Table 8: LCIA characterization results for the Ugandan Green biorefinery system

Impact Category	Green biorefinery (S0), characterization value	Unit
AC	1,30E+01	mol H+-eq.
CC	1,70E+03	kg CO2-eq.
EcF	4,07E+04	CTUe
RUf	2,00E+04	MJ, net calorific value
EuF	4,23E-01	kg P eq.

Impact Category	Green biorefinery (S0), characterization value	Unit
EuM	3,56E+00	kg N eq.
EuT	4,66E+01	mol N eq.
HTP	2,43E-06	CTUh
HTP-NC	4,27E-05	CTUh
IR-HH	5,17E+01	kBq U235-eq.
LU	3,74E+04	dimensionless
RUmm	2,40E-02	kg Sb-eq.
ODP	2,39E-05	kg CFC-11-eq.
PM	1,20E-04	disease incidence
POCP-HH	1,01E+01	kg NMVOC-eq.
WU	1,30E+03	m3 world eq. deprived

Data requirements and data quality assessment

The overarching goal of the accurate representation of the environmental impacts of the Green biorefinery pilot in Uganda, posed the need for the collection of primary on-site data from the life cycle stages of the system under study. The achievement of this goal would allow the creation of accurate datasets in the employed software tools & databases, or the selection of adequately representative and readily available datasets per flow (providers).

As a general remark, it should be mentioned that in some instances the provided data constitute approximate estimations rather than real-life measured data. The reason behind this fact is the very nature of the object of the study (Green biorefinery pilot unit), in which continuous optimization measures are taken for increasing the efficiency and the yield of the production of Green biorefinery products. These measures, despite their improving role in the overall system, present significant obstacles in accurately measuring the necessary data (type and quantity of inputs and outputs) for the LCA study, as they cause almost constant adjustments in the type and quantity of flows necessary for an efficient operation of the overall system.

Collectively, these issues create the need for certain assumptions, add to the potential limitations of the overall study, and lead to the necessity of conducting a data quality assessment, for which the EcoInvent data quality assessment system is employed. In essence, the latter dictates the characterization of each flow of the overall across 5 main data quality areas: Reliability, completeness, temporal correlation, geographical correlation, further technological correlation (**Table 9**).

Table 9: The EcoInvent Data quality system matrix (Weidenma et al., 2013)

Indicator score	1	2	3	4	5 (default)
Reliability	Verified[5] data based on measurements[6]	Verified data partly based on assumptions ***or*** non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered ***or*** >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered ***or*** some sites but from shorter periods	Representativeness unknown or data from a small number of sites ***and*** from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale ***or*** from different technology

The reliability area refers to the expertise level of the provider of the estimation and to the level of the verification of the data. The completeness area assesses the representativeness of the data in terms of covered markets and respective sites, while the temporal correlation area refers to the time difference between the estimation time and the date of publication of the dataset. Geographical correlation area estimates the difference between the geographical area of data sourcing and the geographical area of the dataset, while the further technological correlation area assesses the origin of the data, in terms of being sourced on-site and therefore representing the relevant technology, or from similar (or unsimilar) sites and relevant technologies. For each one of the assessment areas and per flow, a 1 to 5 score is assigned, with 1 representing the utmost data quality and 5 indicating a very low data quality. The scoring of each area per flow leads to the export of uncertainty factors, which between other indications, present the uncertainty of the contribution of each process to the selected impact categories.

It should be noted that the EcoInvent datasets that simulated the inputs and the outputs of the overall system under study are pre-characterized with specific values across the main data quality areas, while the datasets that were manually created (for example the datasets of Ploughing, Baling & Packaging, and the Ugandan electricity mix), were scored manually at a data quality context.

The full data quality assessment is presented below in Table 10.

Table 10: Data quality assessment of Green biorefinery (S0) system under study, by valorising the EcoInvent data quality system (Weidenma et al., 2013)

Impact Category	R	C	TC	GC	FTC	Average score per impact category
AC	2	3	4	4	2	3,0
CC	2	3	4	4	2	3,0
EcF	1	1	4	4	2	2,4
RUf	1	1	2	2	4	2,0
EuF	1	1	4	1	1	1,6
EuM	2	3	4	4	2	3,0
EuT	2	3	4	4	2	3,0
HTP	1	1	5	3	3	2,6
HTP-NC	2	2	5	4	3	3,2
IR-HH	1	1	5	2	1	2,0
LU	4	2	5	5	1	3,4
RUmm	2	2	3	2	1	2,0
ODP	3	3	3	3	4	3,2
PM	3	3	4	3	2	3,0
POCP-HH	2	3	4	3	1	2,6
WU	2	3	4	3	1	2,6
Average per data quality main area	1,94	2,19	4,00	3,19	2,00	2,66

The results of the assessment (**Table 10**) per main area of data quality (Reliability-R, Completeness-C, Temporal Correlation -TC, Geographical Correlation-GC, Further Technological Correlation-FTC) and per EF

3.1 impact category show an overall adequate data quality. In more detail, green and light green values represent a very good and good data quality, respectively, while red and reddish values present a medium to very low data quality.
In terms of data quality per impact category, a range between 1,6 (Ecotoxicity, freshwater) and 3,4 (Land use) is observed. The average value of data quality per impact category is 2,66, indicative of a medium-to-good data quality in that regard. As for the quality of data per main area of data quality, a range of 1,94 (Reliability) to 4 (Temporal Correlation) is present. Yet again, the medium value of average data quality per main area is equal to 2,66, indicating a medium-to-good data quality, with room for improvement in terms of Geographical (4) and Temporal (3,19) correlation.
In any case, the quality of the data can be considered adequate for assessing the environmental impacts of the product system under study.

Selection of impact categories

At the next step of the LCIA phase for the crude production (S0) system under study, the selection of the most important impact categories to be considered for the interpretation of the LCA results is carried out. As mentioned in Section 4.1.1, only the impact categories of which the weighted results that add up (from higher to lower) to 80% of the total weighted impact are taken into further consideration. The weighted results were extracted in the OpenLCA software (**Table 11**) and show that according to the percentage sum of all weighted impact categories, 8 impact categories are relevant for this study: Climate change (CC), Resource Use-minerals and metals (RUmm), Resource Use-fossil fuels (RUf), Particulate Matter (PM), Acidification (AC), Ecotoxicity-freshwater (EcF), Photochemical Oxidant Formation (POCP-HH), and Eutrophication-Terrestrial (EuT). These 8 impact categories add up to almost 83% of the total weighted impacts percentagewise.

Table 11: Selection of important impact categories for the Green biorefinery system under study, according to the 80% criterion (European Commission, 2021)

Impact Category	Weighted results (As extracted by LCA)	Weighted value contribution (%)	Sum of weighted value contribution (%)
CC	0,048	23,13%	23,13%
RUmm	0,029	13,88%	37,01%
RUf	0,026	12,49%	49,50%
PM	0,018	8,82%	58,32%
AC	0,014	7,06%	65,38%
EcF	0,014	6,71%	72,08%
POCP-HH	0,012	5,75%	77,84%

Impact Category	Weighted results (As extracted by LCA)	Weighted value contribution (%)	Sum of weighted value contribution (%)
EuT	0,010	4,76%	**82,60%**
WU	9,64E-03	4,69%	87,29%
EuF	0,00735	3,58%	90,87%
HTP-NC	0,00609	2,97%	93,84%
EuM	0,0054	2,63%	96,47%
LU	0,00363	1,77%	98,23%
HTP	0,00299	1,46%	99,69%
IR-HH	0,00061	0,30%	99,99%
ODP	2,88E-05	0,01%	100,00%
Total	**0,21**	**1**	**100%**

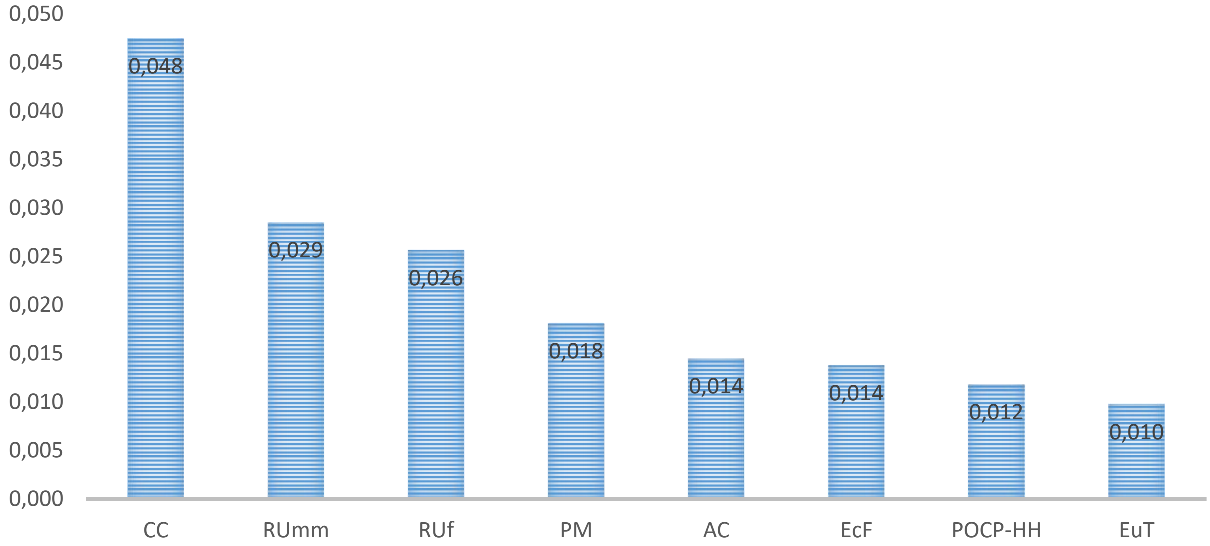
The interpretation of the LCIA results follows in Section 4.1.4.

4.1.4 Interpretation

Weighted LCIA results per selected impact category

The weighted LCIA results per impact category selected for this LCA study is presented in **Figure 15**. Most impacts are observed in the Climate Change (CC) impact category (0,048), almost in double score terms in comparison with the remaining 7 selected impact categories. Significant impacts are also observed in the Resource Use impact categories (RUmm=0,029, RUf=0,026), while the impact categories of Particulate Matter (PM), Acidification (AC), Ecotoxicity-freshwater (EcF), Photochemical Oxidant Formation-Human Health (POCP-HH) and Eutrophication-terrestrial (EuT) are lower (0,018-0,010).

Figure 15: Weighted LCIA results per selected impact category for the Green biorefinery system (S0) under study



Contribution of the different life cycle stages of the Green biorefinery system in the total impact of the selected impact category

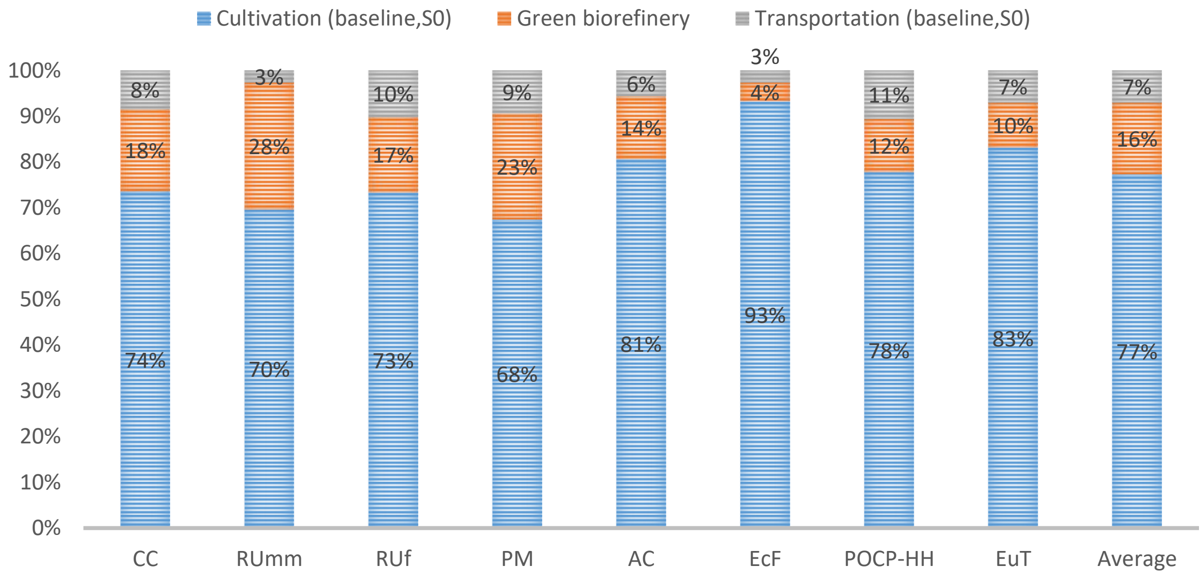
As shown in the next figure, in terms of contribution of the respective life cycle stages to the selected impact categories, the cultivation life cycle stage presents the most significant contribution in every category, ranging from 70% in the Particulate Matter (PM) impact category to 93% in the Ecotoxicity-freshwater (EcF) respective category. The average contribution of the cultivation life cycle stage in all eight selected impact categories amounts to 77%.

At the same time, the second most impactful life cycle stage in terms of impact contribution to the selected impact categories is the Green biorefinery phase, which records a 16% average contribution in all eight selected impact categories. Relatively high contributions of this life cycle stage can be tracked in the categories of Resource Use-minerals and metals (RUmm, 28%), Particulate Matter (PM, 23%), Climate Change (CC, 18%) and Resource Use-fossil fuels (RUf, 17%)

Finally, the Transportation life cycle stage presents the smallest contribution in every selected impact category, with an average contribution of 7% and a range between 3% in the Ecotoxicity-freshwater (EcF) impact category and 10% in the Resource Use-fossil fuels (RUf) impact category.

The average contribution of the three fundamental life cycle stages of the Green biorefinery system in the eight selected impact categories is presented in Figure 16.

Figure 16: Percentile contribution of the Cultivation, Green biorefinery and Transportation life cycle stages per total impact of selected impact categories

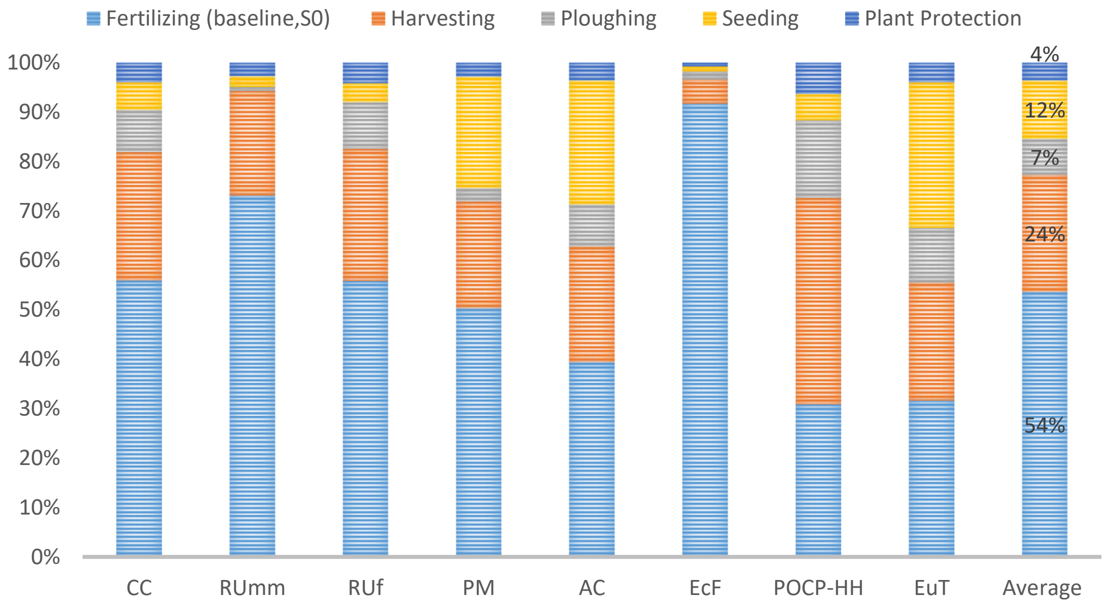


Percentage contribution of the different life cycle stages processes in the total impact of the life cycle stage

An interesting area of performing an impact hotspot assessment is determining the contribution of the respective processes of each life cycle stage in the observed impacts of the selected impact categories (**Figure 17**). Starting from the Cultivation life cycle stage -which presents the highest impact contribution in all eight selected impact categories-, the extracted data from the analysis performed in the OpenLCA software show that the fertilizing process is the most impactful process in the Cultivation phase. In more detail, the average contribution of this process in the total impacts of the Cultivation phase amounts to 54%, while in some impact categories, such as the Ecotoxicity-freshwater (EcF) and the Resource Use-minerals and metals (RUmm) impact categories the fertilizing process records high contributions, amounting to 92% and 73%, respectively.

The next most impactful processes in the Cultivation life cycle stage are the Harvesting and Seeding processes, with an average contribution in all eight selected impact categories of 24% and 12 %, respectively, while the Ploughing and Plant Protection processes contribute a low amount (less than 10% each) in the impacts of the selected impact categories.

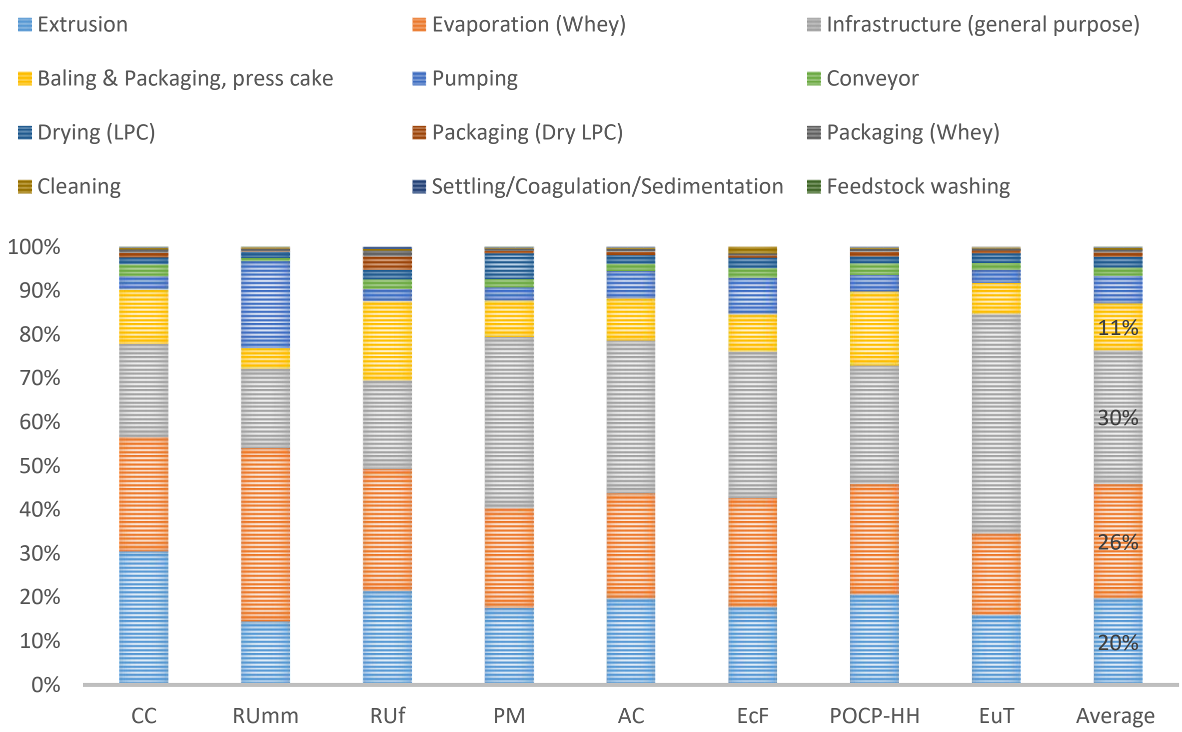
Figure 17: Percentile contribution of the respective cultivation processes in the total Cultivation impact per selected impact category



The impact hotspot assessment for the Green biorefinery life cycle stage (**Figure 18**) uncovers a significant contribution of the "Infrastructure (general purposes)" and "Evaporation (Whey)" processes in the total contribution of this life cycle stage in every selected impact category, amounting to 30 % and 26 % respectively. The construction phase of infrastructure is an expected result, given the impact of construction activities and the 20-year assumed lifetime of the building that houses the Green biorefinery.

Significant contributions in the total impact contribution of the Green biorefinery phase can also be tracked in the average contribution of "Extrusion" (20 %) and "Baling & Packaging, press cake" (11%) processes. Both processes include the consumption of primary energy in the form of electricity, respectively, both of which are often associated with high impacts.

Figure 18: Percentile contribution of the respective Green biorefinery processes in the total Green biorefinery impact per selected impact category



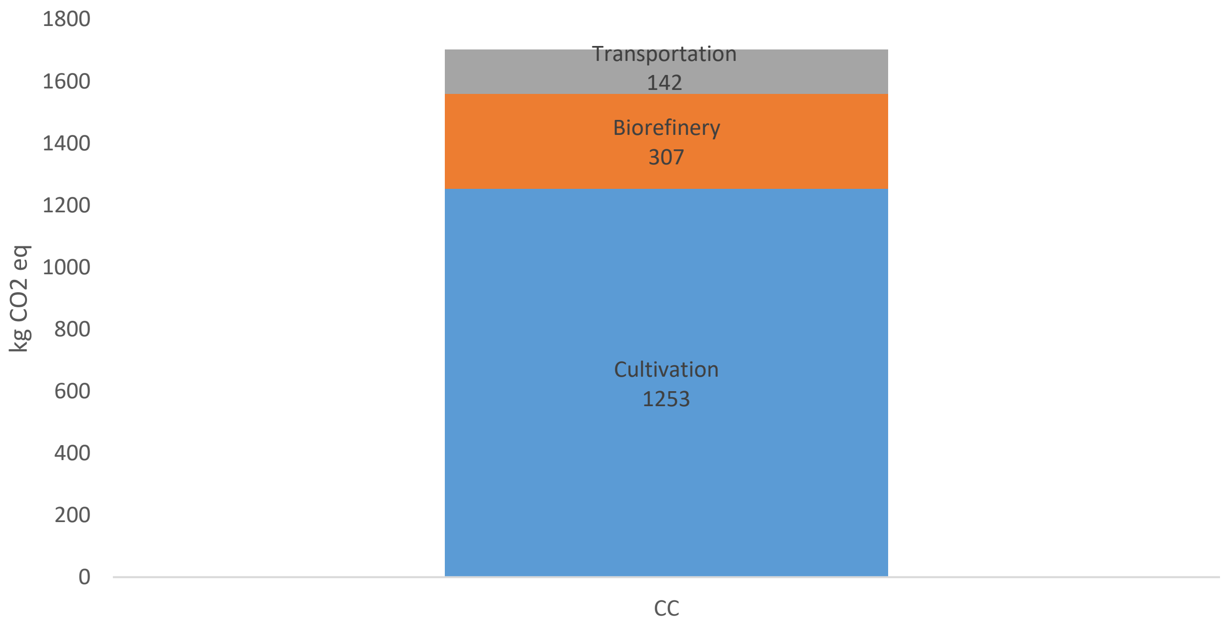
Impact hotspot analysis per selected impact category with high weighted single score (CC, RUmm, RUf)

For the three most significant impact categories in terms of weighted LCIA results (CC, RUmm, RUf), an impact hotspot analysis is performed.

Climate Change (CC)

In regard with the selected category of Climate Change that presents the most significant impacts (as indicated by the weighted results), the quantitative impacts per life cycle stage of the Green biorefinery system (S0) in terms of kg CO2 eq. per life cycle stage are presented (**Figure 19**). The Cultivation life cycle stage emits 1253 kg CO2 eq. per 1 ton of crude protein produced in the Green biorefinery pilot of Uganda, while the respective emissions of the Green biorefinery and Transportation life cycle stage amount to 307 kg CO2 eq. and 142 kg CO2 eq, respectively.

Figure 19: Characterization per life cycle stage of the Green biorefinery system, Climate Change

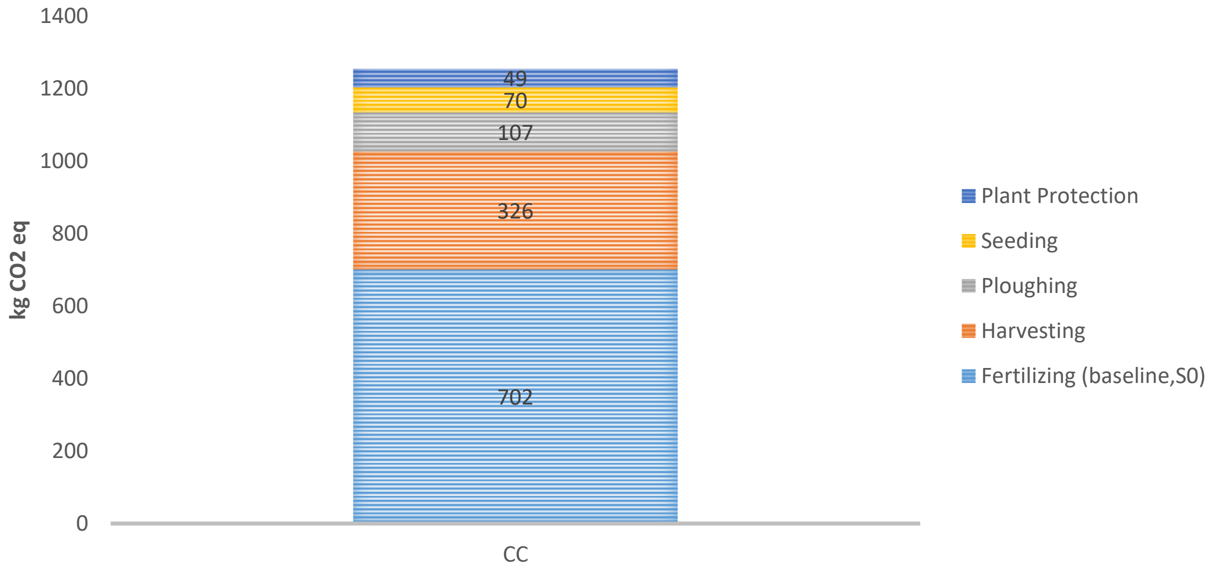


As for the absolute emission values of this life cycle stages, and since most Climate Change-related emissions occur in the Cultivation and the Green biorefinery life cycle stages, an impact analysis in terms of process-related emissions of these two life cycle stages follows.

Starting from the Cultivation life cycle stage (Figure 20), the fertilization stage emits 702 kg CO2 eq. per 1 ton of crude protein produced in the atmosphere. These high CO2 emissions are strongly related to the high carbon footprint of producing primary chemical fertilizers, according to the findings of the analysis conducted in the OpenLCA software. More specifically, the provision of N chemical fertilizers is responsible for 387 kg CO2 eq., while the respective provision of K chemical fertilizers emitted 255 kg of CO2 eq. Finally, the provision of P chemical fertilizers contributed 31 kg CO2 eq., while the rest of the CO_2 related emissions can be attributed to the fertilizing by broadcaster process (29 kg CO2 eq.).

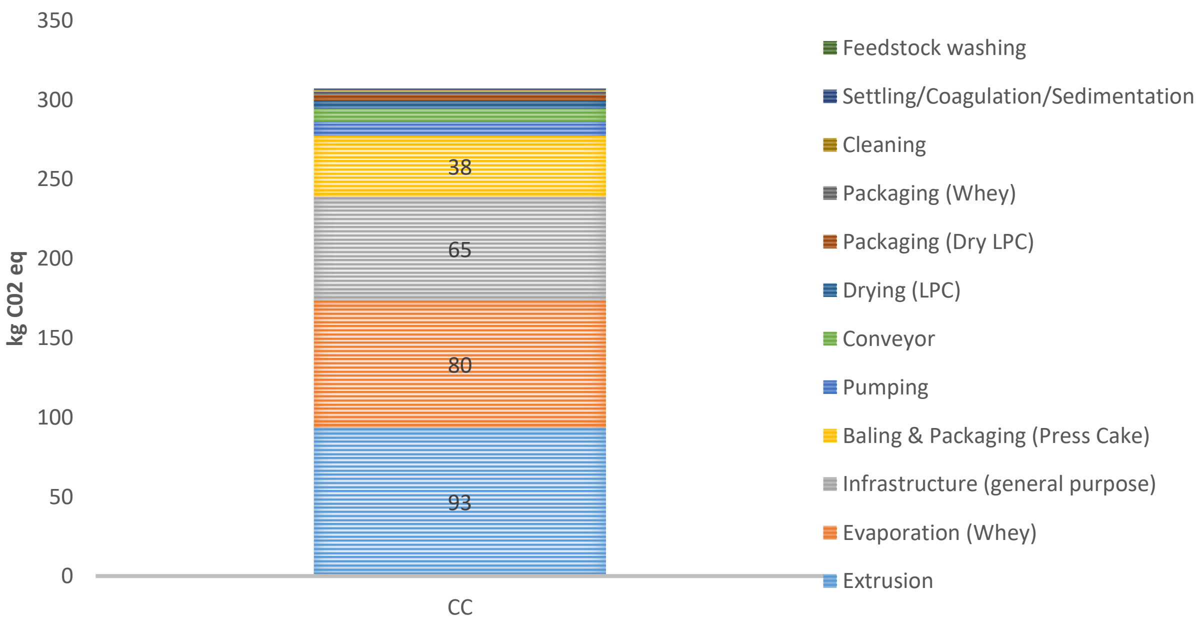
The harvesting process also has significant CO2 emissions in absolute value terms (326 kg CO2 eq.), mostly due to the emissions attributed to the production of the ancillary equipment and infrastructure for this process (agricultural machine, 210 kg CO2 eq.) and to the diesel consumption of this agricultural process (23 kg CO2 eq.). Ploughing, seeding and Plant protection processes of the Cultivation life cycle stage collectively amount to the emission of 226 kg CO2 eq. per 1 ton of crude protein produced in the Green biorefinery pilot.

Figure 20: Characterization per Cultivation process, Climate Change



The same analysis in the Green biorefinery life cycle stage (Figure 21) shows a range of CO_2 emissions between 38 kg CO_2 eq. (Baling & Packaging, press cake) and 93 kg CO_2 eq. (Extrusion) on the high emission side of this life cycle stage. Yet again, most of these CO_2 emissions are closely related primarily to the use of electricity in the extrusion process (45 kg CO_2 eq.), to the production and maintenance of the extruder (49 kg CO_2 eq.), as well as in the production of the evaporation metal sheets (80 kg CO_2 eq.) and to the construction of the Green biorefinery building (65 kg CO_2 eq.).

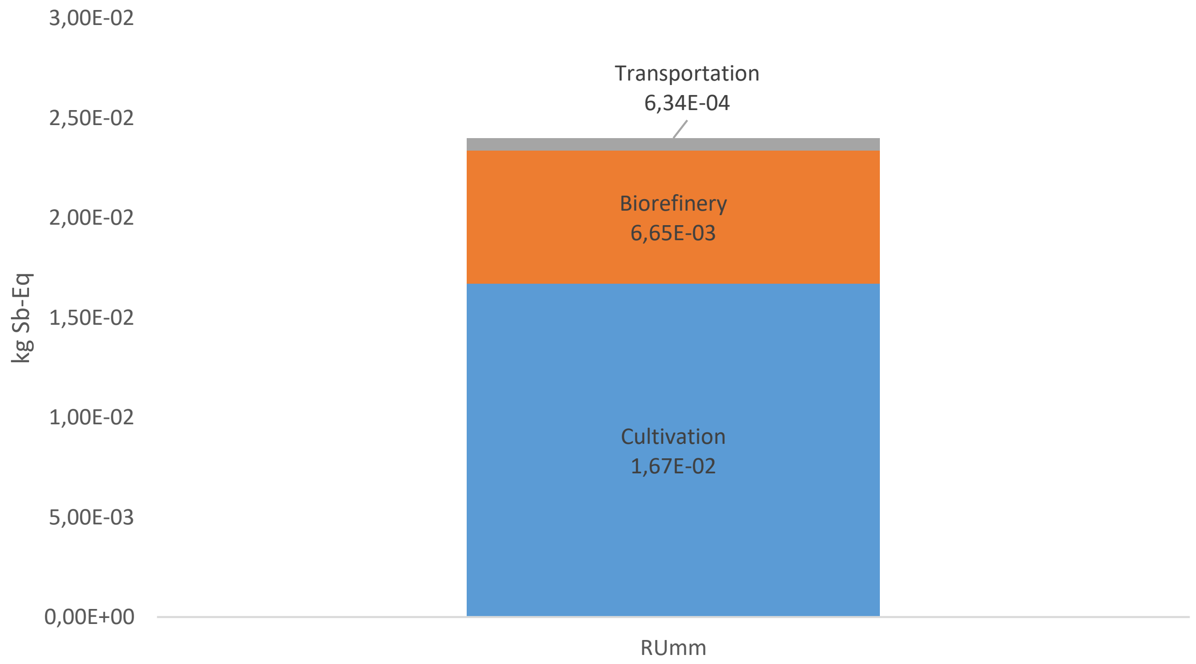
Figure 21: Characterization per Green biorefinery process, Climate Change



Resource Use-minerals and metals (RUmm)

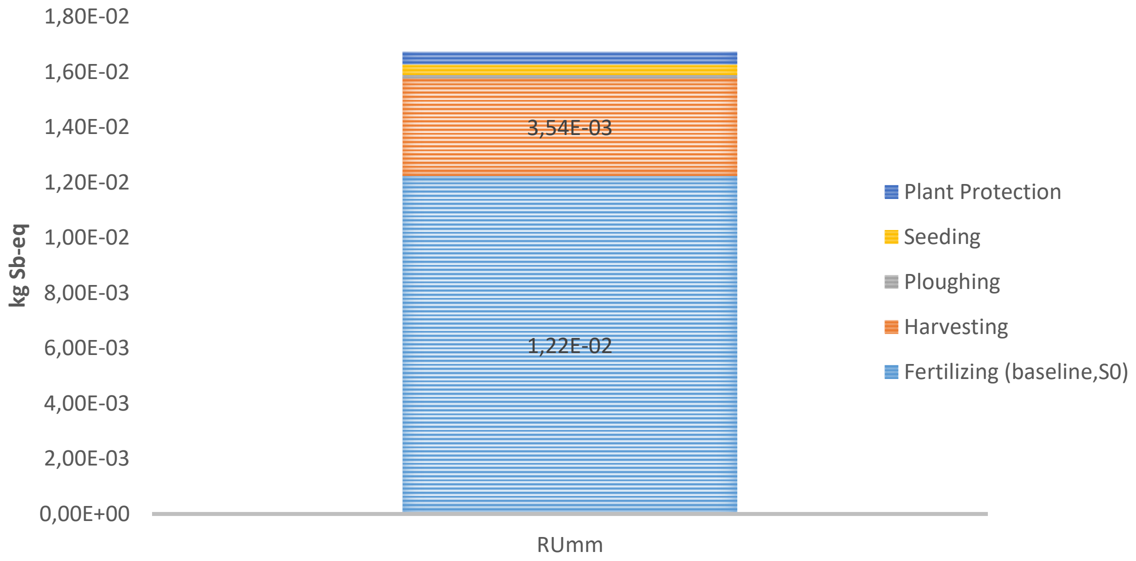
For the second most impactful category according to the weighted results, the Resource use-minerals and metals category, the Cultivation stage is responsible for a material (minerals & metals demand) of 1,67E-02 kg Sb-eq., followed by the respective demand of the Green biorefinery (6,65 E-03 kg Sb-eq.) and Transportation (6,34 E-04 kg Sb-eq.) life cycle stages (Figure 22).

Figure 22: Characterization per life cycle stage of the Green biorefinery system, Resource Use-minerals and metals



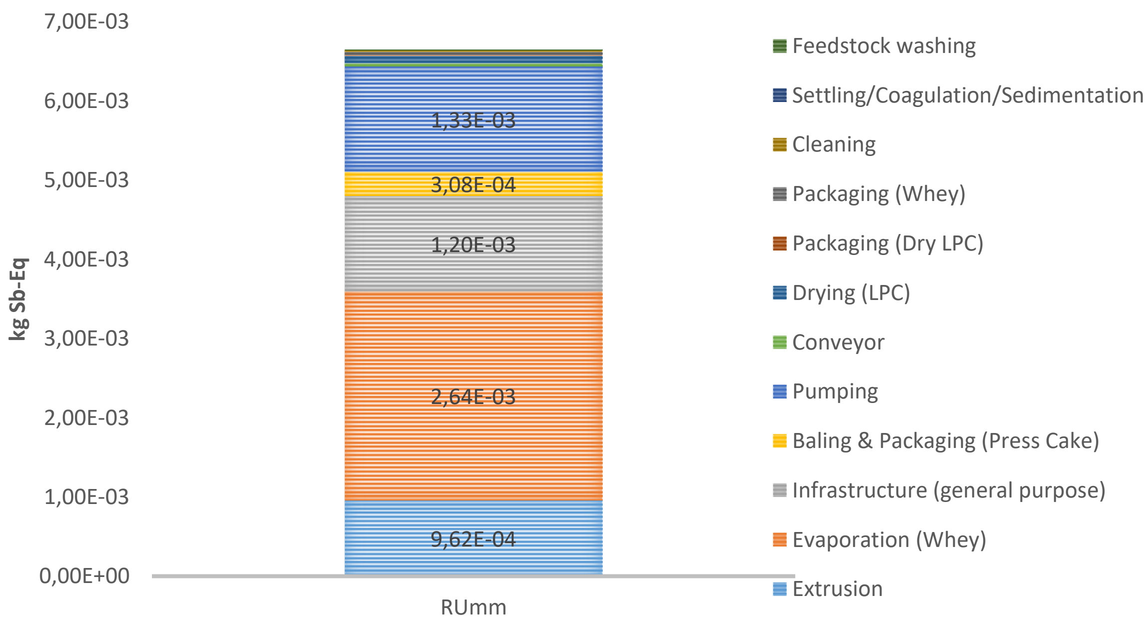
For the Cultivation life cycle phase (Figure 23), the highest emissions once again can be tracked back at the fertilizing process (1,22 E-02 kg Sb-eq.), mostly due to the high demand of material resources during the production of N chemical fertilizers (6,5E-03 kg Sb-eq.), K chemical fertilizers (4,9E-03 kg Sb-eq.) and P fertilizers (5,9E-04 kg Sb-eq.). The harvesting stage comes second (3,54E-03 kg Sb-eq.) in the Cultivation life cycle stage, mostly due to the demand of material resources during the production of the harvesting agricultural machine (3,2E-03 kg Sb-eq.) and infrastructure (3,2E-04 kg Sb-eq.), as well as due to the provision of diesel fuel (1,9E-05 kg Sb-eq.).

Figure 23: Characterization per Cultivation process, Resource Use-minerals and metals



As for the Green biorefinery life cycle phase (Figure 24) the processes with the highest Sb-eq. emissions are the "Evaporation (Whey)" (2,64E-03 kg Sb-eq.), "Pumping" (1,33 E-03 kg Sb-eq.) and "Infrastructure (general purposes)" (1,2E-03 kg Sb-eq.) processes. In more depth, the material demand to produce the evaporation metal sheets contributes 2,63E-03 kg Sb-eq., while in the production and maintenance of the pumps and the extruder a demand of 1,32E-03 kg Sb-eq. and 8,5E-04 kg Sb-eq. is attributed, respectively. The construction of the Green biorefinery building records a 1,2E-03 kg Sb-eq. material resource demand.

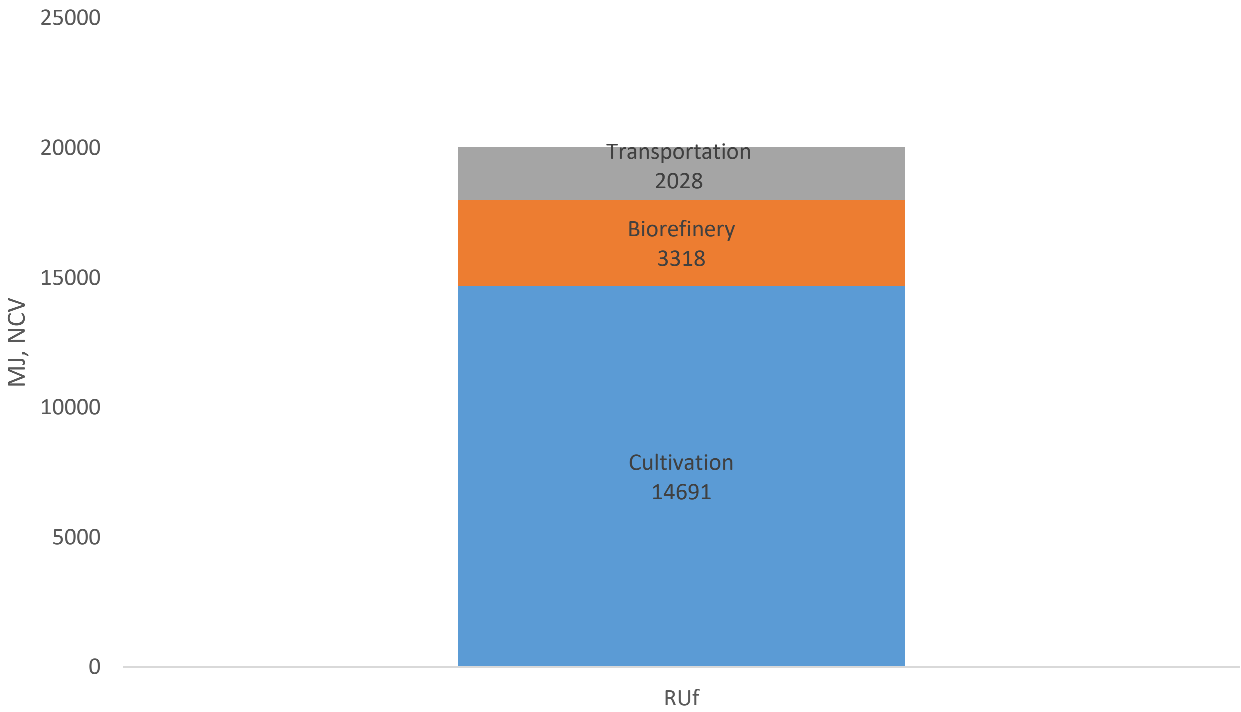
Figure 24: Characterization per Green biorefinery process, Resource Use-minerals and metals



Resource Use-fossil fuels (RUf)

As for the third most impactful impact category of Resource use-fossil fuels (**Figure 25**), most impacts in terms of absolute demand of energy demand (MJ, NCV) occur in the life cycle of Cultivation (14691 MJ), followed by the life cycle stages of the Green biorefinery (3318 MJ) and Transportation (2028 MJ). This is reasonable as it is proportionate to the consumption of fossil fuels in these life cycle stages.

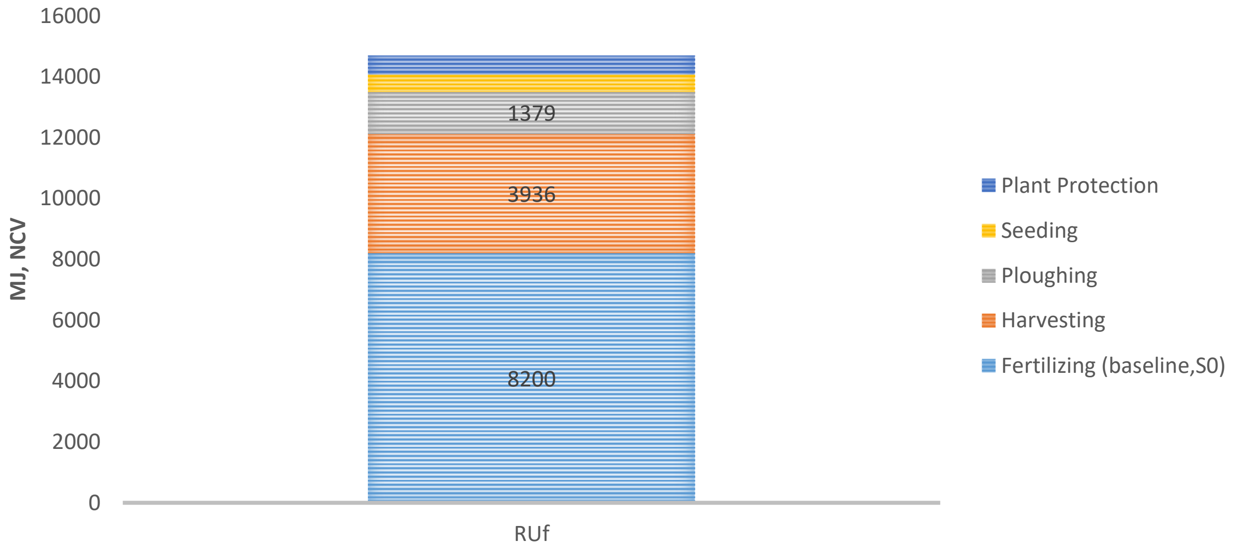
Figure 25: Characterization per life cycle stage of the Green biorefinery system, Resource Use-fossil fuels



A high fossil energy resource demand is observed at the implementation of "Fertilizing, "Harvesting" and "Ploughing" processes of the Cultivation life cycle stage (**Figure 26**), as expected, amounting to 8200, 3936 and 1379 MJ respectively.

Starting with the fertilizing process, the energy demand for the N chemical fertilizers amounts to 4811 MJ, while the respective demand for the K and P chemical fertilizers amounts to 2670 MJ and 344 MJ, respectively. Additionally, a fossil fuel energy demand of 374 MJ Is attributed to the fertilizing by broadcaster process. In the harvesting process, a fossil fuel energy demand of 2310 MJ is observed during the production of the respective agricultural machine, while the respective fossil fuel energy demand for the provision of diesel amounts to 1278 MJ. As for the ploughing process, the fossil fuel energy demand for the provision of diesel consumed in this process amounts to 1254 MJ, while the respective demand for the provision of the respective agricultural machine amounts to 124 MJ.

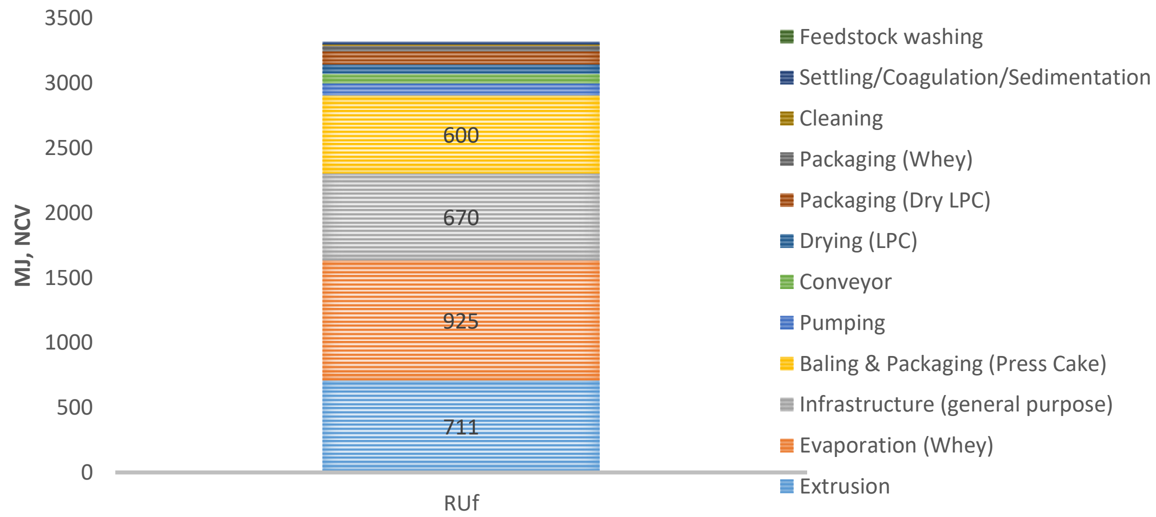
Figure 26: Characterization per Cultivation process, Resource Use-fossil fuels



As for the impact hotspots of the Green biorefinery life cycle stage (Figure 27), they can be identified in the processes of "Evaporation (Whey)" (925 MJ) and "Extrusion" (711 MJ), followed by the processes of "Infrastructure (general purposes)" and "Baling & Packaging (press cake)", which record a fossil fuel consumption of 670 MJ and 600 MJ respectively.

Regarding the processes of whey evaporation and extrusion, most fossil fuel energy demand is attributed to the production of the evaporation metal sheets (927 MJ) and the production and maintenance of the extruder (560 MJ), respectively. In the baling and packaging (press cake process), a fossil fuel energy demand of 297 MJ is recorded for the provision of wrapping foil, while the production of the agricultural machine and the provision medium voltage electricity for the operation of the machine demand a fossil fuel energy amount of 297 MJ and 6 MJ, respectively.

Figure 27: Characterization per Green biorefinery process, Resource Use-fossil fuels



LCIA performance for the selected impact categories per alternative fertilization scenario

This section is dedicated to presenting the environmental impacts of the Green biorefinery system when alternative nutrient (and as a direct result transportation) sources are considered in the fertilization stage. The transportation needs are slightly increased in the scenarios that include the application of manure as soil amendment, due to the transportation of manure from nearby livestock farms to the cultivation site. In more detail, and as described in Section 4.1.2, the scenarios considered are the following:

1. Baseline Scenario 0 (S0): Use mix of manure and chemical fertilizers as a nutrient source.
2. Scenario 1 (S1): Use only chemical fertilizers as a nutrient source
3. Scenario 2 (S2): Use chemical fertilizers in combination with nitrogen input of natural origin from the cultivation of nitrogen-binding legumes
4. Scenario 3 (S3): Use chemical fertilizers, in combination with manure and nitrogen from legumes

The nutrient supply of manure per hectare of cultivation is considered to amount to 100 kg N, 10 kg P and 30 kg N, as shown in **Table 24** (Annex I).

According to the description of the alternative scenarios (S1-S3), changes in the LCI of these scenarios in comparison with the LCI of the baseline scenario (S0) occur only in "Fertilization" process of the Cultivation and Transportation life cycle stage. The latter is associated with the in terms of transportation needs of manure from the livestock farm to the cultivation farm.

By applying the appropriate actions in the OpenLCA software, the following characterization values per selected impact category in terms of absolute values are extracted (**Table 12**).

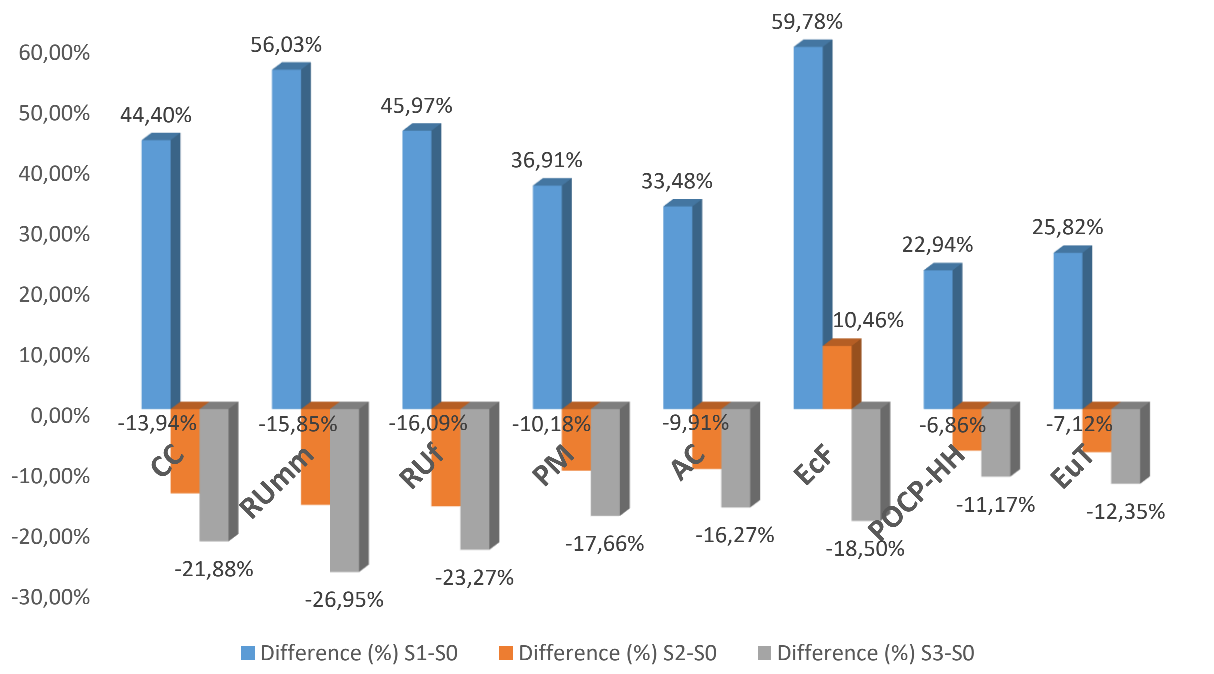
Table 12: Life cycle impact assessment characterization values per selected impact category for the alternative fertilization scenarios (S1, S2, S3)

Impact Category	Unit	Green Biorefinery (S0)	Green Biorefinery (S1)	Green Biorefinery (S2)	Green Biorefinery (S3)
CC	kg CO2-eq.	1,70E+03	2,49E+03	1,46E+03	1,32E+03
RUmm	kg Sb-eq.	2,40E-02	3,76E-02	2,02E-02	1,75E-02
RUf	MJ, net calorific value	2,00E+04	2,95E+04	1,67E+04	1,52E+04
PM	disease incidence	1,20E-04	1,66E-04	1,08E-04	9,87E-05
AC	mol H+-eq.	1,30E+01	1,75E+01	1,17E+01	1,08E+01
EcF	CTUe	4,07E+04	6,53E+04	4,50E+04	3,31E+04

Impact Category	Unit	Green Biorefinery (S0)	Green Biorefinery (S1)	Green Biorefinery (S2)	Green Biorefinery (S3)
POCP-HH	kg NMVOC-eq.	1,01E+01	1,25E+01	9,38E+00	8,92E+00
EuT	mol N eq.	4,66E+01	5,91E+01	4,32E+01	4,07E+01

A deeper look in **Table 12** shows that the alternative fertilization scenarios could potentially bring significant differences in the overall impacts of the Green biorefinery system. The percentage difference between the baseline scenario (S0) with the respective values of the alternative scenarios (S1-S3) can be found in **Figure 28**.

Figure 28: Percentile difference of the total impact of the selected impact category between the alternative scenarios (S1, S2, S3) and the baseline scenario (S0)



At a first glance in **Figure 28**, it can be noticed that the baseline scenario is significantly better compared to the business-as-usual scenario (S1) of chemical fertilizers only. In particular, the increase in chemical fertilizer needs (S1) could significantly worsen the environmental impact of the system. The analysis shows that this scenario would increase the impact of all selected impact categories at a range from +23% (Photochemical Oxidant Formation, POCP-HH) to 59,8% (Ecotoxicity, freshwater). The most significant deterioration would be observed in the impact categories Ecotoxicity-freshwater (EcF), Resource Use-minerals and metals (RUmm), Resource use-fossil fuels (RUf) and Climate Change (CC), with an increase of the respective impacts of 60%, 56%, 46 % and 44%, respectively.

At the same time, the scenario of using nitrogen-binding from the cultivation of legumes instead of the use of manure, as a supplementary nutrient source to the chemical fertilizers (S2) seems to be a slightly better option in environmental terms. Improvements would occur at a range of -6,9% (Photochemical Oxidant Formation, POCP-HH) and -15,9% (Resource Use-minerals and metals, RUmm) in comparison with the respective impacts of S0, while 7 out of the 8 selected impact categories would present an improvement. The only impact category that would further deteriorate is the Ecotoxicity, freshwater (EcF) category at a percentage value of +10,5 % in relation to the respective EcF value of the baseline scenario S0.
Finally, the use of chemical fertilizers and a mix of organic nutrient sources (manure and legumes, S3) would bring very important benefits in terms of the environmental footprint of the Green biorefinery system. S3 is shown to present better environmental performance in all 8 impact categories compared to S0, as a reduction of impacts between 11 - 27% is observed. These improvements would be mostly observed in the Resource Use-minerals and metals (RUmm), Resource Use-fossil fuels (RUf) and Climate Change (CC) impact categories, the impact of which would be reduced by 27%, 23% and 22%, respectively.

Difference in the performance of the Cultivation & Transportation life cycle stages between the scenarios

According to the information provided above, the alternative scenarios (S1-S3) differentiate in relation to the baseline scenario (S0) only in terms of type, composition, and quantity of applied nutrient inputs in the fertilization process, as well as in terms of transportation needs, where manure use is employed. Therefore, these two processes are analyzed in the tables below (Table 13 and Table 14).

Table 13: Percentage change of impacts in the fertilization stage between the baseline and alternative scenarios (S0, S1, S2, S3)

Fertilization life cycle stage			
Impact Category	**Difference (%), S1 vs S0**	**Difference (%), S2 vs S0**	**Difference (%), S3 vs S0**
CC	+112%	-35%	-55%
RUmm	+111%	-31%	-53%
RUf	+116%	-41%	-59%
PM	+111%	-30%	-53%
AC	+109%	-32%	-53%
EcF	+71%	+12%	-22%
POCP-HH	+100%	-30%	-48%
EuT	+102%	-28%	-49%
Average	+104%	-27%	-49%

As indicated by **Table 13** the impact of the fertilization process in the case of S1 (chemical fertilizers only) would be increased at a range of +71% (EcF) to +116% (RUf), while 7 out of the 8 total selected impact categories would be increased in terms of absolute characterization values by at least 100%. This is not the case for S2; nutrient inputs from chemical fertilizers and legumes would improve all impact categories at a range of -28% (EuT) to -41% (RuF), except for the EcF impact category the absolute characterization value of which would increase by 12%. This increase is due to the increased needs of K and P chemical fertilizers in S2 (due to the manure absence) in comparison to the respective needs of the same fertilizers in S0. Scenario 3 would induce further environmental impact improvements, ranging from -22% (EcF) to 59% (RUf).

For the Transportation life cycle stage, the application of the conditions prescribed in each alternative fertilization scenario (S1, S2, S3) would bring negligible difference in the impacts related to this process, as presented in **Table 14**. In essence, the absence of nutrient supply from manure brings small improvements in all 8 selected impact categories at the transportation life cycle stage, due to the absence of the respective transportation needs.

Table 14: Percentage change of impacts in the transportation stage between the baseline and alternative scenarios (S0, S1, S2, S3)

Transportation life cycle stage					
Impact Category	Unit	S0 characterization value	Difference (%), S1 vs SO	Difference (%), S2 vs SO	Difference (%), S3 vs SO
CC	kg CO2-Eq.	1,89E+02	-0,16%	-0,16%	0,00%
RUmm	kg Sb-Eq.	8,46E-04	-0,11%	-0,11%	0,00%
RUf	MJ, net calorific value	2,41E+03	-0,16%	-0,16%	0,00%
PM	disease incidence	1,31E-05	-0,19%	-0,19%	0,00%
AC	mol H+-Eq.	9,43E-01	-0,14%	-0,14%	0,00%
EcF	CTUe	1,39E+03	-0,16%	-0,16%	0,00%
POCP-HH	kg NMVOC-Eq.	1,27E+00	-0,14%	-0,14%	0,00%
EuT	mol N eq.	4,04E+00	-0,13%	-0,13%	0,00%

Comparison of the environmental impacts of soybean feed-derived protein with Green biorefinery-derived protein

In this sub-section, a comparison of the environmental impacts of the production of soybean-derived protein with the respective impacts of Green biorefinery-derived protein takes place. The comparison is enabled by the EcoInvent database, which provides standard soybean cultivation and soybean meal production datasets with geographical specificity. In order to perform the comparison, datasets representative of the current Ugandan market for soybean meal (e.g., Asia, South America) have been employed. The comparison considers the need of importing soybean meal from other countries, which is not needed in the case of locally produced Green biorefinery protein. Before presenting the results of this comparison, it is important to present in contrast the specific LCA aspects of the production of protein from soybean meal and the production of Green biorefinery protein, in order to ensure the comparability of the two products (**Table 15**).

Table 15: LCA aspects considered under the Green biorefinery products and Soybean meal comparison study

LCA aspects	Soybean meal system		Green biorefinery system (S0)	
Functional Unit	1 ton of crude protein Assumption: derived from 2,22 tons of soybean meal (dry matter 90%, crude protein content 50%)		1 ton of crude protein, deriving from 0,91 tons of dry LPC (dry matter 90%, crude protein content 37%), 4,49 tons of whey concentrate (dry matter 36%, crude protein content 6,2%) and 7,71 tons of press cake (dry matter 33%, crude protein content 23%)	
System boundaries and life cycle stages considered	Cradle-to-gate, including “Soybean Cultivation”, “Soybean Processing”, “Transportation”		Cradle-to-gate, including “Cultivation”, “Green biorefinery”, “Transportation”	
Life Cycle Inventory	Soybean cultivation	As in the provider dataset of the EcoInvent flow “soybean production”	Cultivation	As described in **Table 5**, section 4.1.2
	Soybean processing	As in the provider dataset of the EcoInvent flow “soybean, feed production”	Green biorefinery	As described in **Table 5**, section 4.1.2
	Transportation	200 km route between the field and the plant assumed. Represented with the provider dataset of the EcoInvent flow “transport, freight, lorry, unspecified”	Transportation	As described in **Table 5**, section 4.1.2
	Transportation to market	As provided by the respective transportation inputs of the provider dataset of the EcoInvent flow “market for soybean meal”. Representative of the logistics needed for importing soybean meal to Uganda.	Transportation to market	Not applicable. The products are assumed to be consumed locally.

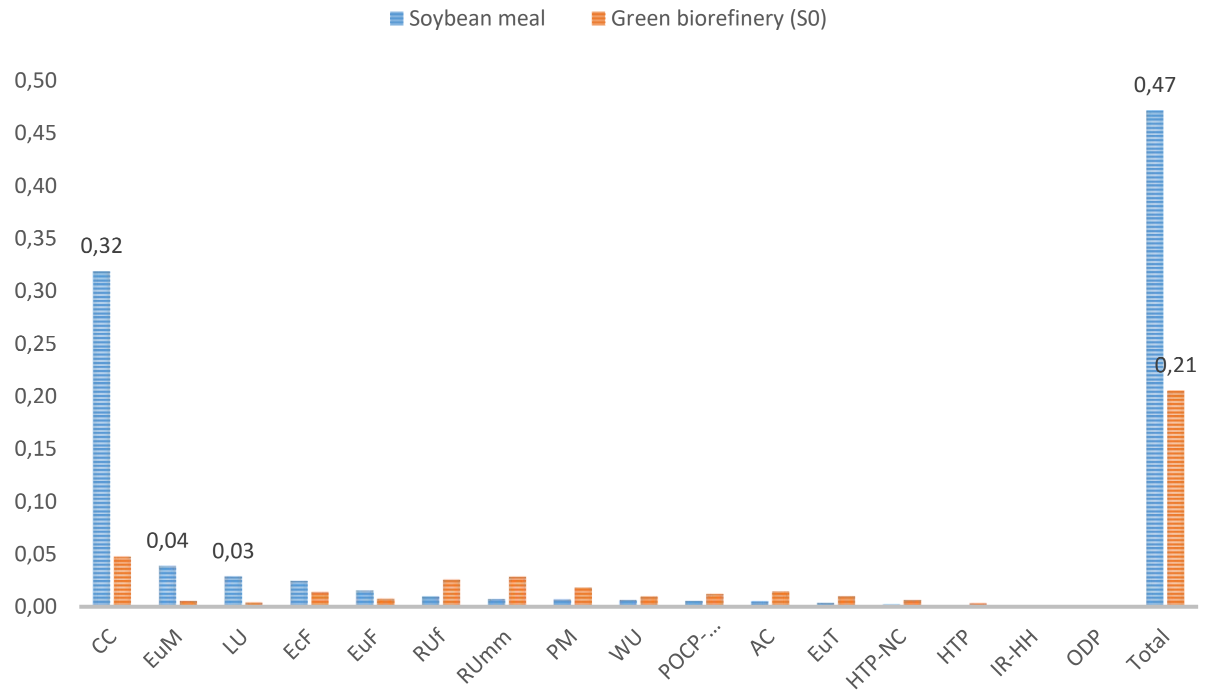
The following characterization values per EF 3.1 impact category are extracted by performing the LCIA in the OpenLCA software (Table 16).

Table 16: LCIA characterization results for the Ugandan Green biorefinery and the soybean meal systems

Impact Category	Unit	Green biorefinery	Soybean meal
AC	mol H+-eq.	1,30E+01	4,56E+00
CC	kg CO2-eq.	1,70E+03	1,14E+04
EcF	CTUe	4,07E+04	7,18E+04
RUf	MJ, net calorific value	2,00E+04	7,35E+03
EuF	kg P eq.	4,23E-01	8,75E-01
EuM	kg N eq.	3,56E+00	2,54E+01
EuT	mol N eq.	4,66E+01	1,69E+01
LU	dimensionless	3,74E+04	2,95E+05
RUmm	kg Sb-eq.	2,40E-02	6,04E-03
PM	disease incidence	1,20E-04	4,54E-05
POCP-HH	kg NMVOC-eq.	1,01E+01	4,40E+00

As for the weighted impacts of the two product systems under comparison (Figure 29), it is shown that the total single score weighted impacts of the soybean meal system are much higher (0,47) than the respective single score weighted impact of the Green biorefinery system (0,21). At the same time, the 3 most significant impact categories according to their weighted impacts of the soybean meal system are Climate Change (CC-0,32), Eutrophication-Marine (EuM-0,04) and Land Use (LU-0,03), which sum to approximately 83% of the total weighted aggregated impact of the soybean meal system. Also, a noticeable finding of this analysis is that the Green biorefinery system performs better in all five most significant impact categories (CC, EuM, LU, EcF, EuF) than the respective soybean meal system.

Figure 29: Weighted impacts of the soybean meal system and the Green biorefinery system (right)



As for the absolute characterization values per process in each system for the five most significant impact categories of the soybean meal system (CC, EuM, LU, EcF, EuF, **Table 17**), he results indicate that the life cycle stages of the Cultivation and the Transportation of the Green biorefinery system have in most cases a better impact than the respective life cycle stages of the soybean meal system. This is not the case for the Processing life cycle stage, as in general the processing of the soybean into soybean meal is less impactful than the respective life cycle stage of the Green biorefinery. This could be attributed to economies of scale achieved with large scale industries.

In general, a deeper look in the differences of the impacts of the two systems, reveals that the biggest impact-related difference between the two compared systems can be attributed to the cultivation life cycle stage. The soybean cultivation life cycle stage, as part of an industrialized system, involves the carbon dioxide emissions related to the land use change necessary for the cultivation of soybean. In particular, when forests are converted to agricultural land, the carbon stored in trees and soil is released into the atmosphere, contributing to carbon emissions. This occurs through deforestation, biomass decay, soil carbon loss, and changes in land management practices associated with agriculture. In contrast, for modelling the cultivation stage of the Green biorefinery system, such emissions where not considered, since the necessary feedstock for the Green biorefinery (elephant grass) is part of the natural vegetation in the area and no land use change has been applied.

Concurrently, the transportation life cycle stage of the soybean meal system is more impactful than the respective Green biorefinery transportation life cycle stage in all five analysed impact categories. This is a reasonable finding, since the transportation of the soybean meal system includes transportation of the soybean meal over longer distances to the local Ugandan markets from other countries and continents, involving other transportation modes as well. At the same time, this transportation need is not relevant in the Green biorefinery system, since the Green biorefinery products are produced and provided in local Ugandan markets.

Table 17: LCIA characterization values per life cycle stage of the compared systems

Compared systems		Green biorefinery products			Soybean meal		
Impact Category	Unit	Cultivation	Green biorefinery	Transportation	Cultivation	Soybean Processing	Transportation
CC	kg CO2-eq.	1253	307	142	11140	56	231
EuM	kg N eq.	2,95	0,3	0,3	25	0,05	0,46
LU	dimensionless	34351	2219	829	292559	271	2165
EcF	CTUe	37938	1683	1063	69805	262	1757
EuF	kg P eq.	0,32	0,09	0,01	0,82	0,03	0,02

4.2 Life Cycle Costing for the Green biorefinery pilot case in Uganda

4.2.1 Goal and Scope

For this life cycle costing (LCC) study, the team is conducting the eLCC because the entire value chain of this system is being investigated. The inventory will involve collecting data on the inputs and outputs of the Green biorefinery plant, including cultivation and transportation. In this Deliverable, the research team will limit their analysis to the Green biorefinery gate and will not study the consumer stage.

The research team to conduct LCC followed the life cycle assessment framework outlined in ISO 14040:2006 and ISO 14044:2006, which includes four main stages as described by Hunkeler et al. (2008).

- Goals and Scope definition
- Information gathering
- Interpretation and identification of hotspot
- Sensitivity analysis and discussion

The primary goal of this economic assessment is to evaluate the economic impacts related to the implementation of the Bio4Africa Green biorefinery pilot in Uganda. This comprehensive assessment aims to achieve the following objectives:

1. **Identification of economic impact hotspots:** The first objective is to identify the respective economic impact hotspots within the different lifecycle stages of the Bio4Africa Green biorefinery pilot.
2. **Comparative economic impact analysis**: The second objective, planned for a later stage of the project, involves comparing the results of the current economic impact study with the respective

economic impacts of conventional animal feed products, such as soybean meal and fishmeal. As mentioned above in Chapter 4.1.1, "This comparison will not take place in this Deliverable, but instead will be performed in the Deliverable 5.6 "Results of the Life Cycle Assessments per Pilot Case - Final Version" due for M44 (January 2025)".

This research aims to determine the costs involved at each stage of the system, from the cultivation of the feedstock to the production of crude protein, which is included in the three mains Green biorefinery products (press cake, dry LPC, whey).

Functional Unit

As stated previously, LCA and LCC share a common functional unit. The life cycle cost is determined on the monetary value associated with the production of 1 ton of crude protein. This includes the costs incurred in the production of dry LPC, whey, and press cake, as well as the costs associated with processing the fresh leaves and maintaining the Green biorefinery unit. The LCC F.U. (Functional Unit) could be expressed in euros (€), which reflects the total cost of producing 1 ton of crude protein. This cost encompasses:

- Production Costs: The cost of producing 0,91 tons of dry LPC, 4,49 tons of whey, and 7,71 tons of press cake.
- Processing Costs: The cost of processing 25.64 tons of fresh leaves in the Green biorefinery unit over 25.64 hours.
- Cultivation Costs: The cost of cultivating the fresh leaves on 1.03 hectares of land over 1 year.

The F.U. regarding LCC for this system is the total cost (in €) required to produce 1 ton of crude protein, which includes the costs associated with producing 0.91 tons of dry LPC, 4.49 tons of whey and 7.71 tons of press cake, processing 25.64 tons of fresh leaves in 25.64 hours and growing these leaves on 1.03 hectares of land for one year.

System boundaries

The boundaries of the system for Life Cycle Cost assessment are determined by following the Cradle-to-Gate methodology. The purpose of setting these boundaries is to gain a comprehensive understanding of all the costs incurred from the initial stages of raw material cultivation, through the construction and operation of the Green biorefinery unit, to the logistical transport of products and by-products. However, it does not consider the costs incurred by the consumer. Chapter 4.4.2 provides a detailed explanation of the expenses involved in conducting this survey.

Financial Assumptions

For calculating the total cost of purchasing and operating the Green biorefinery to estimate the NPV, several assumptions were made, based on the most common practices identified in the literature review. The financial assumption includes the salvage value of the Green biorefinery unit, the discount rate, and the tax rate.

Discount rate: it is used in discounted cash flow analysis to determine the present value of future cash flows. In economic analysis, the discount factor represents the marginal cost of money for the company. This is often based on the interest rate at which the firm can borrow money, adjusted for risk and inflation expectations. In this analysis for Uganda, where inflation is assumed to be 7% (World Bank 2022), the discount rate is assumed to be 10%.

Salvage Value: It reflects the value of the Green biorefinery unit when it is sold, and therefore varies depending on when this may occur. This value is expressed as a percentage of the initial value of the asset.
Corporate tax rate: The tax rate was assumed to be 20-30 %. For income tax purposes, depreciation was calculated over the lifetime of the Green biorefinery unit (T=10-15 years) following the straight-line method of depreciation**.**

Table 18: Overview of financial assumptions

Financial assumptions	Value range
Salvage value	10-30 %
Inflation rate	3-7 %
Discount rate	3-10 %
Corporate tax rate	20-30 %
Lifetime	10-20 years

4.2.2 Life Cycle Costing Inventory

It is important to note that this deliverable only includes the methodology and inventory of the economic assessment. This limitation arises due to the temporary partial unavailability of all necessary data for conducting the LCC from Green biorefinery partners, which the research team required.

Cultivation

The comprehensive cost analysis for elephant grass cultivation is summarized in the table below. This table describes all the necessary costs categorized into capital, variable and fixed costs. Capital costs include initial investments in basic equipment such as tractors, water pumps and harvesters, and consider mandatory costs for studies, permits and approvals related to environmental impacts and land use. Variable costs include the prices of consumable inputs such as seeds, a range of fertilizers (nitrogen, phosphorus, potassium), manure, pesticides, diesel, water and electricity and the maintenance and repair of agricultural machinery. Fixed costs, on the other hand, cover recurrent costs that do not vary with the volume of production, such as labor, which is quantified by the average number of workers, their daily wages and the duration of the work required. In addition, fixed costs include land rents, taxes, machinery insurance and equipment maintenance costs, as well as any administrative fees. Furthermore, the end-of-life costs include the cost of treatment and disposal of solid waste and wastewater produced during the cultivation process.

Table 19: Comprehensive cost inventory for cultivation process

Cost Description	Considered Elements	Measurement Unit	Description
Capital cost	Land acquisitions	€	Cost related to acquiring land
	Agricultural machinery	€	Cost of purchasing or leasing agricultural machinery
	Shed construction	€	Cost for designing and building storage sheds or other farm buildings.
	Tractor acquisition	€	Cost of buying new or used tractors
	Water pumps acquisition	€	Cost of buying water pumps and irrigation systems
	Harvester(s) acquisition	€	Cost of purchasing harvesting machines
Variable Costs	Maintenance and repair costs	€/year	Annual cost of maintaining and repairing farm equipment and facilities.
	Seeds	€/kg	Cost per kilogram of purchasing seeds for planting
	Nitrogen (N)	€/kg	Cost per kilogram of nitrogen-based fertilizers
	Phosphorus (P2O5)	€/kg	Cost per kilogram of phosphorus-based fertilizers
	Manure	€/kg	Cost per kilogram of manure, factoring in costs for drying, processing, and storage.
	Potassium (K2O)	€/kg	Cost per kilogram of potassium-based fertilizers
	Pesticides	€/kg	Cost per kilogram of pesticides
	Diesel	€/kg	Cost per kilogram of diesel in Uganda
	Water	€/m3	Cost per cubic meter of water in Uganda
	Electricity	€/KWh	Price per kilowatt-hour of electrical power in Uganda
	Other variable costs	depends on the input	(e.g., natural gas, heating)

Cost Description	Considered Elements	Measurement Unit	Description
Fixed Costs	Average Number of Workers	people	The typical number of employees needed for farm operations.
	Average Daily Fee per Worker	€/person*day	The standard daily wage paid to each worker
	Average Days of Work per Worker	days	The usual number of days each worker is employed during a given period
	Taxes	€/year	Annual taxes incurred by the farming activities, including land taxes and any other related taxes.
	Rents	€/year	Annual costs related to renting of land, equipment
	Insurance	€/year	Annual Insurance Cultivation Equipment
	Other Fixed Costs	Depends on the input	The cost for recurring expenses such as licenses, permits, and services
Disposal Costs	Cost of Treatment and Disposal of Solid Waste	€/kg	This cost refers to the expenses involved in processing and properly disposing of solid waste generated by the farming operation
	Cost of Treatment and Disposal of Water Waste	€/m^3	This cost pertains to the expenses for treating and disposing of wastewater.

Green biorefinery

Regarding the Green biorefinery plant, which is the main system of this study, the establishment and operation of the Green biorefinery unit includes a complex assessment of various economic components as shown in the table below. Capital costs include the initial investments such as the purchase of land, construction, or acquisitions of the Green biorefinery plant, the main equipment of the Green biorefinery (i.e., extruders, presses, conveyor belts, pumps, and tanks), as well as the cost of office space and storage facilities. Variable costs in the Green biorefinery unit refer to the costs associated with the direct purchase of raw materials, coagulation and sedimentation raw materials, cleaning products, packaging, and various utilities such as heating, and electricity required for the unit operation. The fixed costs in this sector are represented by the labor required to operate the Green biorefinery plant, which is reflected by the average number of employees and their respective wages. These costs are fixed over time, regardless of production levels, and include taxes, rent for land and equipment, insurance for the facility and machinery, and other recurring fees related to operating permits and administrative services. At the end of the production life cycle, the costs for the treatment and disposal of solid waste and wastewater produced during the conversion process are taken into consideration.

In addition to the detailed cost analysis for the Green biorefinery unit, the economic assessment also looks at the revenue streams from the sale of products, which are crucial to the economic feasibility of the unit. The benefits section includes potential revenues from the sale of the Green biorefinery products, i.e., the silage, the dry protein, and the whey concentrate.

Table 20: Comprehensive cost inventory for Green biorefinery unit process

Cost Description	Considered Elements	Measurement Unit	Description
Capital cost	Land acquisitions	€	Cost related to acquiring land for the Green biorefinery unit
	Green biorefinery Building Construction or Acquisition	€	Costs associated with constructing or acquiring a building for the Green biorefinery.
	Green biorefinery Main Equipment Acquisition	€	Expenses for purchasing main equipment.
	Laboratory Main Equipment Acquisition	€	Costs involved in acquiring main equipment for a laboratory setting.
	Office(s) Main Equipment Acquisition	€	Investment needed for purchasing main equipment for office(s).
	Storage Unit Construction or Acquisition	€	Costs related to constructing or acquiring storage units.
	Other Capital Costs	€	Includes costs of voluntary and obligatory background studies
Variable Costs	Maintenance and repair costs	€/year	Annual expenses of maintaining and repairing Green biorefinery equipment and facilities.
	Feedstock	€/kg	Average purchase price per kilogram for feedstock that is directly purchased and not cultivated
	Coagulation & Sedimentation Raw Materials	€/kg	Cost per kilogram of materials used in coagulation and sedimentation processes.

Cost Description	Considered Elements	Measurement Unit	Description
	Cleaning Products	€/kg	Cost per kilogram of cleaning agents used in the Green biorefinery.
	Space and Process Heating	€/KJ	Cost per kilojoule for heating spaces and processes within the Green biorefinery
	Other Raw Materials	€/kg	Cost per kilogram of various other raw materials utilized in operations
	Other Energy Sources	€/KWh	Cost per kilowatt-hour of alternative energy sources used in the Green biorefinery.
	Other Variable Costs	€/kg	These costs depend on the specific inputs used in the Green biorefinery process.
	Water	€/m3	Cost per cubic meter of water in Uganda
	Electricity	€/KWh	Price per kilowatt-hour for electrical power in Uganda
	Other variable costs	depends on the input	(e.g., natural gas, heating)
Fixed Costs	Average Number of Workers	people	The typical number of employees needed for Green biorefinery operation.
	Average Daily Fee per Worker	€/person*day	The standard daily wage paid to each worker
	Average Days of Work per Worker	days	The usual number of days each worker is employed during a given period
	Taxes	€/year	Annual taxes related to the Green biorefinery and other associated activities.
	Rents	€/year	Annual costs related to renting of land, equipment
	Insurance	€/year	Annual insurance costs for the Green biorefinery building, machinery, and other assets.
	Other Fixed Costs	Depends on the input	The cost of recurring expenses such as licenses, permits, and services

Cost Description	Considered Elements	Measurement Unit	Description
Benefits	Silage	€/kg	Average selling price per kilogram
	Dry Protein	€/kg	Average selling price per kilogram
	Whey Concentrate	€/kg	Average selling price per kilogram
Disposal Costs	Cost of Treatment and Disposal of Solid Waste	€/kg	This cost refers to the expenses involved in processing and properly disposing of solid waste generated by the farming operation
	Cost of Treatment and Disposal of Water Waste	€/m^3	This cost pertains to the expenses for treating and disposing of wastewater.

Transportation

The comprehensive cost evaluation of the Green biorefinery unit also includes the transportation, which involves both capital and operational costs. Capital costs include the initial investment in acquiring a fleet of trucks or lorries, potentially with refrigeration capabilities, to ensure the safe and efficient transportation of raw materials and end-products. Variable costs cover a variety of costs related to transport. These range from the costs associated with transporting the raw materials to the cultivation fields, the delivery of manure, and the transport of feedstock from the point of purchase or harvest directly to the Green biorefinery production unit. Fixed costs in the transportation section include the costs related to the workforce required for these logistics' operations. This includes the average number of workers, their daily fees, and the total days of labor needed. For vehicles owned by the facility, there are also annual taxes, insurance costs, and potentially rents or leases associated with the truck/lorry fleet. Transportation costs for disposal are also a critical part of the economic transport model. These include the costs associated with the transport of waste for treatment or disposal, and in cases where hazardous materials are involved, any special handling required prior to transport.

Table 21: Comprehensive cost inventory for transportation process

Cost Description	**Considered Elements**	**Measurement Unit**	**Description**
Capital cost	Trucks/lorries acquisition	€	Cost for trucks/lorries acquisition
Variable Costs	Maintenance and repair costs	€/year	Annual expenses for maintaining and repairing trucks/lorries.

Cost Description	Considered Elements	Measurement Unit	Description
	Transportation of raw materials to cultivation field	€	Costs associated with transporting raw materials to the fields for cultivation
	Transportation of manure to cultivation fields	€	Costs for transporting manure to be used as fertilizer in cultivation fields
	Transportation of feedstock from seller/cultivation field to Green biorefinery unit	€	Costs for moving feedstock from the point of purchase or cultivation to the Green biorefinery
	Transportation of other raw materials from sellers to Green biorefinery unit	€	Costs for transporting additional raw materials required at the Green biorefinery from various sellers
	Transportation for building and machinery transportation purposes	€	Costs incurred for the transportation of building materials and machinery to the site
	Transportation of GRASSA personnel to Uganda for support	€	Travel costs for GRASSA personnel to Uganda for operational support
	Usage Fees	€	Costs of tolls, port fees, and other related usage fees for transportation
Fixed Costs	Average Number of Workers	people	Costs for labour involved in the transportation operations using company-owned trucks/lorries
	Average Daily Fee per Worker	€/person*day	Daily wages paid to workers for transportation services
	Average Days of Work per Worker	days	The average number of working days per transportation worker
	Taxes	€/year	Annual tax expenses associated with the ownership of trucks/lorries

Cost Description	Considered Elements	Measurement Unit	Description
	Rents	€/year	Yearly rental costs for trucks/lorries if not owned outright
	Insurance	€/year	Yearly insurance premiums for company-owned transportation vehicles
	Other Fixed Costs	Depends on the input	The cost for recurring expenses such as licenses, permits, and services
Disposal Costs	Transportation of waste for treatment or disposal	€/kg	Costs for the transportation of waste to treatment facilities or disposal sites
	Special handling of hazardous waste before transportation	€/kg	Costs associated with the special handling of hazardous waste prior to its transportation

4.3 Social Life Cycle Assessment for the Green biorefinery pilot case in Uganda

The Social Life Cycle Assessment of the current study relies on the S-LCA Guidelines general framework (2.1.3), adjusted to the context and the specific goals of the pilot case. The following section presents the methodological approach that will be followed for the assessment of the Green biorefinery case and indicates how the different S-LCA phases planned to be applied.

4.3.1 Goal and Scope

The purpose of this S-LCA is to identify and assess the potential benefits and social impacts (hotspots) that may affect stakeholders with the implementation of the Green biorefinery project in Uganda. The goal of the analysis is to investigate the social impacts from the utilization biomass feedstock to produce bio-based products through a Green biorefinery, in order to be used in the animal feed sector. The results will provide an indication of social impacts of such value chain, as well as potential areas of improvement.
The functional unit is 1 ton of protein content in the total of the three Green biorefinery products.
The S-LCA Guidelines recommend establishing the S-LCA system boundaries considering the system boundaries of the other complementary assessments. Thus, the S-LCA system has been defined using the E-LCA system developed and building upon it (**Figure 12**). Nevertheless, and in line with the S-LCA approach, the division of the product life cycle into life cycle stages has been developed considering the different actors involved instead of focusing on processes. Thus, a cradle-to-gate boundary is considered for the study, including the following main life cycle stages:

i. Cultivation & collection of feedstock (elephant grass)
ii. Feedstock transportation to Green biorefinery

iii. Green biorefinery operation for the production of crude protein

As can be observed in **Figure 12**, the LCA and S-LCA product systems coincide in their main phases.

Identification of stakeholders, impact categories and social indicators

The S-LCA Guidelines consider stakeholder category as “a group type that can be affected by the activities of organizations involved in the life cycle of the product, service, or organization under consideration”. The six main stakeholder categories that are proposed from the S-LCA Guidelines are: *workers, consumers, society, value chain actors, local community, and children.* There is the option of including new categories, subdividing, or excluding ones, if relevant to the studied system.

In the current S-LCA approach, the categories *consumers* and *children* are excluded as they are not involved or affected from the life cycle stages under study. Subsequently, stakeholder categories are divided further into subcategories, also considering the stakeholder mapping that conducted within Bio4Africa Deliverable 5.2[1]. A short description of the stakeholders that have been selected to be studied, as well as the type of relation to the system, are shown in

Table 22.

Table 22: Definition of the stakeholder categories included in S-LCA stages within Green biorefinery pilot case of Uganda

Stakeholder category	Stakeholder Subcategory	Definition	Type of relation
Workers	Agricultural workers	Employees within the production sector, who work in farms or holdings bit do not own those agricultural businesses	**Affected** by the organization practices and decisions.
	Processing workers (Green biorefinery workers) & retail workers	Employees working withing the processing and retail sectors	**Affected** by the organization practices/local/national transportation policies
	Worker unions	Representative entities for employees in the organization and or the sector.	**Concerned** about the social and socio-economic risks generated by specific activities on the workers. **Could influence** the decision-making to protect workers’ rights in the organization
Value chain actors	Farmers and suppliers of raw material	Agricultural producers of the crop biomass feedstock for feed processing, who own businesses and whose economic situation and well-being depend on the profitability and performance of what they produce	**Directly involved** in the decision-making process /supply chain of the product/

[1] D5.2 Report on Inclusive and Sustainable bio-based business models for rural Africa.pdf

Stakeholder category	Stakeholder Subcategory	Definition	Type of relation
	Manufacturer/Technology provider	Designer and developer of the final product/technology	**Directly involved** in the decision-making process
	Industrial partners and feed processors	People engaged during the feed processing or conversion	**Involved** in the decision-making process /supply chain of the product/technology
	Local agribusinesses (agro-input dealers traders, commercial farmers)	People who act as the off-takers of novel food resources	**Involved** in the decision-making process/supply chain of the product/technology
Local community	District Local Governments (DLG) Community leaders	Local authorities that define the local politics and regulations to be respected by the organizations	**Concerned** by the environmental, social, and economic performance of available products/technologies in the market. **Define local actions and plans** to manage products/organizations impacts on a local scale
	Farmer institutions Farmer groups/unions	Representative entities for farmers in the sector	**Concerned** about the social and socio-economic risks generated by specific activities on the farmers. **Could influence** the decision-making to protect farmers' rights in the sector
Society	Academic & research institutions (universities, agricultural research bodies)	Bodies that execute applied feed research to find new applications	**Concerned** by the environmental, social, and economic performance of available products/technologies in the market. **Involved** in the decision-making process
	Non-Governmental Organizations (NGOs) Community-based Organizations (CBOs)	Organizations engaged in promotion of ecofriendly, sustainable and climate-smart agricultural technologies and innovations	**Concerned** by the environmental, social, and economic performance of available products/technologies in the market. Have great **influence** on the decision- making process

Indicators Selection

Impact subcategories are socially significant issues to be assessed using socio-economic indicators (S-LCA Guidelines). Most of the impact subcategories of this S-LCA have been selected using the internationally recognized list of subcategories proposed in the S-LCA Methodological Sheets (Traverso et al., 2021) which were developed as a complement source to S-LCA Guidelines. The Sheets provide a list of socio-economic indicators (generic and specific) for each impact subcategory based on data provided by international agreements, standards, and guidelines. The social inventory indicators (or social flows) are usually described as simple variables (e.g., salary, number of accidents at workplace) providing the most direct evidence of social condition of a certain topic/life cycle stage/process. In S-LCA, indicators can be qualitative, semiquantitative, or quantitative, as well as company specific, site-specific, generic, primary, or secondary.
Many of these indicators and subcategories are included within the Social Hotspot Database (SHDB), helping to save time or fill data gaps in the data collection phase. The SHDB can be used to model the product systems and conduct the initial assessment of potential social impacts (social hotspots) in the whole supply chain.

The indicators selection process is based on a combined bottom-up and top-down approach, as it is proposed by JRC (Mancini et. al, 2018), and will follow three steps: i. indicators screening on published material, ii. social impact identification using the SHDB and iii. engagement of a consultation group. The bottom-up approach consists of selecting sector-specific indicators from the screening of Methodological Sheets and a targeted literature review (Fürtner et al., 2021; Marting Vidaurre et al., 2020; Solarte-Toro et al., 2023; Aristizábal-Marulanda et al., 2020; Silva et al., 2017) on bio-based value chains and products and biorefinery systems aiming to answer the following research question: *"Which social aspects and indicators are relevant for the socioeconomic assessment of alternative bio-based feed products from the biorefinery system?"*. Thus, only indicators that are relevant for the specific stakeholder groups linked to the value chain stages of the studied system are considered. A preliminary selection of the indicators is shown in Table 23.
The above approach will be complemented by an analysis of social impacts on macro (country) and micro (sector) scale using the SHDB (top-down approach). This analysis allows to screen the global supply chains, aiming to identify the social hotspots of the supply chains relevant to the study.
In S-LCA Guidelines, it is also highly recommended to apply participatory approaches engaging all the relevant stakeholders for the selection and prioritization of social impacts. Thus, a consultation group can be established to prioritize the identified social impacts from previous steps and propose additional site-specific indicators that reflect stakeholder groups' values and can be of interest to the study. The consultation group can be formed by project partners, process/ value chain experts, employes & workers representatives, representatives of local communities, NGO's, business partners representing value chain actors. This combined approach that general indicators must be complemented with more specific indicators is also in line with JRC (Sala et. al, 2015). The final list of the indicators will emerge after the system refinement step in the inventory analysis phase, as suggested in S-LCA Guidelines.

Table 23: Preliminary selection of impact subcategories and their corresponding inventory indicators

Stakeholder category	Impact subcategory	Indicator
Worker	Fair salary	Average living wage
		Minimum living wage ratio
	Hours of work	Contractual working hours (hours of work per employee/day)
	Equal Opportunities/Discrimination	Difference in the number of male and female employees
		Rate of workers from regional minorities
	Health and Safety	Accessibility to health care and water
		Number of occupational accidents (fatal/non-fatal) and diseases

Stakeholder category	Impact subcategory	Indicator
		Exposure to toxic chemicals
	Child labour	Percentage of working children under the legal age or 15 years old (14 years old for developing economies)
	Forced labour	Evidence of forced labour in the production processes
	Freedom of association and collective bargaining	Presence of unions within the organization is adequately supported
	Smallholders including farmers	Access to services
		Social inclusion/exclusion of small producers from the market
Society	Contribution to Economic Development	Contribution to economic progress
		Contribution to household/farm income
	Commitment to Sustainability Issues	Contribution to the sustainable production of animal feed (input used and efficiency)
		Corporate sustainability and responsibility reporting, code of conduct
	Technology development	Research and development costs spent
	Corruption	Anti-corruption program carried out
		Commitment to prevent corruption
Local community	Community engagement	Community involvement in decision-making
		Number and quality of meetings with community stakeholders
	Respect of indigenous rights	Land rights, energy sovereignty of indigenous peoples
	Local employment	Number of local full time equivalent created jobs
		Percentage of workforce hired locally
	Access to material resources	Access to land
		Access to food

Stakeholder category	Impact subcategory	Indicator
		Access to water, water rights
		Infrastructure for community access developed
	Safe and healthy living conditions	Odor and pollution levels
		Human health, exposure to pollutants
		Management effort to minimize use of hazardous substances
	Regional value creation	Regional value added
Value chain actors	Supplier relationships	Relationship between Green biorefinery plant and family farming cooperatives
	Promoting social responsibility	Absence of coercive communication with suppliers
		Practices of suppliers, contractors, sub-suppliers, sub-contractors
	Fair competition	Country (sectoral) law and regulations
		Involvement in and performing anti-competitive business practices

Data collection strategy

In the inventory analysis phase, the data collection will be based on the SHDB for the average country sector specific data, while field surveys and interviews with key actors will be conducted to collect site specific data, as well. Other data sources include documentation by governmental and non-governmental organizations such as International Labor Organization, Organization for Economic Co-operation and Development, Human Development Index, United Nations Development Program, and national and international databases such as the National Food and Agricultural Statistics System (NFASS) Database, FAOSTAT, etc. The final list of indicators will be derived from the data availability and source reliability (system refinement).

Evaluation of social performance

The study will use the Reference Scale Approach for Life Cycle Impact Assessment (RS S-LCIA) to assess the social performance and risks of the studied system. A Reference Scale S-LCIA assesses the behaviour of organisations in the product system based on reference points that set different levels of social performance or risk. It relies on data and provides results that focus on the activities of companies in the product system or their immediate effects (Benoît- Norris et al., 2020). Once the data collection phase will be completed, reference scales ought to be developed for each indicator used, and each level of the scale should be defined.

From a data perspective, social performance is often measured with company-specific data (or close proxies), and social risk with generic, sector/country level data effects (Benoît- Norris et al., 2020). The social risk assessment is usually supported by databases.

An activity variable can be used to represent the relative significance of each unit process in the entire system (Benoît- Norris et al., 2020). In this study, the S-LCIA will be performed using SimaPro software (9.3.1) and version 5 of SHDB for the assessment of social risks. SHDB uses the activity variable "worker hours", which represents the time needed to produce 1 USD of output product. Social risks related to all life cycle stages are aggregated by price (inputs), working time (activity variable) and impact factors (characterization factors), which enables expressing the results in *medium risk hours*. The reference scale adopted by SHDB to differentiate risk levels ranges from "low risk" to "very high risk".

5. Conclusions

The results of the LCA study offer significant findings regarding the impacts of the respective life cycle stages and processes of the Green biorefinery system. As a first task, the LCA study allowed the identification of the most significant impact categories to be considered according to their weighted contribution in the total impact of the Green biorefinery system. These impact categories, in order of significance were the Climate Change (CC), Resource Use-minerals and metals (RUmm), Resource Use-fossil fuels (RUf), Particulate Matter (PM), Acidification (AC), Ecotoxicity-freshwater (EcF), Photochemical Oxidant Formation-Human Health (POCP-HH) and Eutrophication-terrestrial (EuT) impact categories were found to contribute accumulatively to the 83% of the total impact of the product system.

At a second step, an impact hotspot analysis took place for the current fertilization (baseline) conditions (S0). The results indicate that the most impactful life cycle stage, as expected, was the cultivation stage with an average contribution of almost 77% in all selected impact categories. A closer look in this life cycle stage highlights the high contribution (54%) of the fertilizing process, and therefore the potential of reducing these impacts by applying measures (manure, cultivation of nitrogen-binding legumes) that will mitigate the need for applying chemical fertilizers.

Indeed, the results of the LCA studies applied on alternative fertilization scenarios that result in the reduction of primary fertilizer needs (S2, S3) showcase this potential; the three identified impact categories with the most significant impact (CC, RUmm, RUf) all present significant improvement when manure application and legumes cultivation measures are applied: The results of S2 (legumes only) highlight an impact reduction ranging from 14% to 16% in these 3 impact categories, while S3 (legumes, manure) is accompanied with even further improvements, with an impact reduction ranging from 22% to 27% for the same impact categories. Therefore, it can be safely said that the application of both measures has a significant improving impact on the environmental footprint of the technology.

As for the remaining life cycle stages of the Green biorefinery system, the second most impactful life cycle stage was identified as the Green biorefinery stage. The insights of the LCA study highlight the high contribution of the infrastructure (30%), whey evaporation (26%), extrusion (20%) and baling & packaging of the press cake (11%) in the overall footprint of this life cycle stage. By considering the impact of the respective flows located within these processes, it can be concluded that the reduction of electricity and diesel consumption for their implementation, as well as the extension of the life cycle of infrastructure, machinery, equipment flows would mitigate the impacts associated with these processes and this life cycle stage.

Finally, a comparison of the life cycle impacts of the production of crude protein in the Green biorefinery system against the respective impacts of the production of crude protein in the soybean meal system was conducted. The results indicate a significant superiority of the former system in terms of environmental impacts, which can be attributed to the lower impacts associated with the cultivation and transportation phase. Also, a deeper analysis in this aspect revealed that soybean meal system is associated with significant land use change emissions in the soybean cultivation phase and high emissions during the importing of the animal feed in Ugandan markets.

As for the limitations of the study, the employment of certain assumptions and secondary data for filling in data gaps may carry a level of uncertainty for the overall results of the study. For this reason, a data quality assessment took place, and the results indicate an overall adequate level of data quality, which could be further improved if more primary data was available in the life cycle inventory phase.

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ANNEX I –LCA INVENTORY OF ALTERNATIVE FERTILIZATION SCENARIOS (S1, S2, S3)

Table 24: Life Cycle Inventory per alternative fertilization scenario (S1, S2, S3), only for life cycle stages and respective processes with different inputs/outputs from S0

Life Cycle Stage	Life Cycle Stage Process	Flow Category	Flow(s)	S0 Quantity per F.U. (as described in Section 4.1.1)	S1 Quantity per F.U. (as described in Section 4.1.1)	S2 Quantity per F.U. (as described in Section 4.1.1)	S3 Quantity per F.U. (as described in Section 4.1.1)
Cultivation	**Fertilizing**	**Inputs**	Fertilizing, by broadcaster	1,03 ha	1,03 ha	1,03 ha	1,03 ha
			Fertilizer (N)	61,8 kg	164,8 kg	-	-
			Fertilizer (P)	10,3 kg	20,6 kg	20,6 kg	10,3 kg
			Fertilizer (K)	72,1 kg	103 kg	103 kg	72,1 kg
			Manure (100 kg N, 10 kg P, 30 kg K)	144,2 kg	-	-	144,2 kg
		Outputs	-	-	-	-	-
Transportation	**Transportation (feedstock)**	**Inputs**	transport, freight, lorry 3.5-7.5 metric ton, EURO3	253,91 t * km	253,91 t * km	253,91 t * km	253,91 t * km
		Outputs	-	-	-	-	-
Transportation	**Transportation (manure)**	**Inputs**	transport, freight, lorry, unspecified	1,45 t * km	-	-	1,45 t * km
		Outputs	-	-	-	-	-