BioINSouth

Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe

Deliverable 4.3

Environmental Assessment Methodology

- Cyprus
- Czech Republic
- France
- Greece
- Portugal
- Italy
- Slovenia
- Spain
- Türkyie

Bio-based Industries Consortium

Circular Bio-based Europe Joint Undertaking

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Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe

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Acronyms and abbreviations

ABBREVIATIONS	Description
LCA	Life Cycle Assessment
TRL	Technology Readiness Level
EU	European Union
PEF	Product Environmental Footprint
SSBD	Safe and Sustainable by Design
PEFCRs	Product Environmental Footprint Category Rules
CC	Climate Change
ODP	Ozone Depletion
IR	Ionizing Radiation (human health)
POF	Photochemical Ozone Formation
PM	Particulate Matter
AC	Acidification
TEU	Eutrophication (Terrestrial)
FEU	Eutrophication (Freshwater)
MEU	Eutrophication (Marine)
LU	Land Use
WU	Water Use (Water Scarcity)
FRD	Resource Use (Fossil)
MRD	Resource Use (Minerals/Metals)
ECOTOX	Ecotoxicity (Freshwater)
HTOX_c	Human Toxicity (Cancer)
HTOX_nc	Human Toxicity (Non-cancer)
ALCA	Attributional LCA
CLCA	Consequential LCA
EoL	End-of-Life
LCI	Life Cycle Inventory

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ABBREVIATIONS	Description
IAMs	Integrated Assessment Models
WP	Work Package
FU	Functional Unit
GHG	Greenhouse Gases
CNC	Cellulose nanocrystals
BTI	Bio-Based Transition Indicator

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1 Executive summary

The present deliverable provides the evaluation of the environmental performance of bioprocesses and bioproducts under a life cycle perspective. Firstly, the methodological frameworks for Life Cycle Assessment (LCA) are detailed and addressed for bioeconomy processes, which is complemented with feedback received from ongoing European projects that are developing LCA approaches within the bioeconomy. Secondly, this work aims at identifying environmental hotspot by evaluating key bioprocesses under a "cradle -to-biorefinery-gate approach". Finally, this deliverable provides guideline and recommendations for the validation of methodologies during the next steps of the project.

In order to assess the conditions under which biomass feedstocks can be sustainable produced and sustainable transformed, the adoption of life cycle approaches is essential since it facilitates the evaluation of impacts on the different aspects (indicators) (i.e. land use, climate change, water use), and enables the elaboration of recommendations to reduce negative effects on the environment. While the conditions of the biomass processes can vary over space and time, the use of resources and the generation of emissions along the value chain need to be interpreted under an impact perspective. LCA is the most recommended approach to address the environmental performance of products and processes, but the interpretation of impacts within the bioeconomy requires specific attention due to the particularities of the biosphere mechanisms and fluxes. Although, emerging bioprocess at low TRL can be evaluated by simplified LCA, the complexity and uncertainties of the studies increase with higher TRL when consequences and future scenarios are considered for modelling impacts.

In the context of this project, the feedback received from different specialized consortia from other EU projects evidence that there is no harmonisation on LCA applied to bioeconomy, as different approaches to model impacts are suggested. However, in terms of indicators, climate change is highlighted that the most relevant aspect that should be considered in all LCA studies.

The revision of literature data is also part of the present deliverable, which aims at evaluating impacts following the LCA standards and updated impact models. Through the interpretation of inventory data from a cradle to gate perspective, the consumption of energy and raw materials by the transformation of biomass is highlighted as the main hotspot of the processes. However, the consideration of non- burden free impacts of feedstock would lead to different conclusions. More solid conclusions from the bioeconomy environmental profile could be elaborated whenever primary data at industrial are available.

Finally, this work provides a comprehensive review of recent research initiatives and technical developments to better integrate the life cycle perspective in the environmental assessment of bioeconomy projects. By compiling literature studies and synthesising lessons learned from other projects, relevant conclusions are drawn for the improvement of the environmental footprint of bioprocesses and successful implementation of the methodology during the next project phases.

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2 Methodological approach in BioINSouth project

The present chapter outlines the methodology for implementing the environmental assessment of bio-based systems in the project. The suggested framework follows the European guidelines (PEF) and incorporates considerations from the recent Safe and Sustainable by Design (SSBD). This chapter also orientates to specific methodological decisions for the modelling of impacts.

2.1 Environmental footprint method- PEF initiative

The Product Environmental Footprint (PEF) methodology, developed by the European Commission[1], is a standardized approach that essentially follows the core of ISO 14040 and 14044, for measuring and communicating the environmental performance of products throughout their entire life cycle, from raw material extraction to disposal. Based on Life Cycle Assessment (LCA) principles, it evaluates multiple environmental impact categories, such as climate change, resource use, and water depletion, using consistent rules to ensure comparability across products and sectors. PEF relies on Product Environmental Footprint Category Rules (PEFCRs) and strict data quality requirements to deliver reliable, transparent, and comparable environmental information, supporting sustainable decision-making by businesses, policymakers, and consumers. The environmental footprint methodology is based on the following interconnected steps (Figure 1).

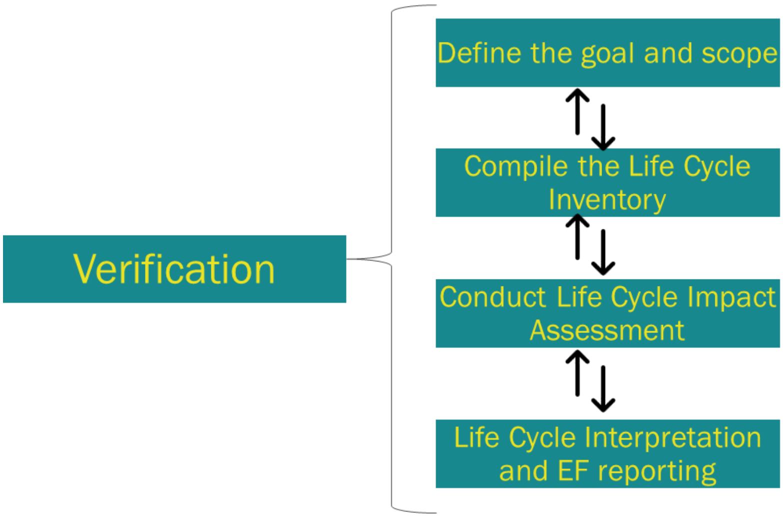

Figure 1 Phases of the Product Environmental Footprint (PEF) studies (source: adapted from COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021)

The assessment of impacts requires the incorporation of characterization, together with the normalization and weighting. Normalisation is the step in which the life cycle impact assessment results are divided by normalisation factors that represent the overall inventory of a reference. Normalised results express the relative shares of the impacts of the analysed system, in terms of the total contributions to each impact category per reference unit. Normalised results reflect only the contribution of the analysed system to the

[1] EU Recommendation 2013/179/EU

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total impact potential, not the severity/relevance of the respective total impact. Weighted results reflect the perceived relative importance of the impact categories considered. Next table shows the 16 environmental impact categories to be used in PEF studies.

Table 1. EF Impact Categories (source: adapted from COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021)

Impact category	Description	Unit	Relevance
Climate Change (CC)	Contribution of greenhouse gases to global warming.	kg CO_2-equivalent	Assesses effects like rising temperatures and sea-level changes.
Ozone Depletion (ODP)	Impact of substances that deplete the stratospheric ozone layer.	kg CFC-11-equivalent	Protects against increased UV radiation risks (e.g., skin cancer).
Ionizing Radiation (human health) (IR)	Harm to humans from ionizing radiation due to radioactive substances.	kBq U-235-equivalent	Includes impacts from nuclear power and radioactive waste.
Photochemical Ozone Formation (POF)	Formation of ground-level ozone (smog) from pollutants like NO_x and VOCs.	kg NMVOC-equivalent	Affects human respiratory health and ecosystems.
Particulate Matter (PM)	Health effects of fine particles and their precursors (e.g., SO_2, NO_x).	Disease incidence	Links to respiratory and cardiovascular diseases.
Acidification (AC)	Potential for acidifying substances to harm terrestrial and aquatic ecosystems.	mol H^+-equivalent	Impacts soil quality, water bodies, and biodiversity.
Eutrophication (Terrestrial) (TEU)	Nutrient enrichment in terrestrial ecosystems (e.g., nitrogen compounds).	mol N-equivalent	Can lead to loss of biodiversity in sensitive areas.
Eutrophication (Freshwater) (FEU)	Nutrient enrichment (e.g., phosphorus) affecting freshwater ecosystems.	kg P-equivalent	Leads to algal blooms and oxygen depletion in water bodies.
Eutrophication (Marine) (MEU)	Nutrient enrichment (e.g., nitrogen compounds) affecting marine ecosystems.	kg N-equivalent	Causes algal blooms and hypoxic zones in oceans.
Land Use (LU)	Changes in land use affecting soil quality, biodiversity, and carbon storage.	Pt ($PDF \cdot m^2 \cdot yr$)	Examines the transformation and occupation of land.
Water Use (Water Scarcity) (WU)	Impacts of water consumption on water availability in regions with scarcity.	m^3 world-equivalent	Addresses the effects on ecosystems and human needs.
Resource Use (Fossil) (FRD)	Depletion of fossil fuel resources like coal, oil, and natural gas.	MJ	Highlights energy demand and resource scarcity.

Impact category	Description	Unit	Relevance
Resource Use (Minerals/Metals) (MRD)	Depletion of abiotic resources like metals and rare earth elements.	kg Sb-equivalent	Accounts for resource availability and extraction impacts.
Ecotoxicity (Freshwater) (ECOTOX)	Toxic impacts of chemicals on freshwater ecosystems.	CTUe (Comparative Toxic Unit)	Reflects harm to aquatic life from pollutants.
Human Toxicity (Cancer) (HTOX_c)	Potential for chemicals to cause cancer in humans.	CTUh (Comparative Toxic Unit)	Examines long-term human health risks.
Human Toxicity (Non-cancer) (HTOX_nc)	Toxic effects of chemicals unrelated to cancer (e.g., organ damage).	CTUh	Includes effects like organ damage and reproductive issues.

For the interpretation of impacts, the EF framework provides a recognized set of guiding principles for hotspots analysis and identification. The hotspots analysis in the EF context aims to identify the most relevant impact categories, life cycle stages, processes and elementary flows.

Hotspots serve as a warning about the area where the interested organisation should focus their attention to improve the environmental performance of a product (PEF). Furthermore, the processes which contribute the most to the final environmental impact results are those which the best quality data should be provided. In particular, the interpretation of the environmental impacts should incorporate the following analysis:

- Most relevant impact categories: from the normalised and weighted results of PEF, the impact categories contributing cumulatively at least 80 % of the total environmental impacts.
- Most relevant life cycle stages: for each most relevant impact category, all life cycle stages contributing cumulatively more than 80 % to that impact category.
- Most relevant processes: for each most relevant impact category, all processes contributing cumulatively (along the entire life cycle) more than 80 % to that impact category, considering absolute values.
- Most relevant elementary flows: for each most relevant process and most relevant impact categories, all elementary flows contributing cumulatively at least 80 % of the total impact category. Once the most relevant elementary flows have been identified they shall be linked to the processes emitting them.

2.2 Safe and Sustainable by Design (SSBD)

In the context of the innovation process for the development of new products and processes, the SSBD framework[1] aims to support the decision making towards safer and more sustainable chemicals and materials over their life cycle. It provides a “step by step” framework that starts with the screening of the environmental performance of emerging chemical, processes and products to re-design them considering the reduction of potential environmental hotspot. Although it refers to the sustainability, only the environmental dimension is mandatory, and the consideration of social and economic aspects in the assessment are only recommended.

In terms of LCA, the SSBD framework proposes simplified approaches when the system under study is developed at low TRL. While the simplified LCA helps to identify the most important life cycle stages and processes, the full LCA for high TRL projects are part of a more complex and interactive process which incorporates the refinement of data collection when the maturity of the innovation increases. Both tiered LCAs, simplified and full LCA, essentially follows the recommendations provided by PEF, (i.e. the definition of functional units). Therefore, when contextualising the environmental assessment of bioprocesses in an innovation project, the SSBD is strongly recommended as a reference framework, as it guides for an interactive process along the design steps.

2.3 Modelling considerations

2.3.1 Consequential vs Attributional

Two main modelling principles are used in LCA: attributional and consequential. Attributional modelling principle is intended to provide a static representation of average conditions (excluding market-mediated effects)[2], and the consequential modelling aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy[3].

Table 2 Differences between the 2 main LCA modelling principles[3]

ATTRIBUTIONAL LCA (A-LCA)	CONSEQUENTIAL LCA (C-LCA)
Evaluation of potential environmental impacts of a system over its life cycle.	Evaluation of impacts considering consequences that a decision has on other systems, in the background and outside the boundaries.
It uses historical, average, measurable data of known/know-able uncertainty It includes all processes identified as relevant contributors to the system being studied. The analysed system is modelled as it is.	The modelling is driven by market-mechanisms and potentially includes political interactions and consumer behaviour changes. It models the studied system around these consequences, as a hypothetical, generic supply-chain.

While attributional LCA question answers "*what are the environmental impacts associated with product X*", the consequential approach addresses *"what are the environmental impacts associated with a change in the consumption of product X"*[4].

Within an A-LCA data collection is allocated to the specific supply-chain, assessing the impacts at commodity-level. On the consequential approach, the assessment is done at system-level. For example, when a product is produced as a by-product, that is displacing something else. Therefore, the production is modelled considering a negative input which represents the reduction in demand. Producing more by-products will reduce the demand for the substitutes. Since no partitioning and no cut-offs are made, the consequential models maintain all mass, energy and monetary balances in every dataset and every product life cycle.

For a better interpretation of both approaches, ALCA and CLCA, this chapter also explores the example of ethanol, evaluating the methodological differences between approaches and their implications for assessing the life cycle impacts. By applying both methods to a common case study, this work aims to highlight how each framework shapes the understanding of ethanol's environmental performance, offering critical insights for decision-making when applying the LCA methodology to the BioINSouth project.

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While the ALCA provides the snapshot of its environmental footprint under current market conditions, CLCA considers broader systemic changes, capturing the indirect and market-mediated effects of increased ethanol demand, such as land-use changes or shifts in agricultural production. Figure 2 shows the comparison between the ALCA and the CLCA related to ethanol production from ethylene. The comparison shows differences between both approaches, the CLCA has a higher impact in 13 out of 16 impact categories, only acidification, particulate matter and ionising radiation have lower impact values, being this last one not just lower but even positive to the environment.

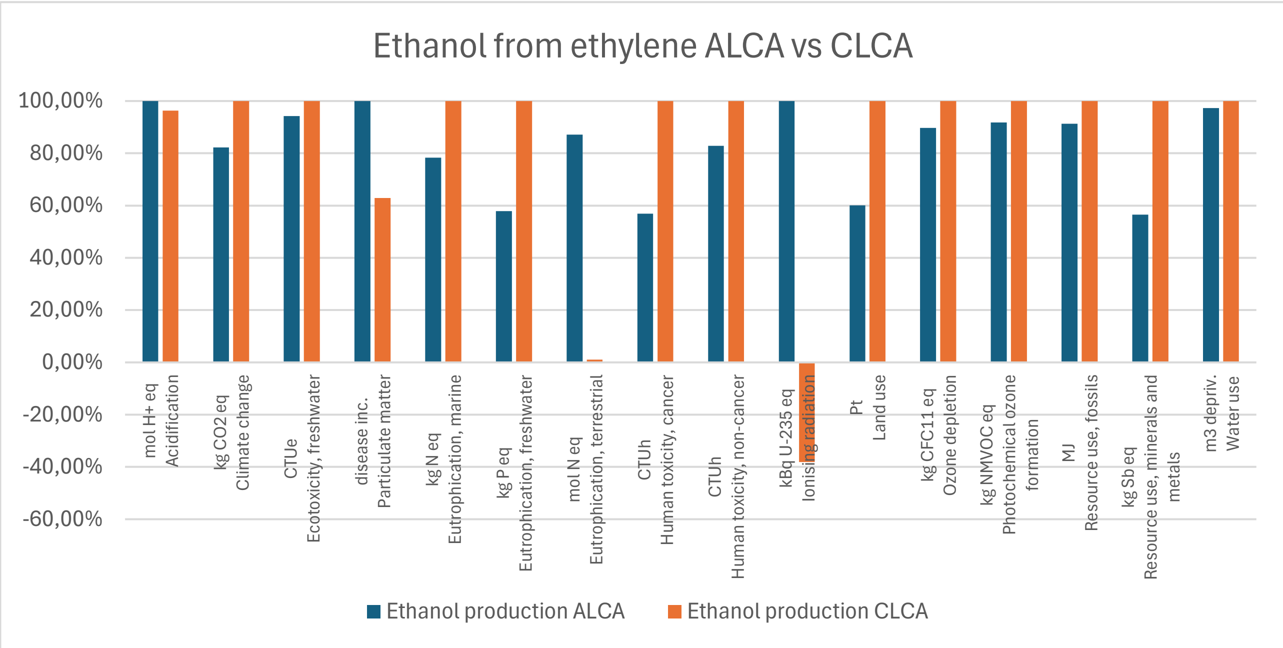

Figure 2. Comparison between Ethanol ALCA and CLCA

Focusing on the Climate change impact category, the distribution between impacts linked to Ethanol production from ethylene is shown in Figure 3, and are mainly related to the steam cracking operation to obtain the ethylene, followed by the natural gas used during the production process, and then in a lower term, the impacts are related to the sweet gas burned for the production process, the heat needed (from natural gas and other sources, the management of residual natural gas, and the naphtha production.

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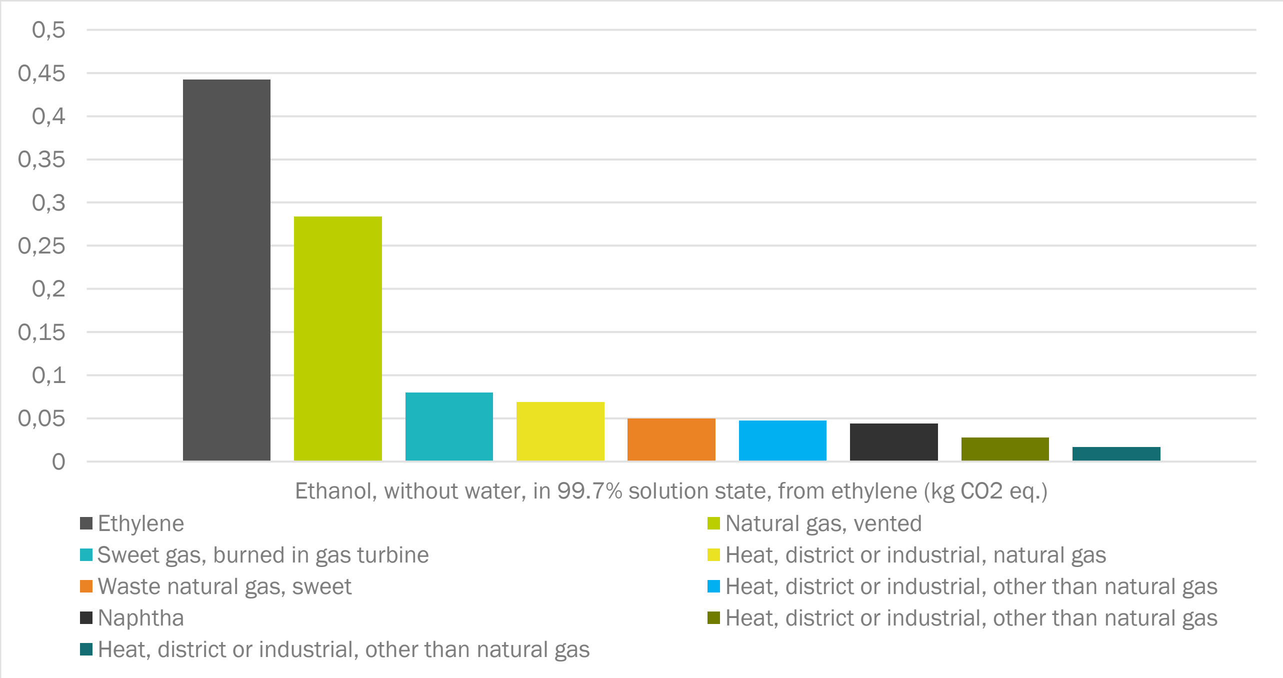

Figure 3. Climate change impact category Attributional LCA of Ethanol

Relevant differences are detected when looking at the same product and impact category but following the Consequential LCA approach in terms of major contributors, with the inclusion of the third major contributor, the heat from natural gas, in a power co-generation plant where, in many cases, marginal heat supply is met by this source and it has a higher carbon intensity than the average heat sources in ALCA (which usually include a mix of renewables and other sources). Other minor additional contributions that increase the Climate change indicator are related to other heat sources (with no traceability), and benefits into the climate change indicator are detected mainly due to the electricity generated from the natural gas and refinery gas as outcome, together with the hydrogen production avoided due to the steam methane reforming. Despite the avoided impacts represented as negative values in Figure 4, the balance between both approaches (ALCA and CLCA) shows a higher impact related to the consequential LCA of Ethanol produced from ethylene when looking at the Climate change indicator.

When looking at the Resource use, minerals and metals impact category, it is difficult to have a clear interpretation of the results. As can be seen in Figure 2, the impact is even higher following the CLCA when compared with the ALCA, but in this case the increased impact is related directly to the emissions from Tellurium extraction, linked to the copper mine operation. Even though the source of the increased impact in the Resource use, mineral and metal impact category is identified, there is no specific explanation when analysed.

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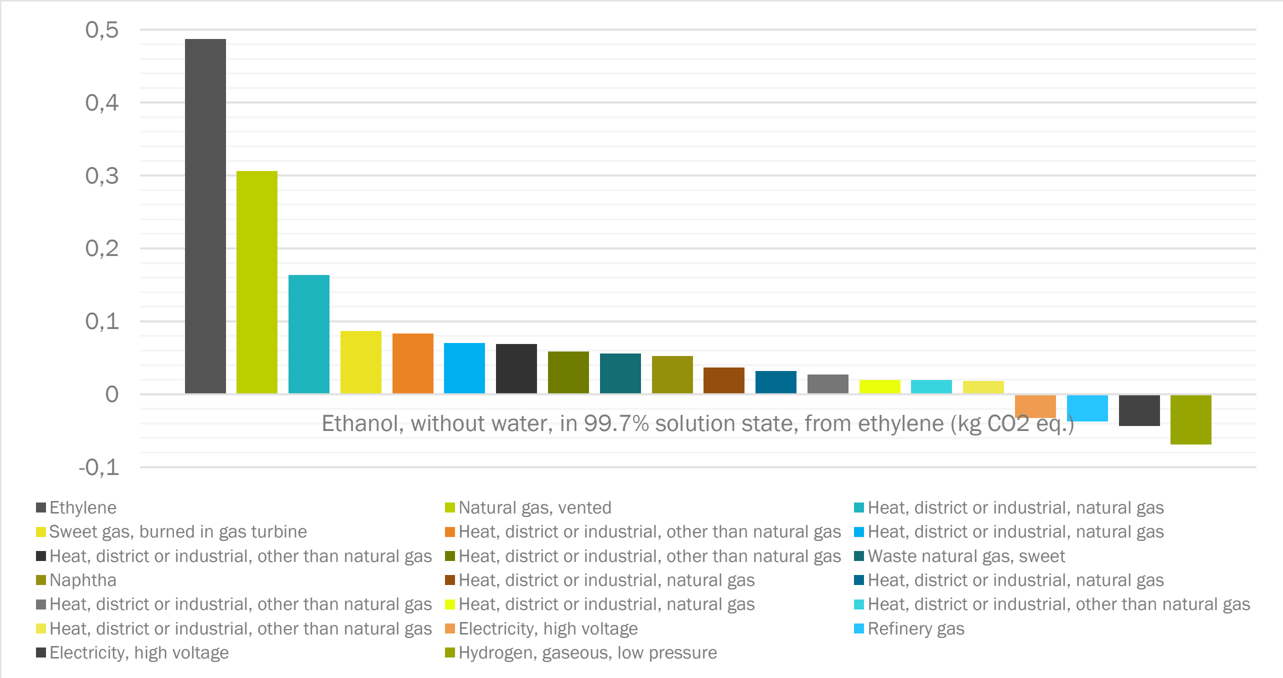

Figure 4. Climate change impact category Consequential LCA of Ethanol

Regulatory frameworks have been usually evaluated under an attributional and simplified LCA Approach[3]. However, to assess the impact of policy choices, LCA should address the impacts on a broad range of risk, representing the situation across scales and sector affected directly or indirectly by the policy. This is part of the studies relying on Integrated Assessment Models (IAMs), with a significant high level of complexity in terms of modelling and high uncertainties. Based on this, industry initiatives that aim to standardize LCA are inclined towards attributional LCA. PEF or EPD frameworks are industry-led standardisation initiatives more tended to develop attributional LCA rather than consequential, since less uncertainly is perceived[5]. In this sense, PEF initiative may not be reflecting constraints thus not addressing challenges within the production systems which demand for constrained bioresources[6].

PEF initiative suggests attributional approaches that allow a simpler interpretation of the context of product environmental footprints. Together with this, the wide variety of value chains covered by BioINSouth does not make it feasible to study cascading effects and constraints for each biomass flow. Therefore, the LCA framework developed within the project focuses on attributional LCA, but we recognise that consequential LCA increases the robustness of the studies and the incorporation of consequential thinking into ACLA would be beneficial (Figure 5). For example, ALCA study that does not give the answer whether the replacement is likely to happen, and it will not define in which quantities such replacement may happen but a study that provides red flags that will need to be monitored and managed carefully in case a policy to increase the demand of a certain bioproduct[3].

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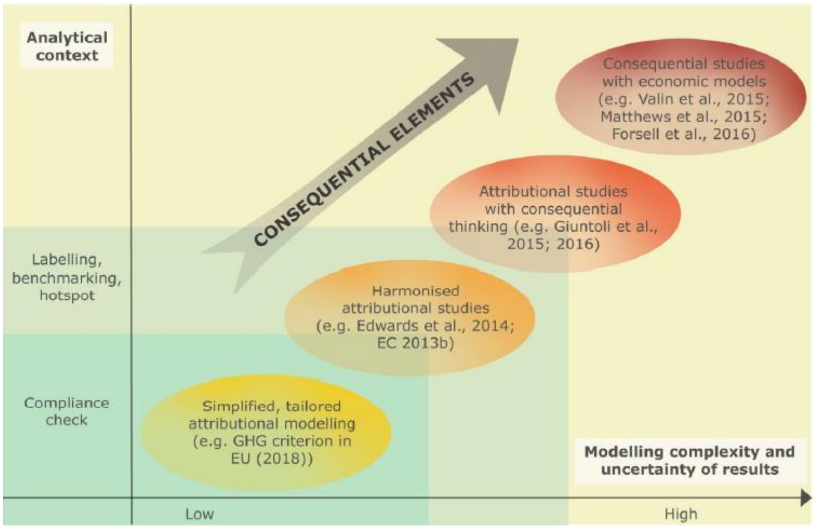

Figure 5 LCA studies used for policy support and LCA methodology implementation in EU policy, classified according to analytical context and modelling complexity (source[3])

2.3.2 Modelling End of life scenarios

Within ALCA, cut-off approach considers that the recycled product is made from burden-free feedstock and burdens of the recycling activities are allocated to the recycled product. It is a frequently used approach since it is easy to communicate. This model allocates burdens at the point where a product is sold and applies a cut-off at the point the recyclable material leaves the product system[2].

On the other hand, the substitution approach used in ALCA, also named “EoL recycling approach” does not give any credit to the recycled product, but to the producer of the recycled material. The primary products have credit since they avoid future primary production. When substitution is applied in an LCA that includes the main product of the biorefinery, the environmental burden is calculated as the emissions from the biorefinery minus the avoided emissions from the avoided production of the products displaced by the biorefinery co-products[7]. Within the circularity indicator within the PEF initiative, a 50:50 approach is taken (see Figure 6), where the burdens and credits from recycling are shared equally between the primary and recycled [8]

2 https://pre-sustainability.com/articles/finding-your-way-in-allocation-methods-multifunctional-processes-recycling/

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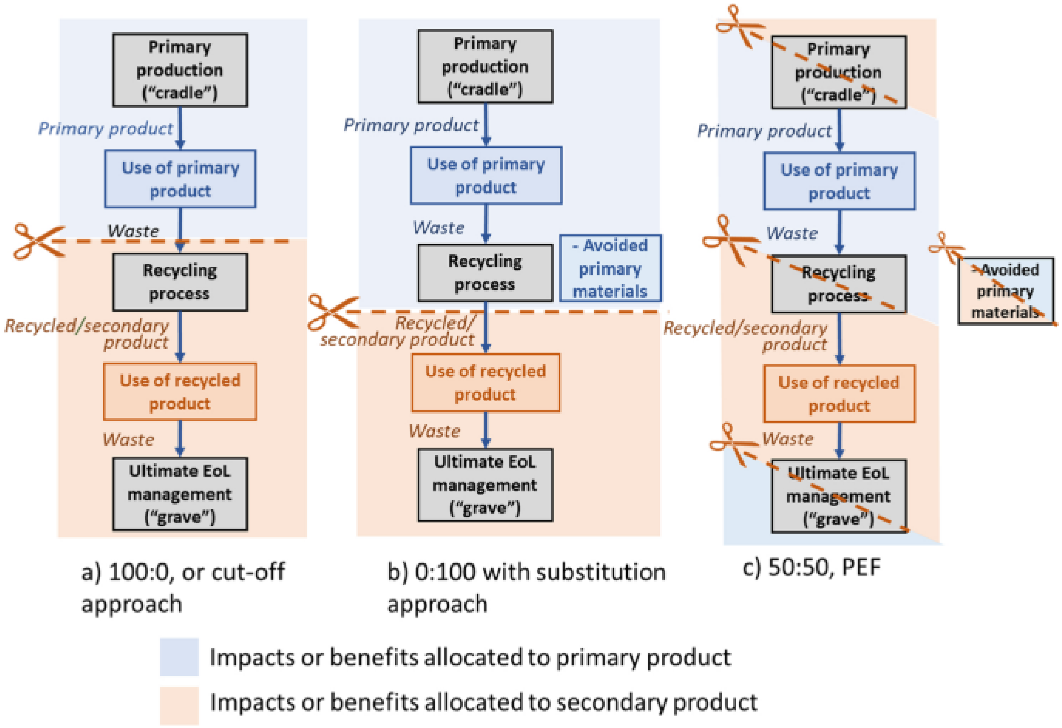

Figure 6 Common approaches of Allocation LCA (source [8]):

Applied to the bioeconomy, and more specifically to the BioINSouth context, biomass recycling is considered when waste streams are treated to produce secondary materials. Biorefineries are part of the value chain addressed in the project, so the burdens of recycling should be part of the scope, as different recycling or treatment processes would determine the environmental footprint of the final products. As part of the BioINSouth HUBs strategies, it expected that they will select the most promising biomass value chains, considering, among other aspects, the environmental profile of the existing alternatives of biomass conversions.

2.3.3 Prospective LCA

Prospective LCA extends the traditional LCA framework to explore potential environmental impacts of future products, technologies, or scenarios. It is particularly useful for assessing emerging technologies or strategies under development, where conventional LCA may not capture the dynamic nature of technological change, market evolution, and policy interventions. Within this context, the structure and data requirements of Prospective LCA closely align with those articulated in the PEF methodology.

In accordance with the PEF methodology, the life cycle model of a product or service is typically divided into foreground and background systems. The foreground system comprises the processes that are under the direct influence or control of the LCA practitioners conducting the study. These processes include foreground elementary flows, which represent exchanges of material and energy directly related to the product system, as well as emissions to the environment and resource use that can be attributed to specific process activities. In Prospective LCA, foreground processes often reflect emerging technologies or innovative interventions. These may be characterized by a higher degree of uncertainty due to limited empirical data, reliance on lab-scale measurements, pilot data, or modelling projections.

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In one hand, to ensure consistency with the methodology, Prospective LCA enhance the use of company-specific datasets for modelling the foreground system, as it is recommended by the PEF methodology guidelines. These datasets provide specific product information, that reflect actual or expected performance of the system in terms of characteristics, operational parameters, and environmental profiles of the new technologies or practices that are being assessed. The data accuracy will determine the relevance and accuracy of the assessment results.

On the other hand, the background system includes processes and activities that are related to the study, the implications affect directly to the studied process, but impacts are defined upstream in the value chain and are needed to complete the inputs of the Life Cycle model. In the PEF methodology, background processes usually are defined by generic data sourced from high quality databases like Ecoinvent. However, in prospective LCA, the background system may also be modified to reflect future scenarios, in this can include projections related to changes in energy mixes, markets trends, policy guidelines, that are important when assessing the future environmental performance of innovative technologies.

2.3.3.1 Premise

The *premise* tool is an open-source Python library designed to integrate prospective scenarios of socioeconomic and technological development into LCA databases, thereby supporting the implementation of Prospective LCA[9]. Its main purpose is to enable LCA practitioners to assess the future environmental performance of products and technologies in alignment with forward-looking narratives such as those defined in Integrated Assessment Models (IAMs). By coupling these scenarios with LCI databases, *premise* facilitates more realistic and policy-relevant environmental evaluations of emerging technologies within dynamic socio-technical contexts.

At its core, *premise* systematically modifies background processes in LCI databases (primarily Ecoinvent) to reflect projections of future energy systems, material flows, and industrial transformations. It integrates scenario data from IAMs, such as IMAGE, REMIND, and TIAM-UCL, covering key sectors like energy production, transportation, cement and steel production, and waste management. This integration adjusts the underlying inventories to represent future states in terms of energy mix decarbonization, efficiency improvements, and technology deployment pathways.

For foreground processes, *premise* provides the capacity to adapt to projected changes in upstream supply chains, ensuring consistency between specific emerging technologies under evaluation and their evolving background conditions. Although *premise* does not generate company-specific datasets, its modification of the background system ensures that any foreground elementary flows introduced by practitioners are situated within a prospective context.

In the context of BioINSouth project, the environmental assessment of bioeconomy (products and processes) will be essentially based on PEF methodology, which does not contemplate the prospective approach.

3 LCA of bioeconomy in the context of EU projects

In the context of WP4 but also addressing the objectives of the clustering pilar of the project (WP7), BioINSouth explored the ongoing initiatives (projects) at EU level, where the environmental assessment of the bioeconomy was a backbone of their work plans. After gathering all the initiatives identified by the

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BioINSouth partners, their objectives and programs were evaluated to identify those projects where new LCA methodologies were being developed or projects developing specific tools for monitoring the environmental profile of bio-based industries. As result, 7 European projects were contacted, for which the main objectives and LCA actions are summarized in Table 3

Table 3 Prioritization of EU projects to activate clustering activities regarding LCA approaches

Project	Project objective	LCA actions	Sectors covered	Countries
BIORECER	To promote the use of biological feedstocks as raw materials.	Environmental impact and circularity assessment methodologies for bio-based feedstock	Fishery Urban Biowaste Agriculture Forestry	Spain Italy Greece Sweden
BIOTRANSFORM	To provide a development plan to accelerate the transition to circular bio-based systems.	Environmental assessment	Forestry Agri-food Lignite and minerals Chemicals	Austria, Czech Republic, Finland, Germany, Greece, and Spain
C4B	To develop and promote innovative and sustainable business models.	Environmental assessment	Agriculture Forestry	Germany Italy Greece Sweden Austria Switzerland
CALIMERO	To create a common framework to improve existing LCA methodologies.	Improve existing sustainability assessment	Construction Woodworking Textile Pulp & paper Biochemicals	France Belgium Spain Sweden
ESCIB	To develop a new methodology for bio-based systems sustainability assessment.	Consequential LCA Spatial-temporal land use models	Packaging Textiles Chemicals Construction	Portugal, among others
LCA4BIO	To develop methodologies for environmental assessment and circularity.	Environmental assessment Prospective LCA	Woodworking Construction Chemicals Textile	Portugal Spain
SUSTRACK	To help policymakers to develop sustainable pathways to implement circular biobased systems.	Review of assessment methods, tools, models, indicators and data	Construction Textile Chemical Plastic Energy	Italy, France, Germany, Belgium, among others

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In order to encourage such synergies, a questionnaire was developed and distributed to the prioritized EU projects to gather feedback that could be the basis for the elaboration of the methodological approach in BioINSouth. The questionnaire was designed by addressing the main challenges and barriers that are typically identified in literature [5,10], covering the following areas:

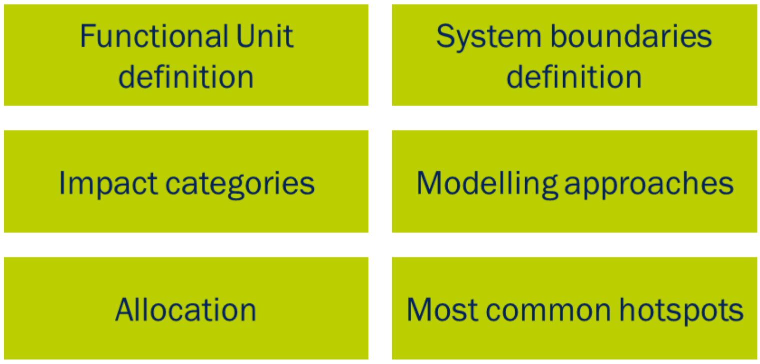

Figure 7 Topics within questionnaire

The full questionnaire is included in Annex 1. The questions regarding circularity issues are presented in the context of Deliverable 4.1 regarding the circularity monitoring system.

1. Which functional unit would be more suitable for LCA studies of bioeconomy systems?

Five of seven project answered that the functional unit (FU) that was more appropriate for LCA studies of bioeconomy systems should be based on the outputs. The two remaining considered that no option was suitable and specified what they considered the best in question 2. No one chose feedstock-based nor land-based.

2. Please specify which functional unit would be more suitable for LCA studies of bioeconomy systems.

The two projects who selected the option *Other* in the previous question, stated that the selection of the FU relied on the approach because sometimes there was a need to highlight how a certain feedstock was utilised whilst other times the focus was on the final bio-product. They also claimed that "it depends on the research question and if there is any aim of comparing results".

3. Which system boundaries definition would be more appropriate for bioeconomy systems?

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Two projects chose cradle-to-gate as the most appropriate system boundaries definition for bioeconomy systems, while only one project selected cradle-to-gate approach. The rest of the projects considered that "it depends" (more elaboration in the next question)

4. Please specify which system boundaries would be more appropriate for LCA on bioeconomy systems.

Two of the projects consulted stated that the most suitable approach would be cradle to cradle (circular economy). One considered that cradle-to-grave was ideal when the use phase and end-of-life were known, if not cradle-to-gate was more applicable. Last answer stated that it depended on what it was needed to contemplate, for example where the system started or what processes and actors were considered.

5. Which impact categories should be included as part of the impact assessment of bioeconomy systems?

"GHG emissions, biodiversity, land use, social aspects".
"Climate change, water depletion, fossil fuel depletion, land use, ozone depletion, ecotoxicity".
"Climate change, land use, water scarcity, fossil and mineral depletion, toxicity, eutrophication".
"Global warming potential, particular matter, human toxicity (non-cancer effects, cancer effects), photochemical ozone formation, eutrophication, acidification, ecotoxicity for aquatic fresh water, intensity of fossil fuel use, resource depletion (mineral, fossil), water consumption, soil quality and biodiversity use".
"In order to establish a standard procedure to enable comparability, at least the 16 impact categories of the PEF method should be considered2.
"Ideally this should be decided within a materiality analysis including various stakeholders. It should be as comprehensive as possible but consider data limitations of the specific case. Climate change and biodiversity are the most pressing issue of our time, so those should be covered somehow. However, the methodology for assessing impacts on biodiversity is still underdeveloped".

One person didn't answer the question.

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6. Which modelling approaches should be used on bioeconomy systems?

43 % of the total projects consulted, considered that attributional modelling approach should be used on bioeconomy system and 14 % considered the consequential was the best option, whereas 43 % conclude that it depended on other aspects, detailed in question 7.

7. Please specify which modelling approach should be used on bioeconomy systems.

The two projects which selected the option *It depends* in the previous question, considered that the attributional approach should be mainly used in LCA as the minimum requirement, but whenever possible it should be complemented by consequential. The project did not specify what it depended on.

8. Which system modelling should be used to allocate burdens between products produced within biorefineries if system expansion is not possible?

Mass and economic allocation tied results with the 43 % of the total answers as the best system modelling to allocate burdens between products produced. Only one project considered that it would be more suitable to use energy allocation.

9. The selection of the best allocation method for bioeconomy systems should be based on:

None answer was provided to question 9; so, there was no recommendations on the best allocation method for bioeconomy systems.

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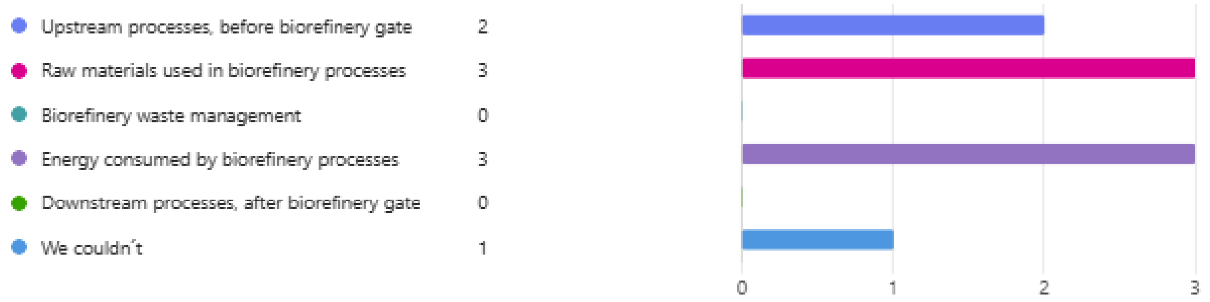
10. For residue feedstock which of the following approaches do you consider within LCA of bioeconomy systems?

For residue feedstock, three projects did not consider any upstream burden allocation within LCA of bioeconomy systems while three others contemplated partial burdens from upstream processes. One project stated that it relied on additional considerations, described in question 11.

11. Please specify main aspects that should be considered when allocating the environmental burdens of residual feedstocks?

It was considered that the type of feedstock was relevant and should be featured when allocating the environmental burdens of residual feedstocks.

12. Could you conclude where the main hotspot is usually identified in LCA studies applied to bioeconomy processes??



Regarding LCA studies applied to bioeconomy processes, raw materials used and energy consumption in biorefinery processes usually were identified as the main hotspots. Also, upstream processes, those before biorefinery gate, were also considered relevant in LCA. One project could not identify the main hotspot.

13. What is the main challenge for the development of territorial LCAs?

There were few aspects that interviewee had in common when identifying the main challenges for territorial LCAs: the lack of reliable and high-quality data, together with the challenges of obtaining accurate information, which make it difficult to conduct proper inventory analysis. Additionally, the projects highlighted that data requirements were much higher in territorial than conventional LCA and comparability between regions were difficult due to the complexity and characteristic of each territory.

Based on the outputs received, key highlights were gathered regarding the best strategy to implement LCA studies in bioeconomy. Next chapter compiles the application of this recommendation for the evaluation of the environmental impacts of 9 different bioprocesses.

4 The environmental performance of the bioeconomy

This section addresses the environmental performance analysis of different bioprocesses based on the literature research. In total, 51 scientific papers which addressed the impacts of biomass transformation were identified. After screening the goal and scope of each study, only the studies providing inventory data was selected. Aiming to achieve a good representation of the most promising biomasses, 10 simplified LCA was finally carried out based on literature data.

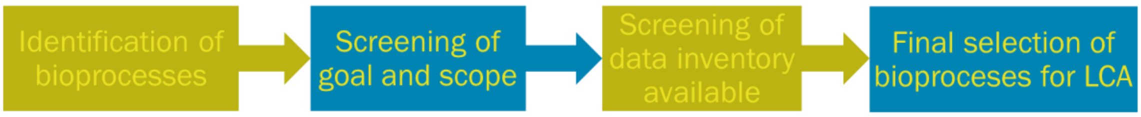


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Figure 8 Methodological approach for the selection of simplified LCA of bioeconomy processes

4.1 Environmental footprint of bioprocesses

The reviewed studies were based on 4 different feedstock types: agricultural biomass, industrial waste, forest biomass and aquaculture biomass, which were classified depending on the origin of the raw material supplied.

Table 4 Literature review

Sector	Feedstock	Outputs	Reference	Year
Agricultural biomass	Almond shells	Oligosaccharides, lignin, cellulose nanocrystals	Sillero et al.	2021
	Pomegranate peels	Ellagic acid, lignin, pectin	Shinde et al.	2020
	Citrus peel waste	Ethanol, limonene, methanol	Joglekar et al.	2019
	Rice straw	Ethanol, food grade CO_2, methanol, silica, inorganics	Parajuli et al.	2019
	Grape marc	Vermicompost, Polyphenols-rich extract, seed oil, brandy	Cortés et al.	2020
	Wheat straw	Ethanol	Sreekumar et al.	2017

Sector	Feedstock	Outputs	Reference	Year
Industrial waste	Barley straw & brewers spent grains	Xylooligosaccharides, ethanol	González-García et al.	2018
Forest biomass	Poplar biomass	Acetic acid, lignin	Budsberg et al.	2020
	Alfalfa biomass	Lactic acid, feed protein, fodder silage	Parajuli et al.	2017
Aquaculture biomass	Microalgae biomass	Polysaccharides	Saadia et al.	2017

The studies considered cradle-to-gate systems. Manufacturing and transport of raw materials were included within the system boundaries, while the biobased feedstock was interpreted as free of environmental impacts. Moreover, the LCAs included energy production and both, emissions and waste treatment

The functional unit was based on feedstock, but results were presented not only for inputs but also for output based. The study was carried out with data from the literature, that were used to complete the inventory phase, finally SIMAPRO 9.6 software were used to evaluate the impacts. The impacts were weighted and normalised in line with PEF recommendations, as well as carried out the damage assessment distribution, to later recognize the main hotspots of each process.

Whenever the biorefineries under review had various value-added chemicals as by-products, a proportional distribution of the total system impacts was made by using impact allocation. To do so, two approaches were taken to distribute more fairly the impacts:

- Mass allocation: based on the mass quantities of the different products produced.
- Economic allocation: based on the total revenue generated by the different products.

4.1.1 Grape marc valorisation

Cortés et al.[11] analysed the valorisation route for grape marc valorisation to establish its environmental impacts so as to identify the environmental hotspots of the process. The conversion of grape marc as feedstock, produces different compounds such as vermicompost (78 %), polyphenols-rich extract (1 %), seed oil (2 %) and brandy (19 %). According to Cortés et al.[11], the selling prices of this substances are 1.2 €/kg, 146.67 €/kg, 300 €/kg and 8.57 €/kg, respectively.

Table 5. Cortés et al.[11] Grape marc valorisation route.

Biomass input
Grape Marc
Output
Vermicompost, Polyphenols-rich extract, seed oil, brandy
Geography area
Spain
Paper

Unraveling the environmental impacts of bioactive compounds and organic amendment from grape marc
Author
Antonio Cortés, Maria Teresa Moreira, Jorge Domínguez, Marta Lores, Gumersindo Feijoo
Year
2020
Functional Unit
1 ton of grape marc waste transported from winery for distillation and filtering, to after mill and press part of the seed to obtain oil, process part of the seed to obtain polyphenols, and vermicompost the exhausted grape marc to produce vermicompost.
Reference flow
1000 kg of grape marc waste

Under a cradle to gate perspective, the environmental impacts related to 1 ton of grape marc valorisation are shown in Table 6, which include impacts of raw materials extraction and processing. Table 7 and Table 8 show the allocation basing the impact interpretation on the output products.

Table 6. Damage assessment of grape marc valorisation (based on data from Cortés et al.[11]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	mol H+ eq	2.42E+00	2.42E-03
Climate change	kg CO2 eq	4.75E+02	4.75E-01
Ecotoxicity, freshwater	CTUe	2.21E+03	2.21E+00
Particulate matter	disease inc.	2.31E-05	2.31E-08
Eutrophication, marine	kg N eq	3.64E-01	3.64E-04
Eutrophication, freshwater	kg P eq	1.14E-02	1.14E-05
Eutrophication, terrestrial	mol N eq	7.49E+00	7.49E-03
Human toxicity, cancer	CTUh	1.44E-06	1.44E-09
Human toxicity, non-cancer	CTUh	2.57E-06	2.57E-09
Ionising radiation	kBq U-235 eq	1.21E+01	1.21E-02
Land use	Pt	1.11E+03	1.11E+00
Ozone depletion	kg CFC11 eq	1.41E-05	1.41E-08
Photochemical ozone formation	kg NMVOC eq	1.39E+00	1.39E-03
Resource use, fossils	MJ	6.58E+03	6.58E+00
Resource use, minerals and metals	kg Sb eq	7.47E-04	7.47E-07
Water use	m3 depriv.	5.17E+02	5.17E-01

Table 7. Mass allocation from Damage assessment (based on data from Cortés et al.[11]).

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Damage category	Unit	Mass Allocation			
		Vermicompost	Polyphenols-rich extract	Seed oil	Brandy
AC	mol H+ eq	1.90E+00	1.92E-02	3.79E-02	4.65E-01
CC	kg CO2 eq	3.72E+02	3.77E+00	7.43E+00	9.13E+01
ECOTOX	CTUe	1.73E+03	1.75E+01	3.46E+01	4.24E+02
PM	disease inc.	1.81E-05	1.83E-07	3.61E-07	4.44E-06
MEU	kg N eq	2.86E-01	2.89E-03	5.70E-03	7.00E-02
FEU	kg P eq	8.94E-03	9.05E-05	1.78E-04	2.19E-03
TEU	mol N eq	5.88E+00	5.95E-02	1.17E-01	1.44E+00
HTOC_c	CTUh	1.13E-06	1.14E-08	2.25E-08	2.77E-07
HTOC_nc	CTUh	2.02E-06	2.04E-08	4.02E-08	4.94E-07
IR	kBq U-235 eq	9.49E+00	9.61E-02	1.89E-01	2.33E+00
LU	Pt	8.71E+02	8.82E+00	1.74E+01	2.13E+02
ODP	kg CFC11 eq	1.11E-05	1.12E-07	2.21E-07	2.71E-06
POF	kg NMVOC eq	1.09E+00	1.10E-02	2.17E-02	2.66E-01
FRD	MJ	5.16E+03	5.23E+01	1.03E+02	1.27E+03
MRD	kg Sb eq	5.86E-04	5.93E-06	1.17E-05	1.44E-04
WU	m3 depriv.	4.05E+02	4.11E+00	8.09E+00	9.94E+01

Table 8. Economic allocation from Damage assessment (based on data from Cortés et al.[11]).

Damage category	Unit	Economic Allocation			
		Vermicompost	Polyphenols-rich extract	Seed oil	Brandy
AC	mol H+ eq	2.69E-01	3.36E-01	1.34E+00	4.72E-01
CC	kg CO2 eq	5.28E+01	6.58E+01	2.64E+02	9.25E+01
ECOTOX	CTUe	2.46E+02	3.06E+02	1.23E+03	4.30E+02
PM	disease inc.	2.57E-06	3.20E-06	1.28E-05	4.50E-06
MEU	kg N eq	4.05E-02	5.05E-02	2.02E-01	7.10E-02
FEU	kg P eq	1.27E-03	1.58E-03	6.33E-03	2.22E-03
TEU	mol N eq	8.34E-01	1.04E+00	4.16E+00	1.46E+00
HTOC_c	CTUh	1.60E-07	2.00E-07	8.00E-07	2.81E-07
HTOC_nc	CTUh	2.86E-07	3.57E-07	1.43E-06	5.01E-07
IR	kBq U-235 eq	1.35E+00	1.68E+00	6.72E+00	2.36E+00
LU	Pt	1.24E+02	1.54E+02	6.17E+02	2.16E+02
ODP	kg CFC11 eq	1.57E-06	1.96E-06	7.83E-06	2.75E-06
POF	kg NMVOC eq	1.54E-01	1.92E-01	7.69E-01	2.70E-01
FRD	MJ	7.32E+02	9.13E+02	3.65E+03	1.28E+03
MRD	kg Sb eq	8.31E-05	1.04E-04	4.15E-04	1.46E-04
WU	m3 depriv.	5.75E+01	7.17E+01	2.87E+02	1.01E+02

As shown in Figure 9m, from a wider range of environmental impacts, the most relevant impact categories were selected from those described in section 2.1. Thus, the more relevant impact categories from Cortés et al.[11] were climate change (33.38 %), resource use (fossils) (21.24 %), water use (10.29 %), particulate matter (8.76 %) and acidification (6.81 %), since the total number of these indicators represents 80.47 % of the total environmental impacts.

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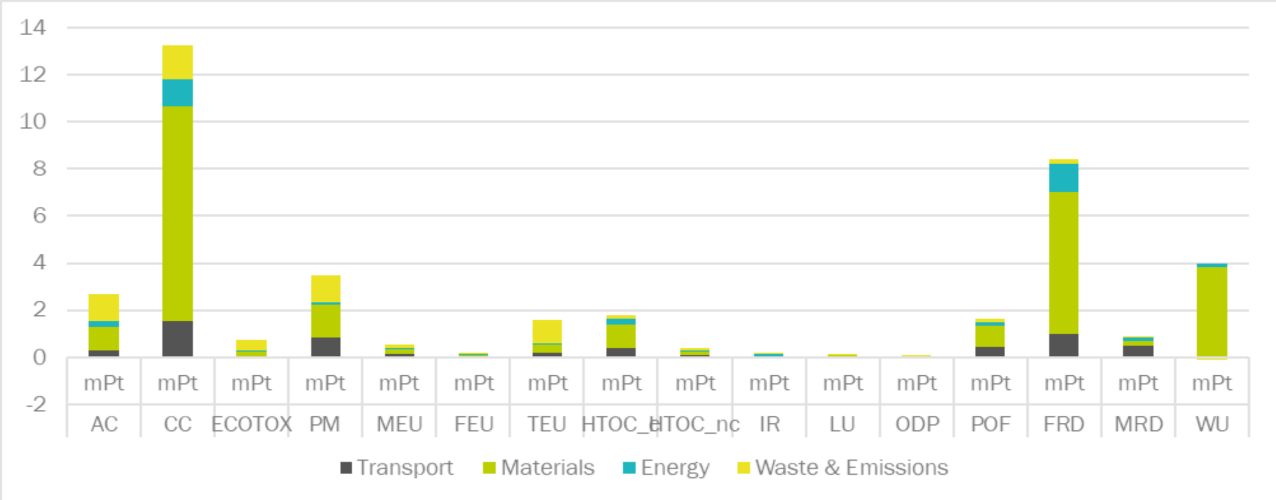

Figure 9. Grape marc valorisation impact category relevance (based on data from Cortés et al.[11])

As shown in Figure 10, the most relevant flows for climate change impact category were raw materials and waste flows; for acidification, the major contribution was related to the materials and waste flows; resource use (fossils) burdens come directly from materials and energy flows; the particulate matter had major contributions from materials, waste and transport; and finally, the water use indicator has its all major contribution from materials flow.

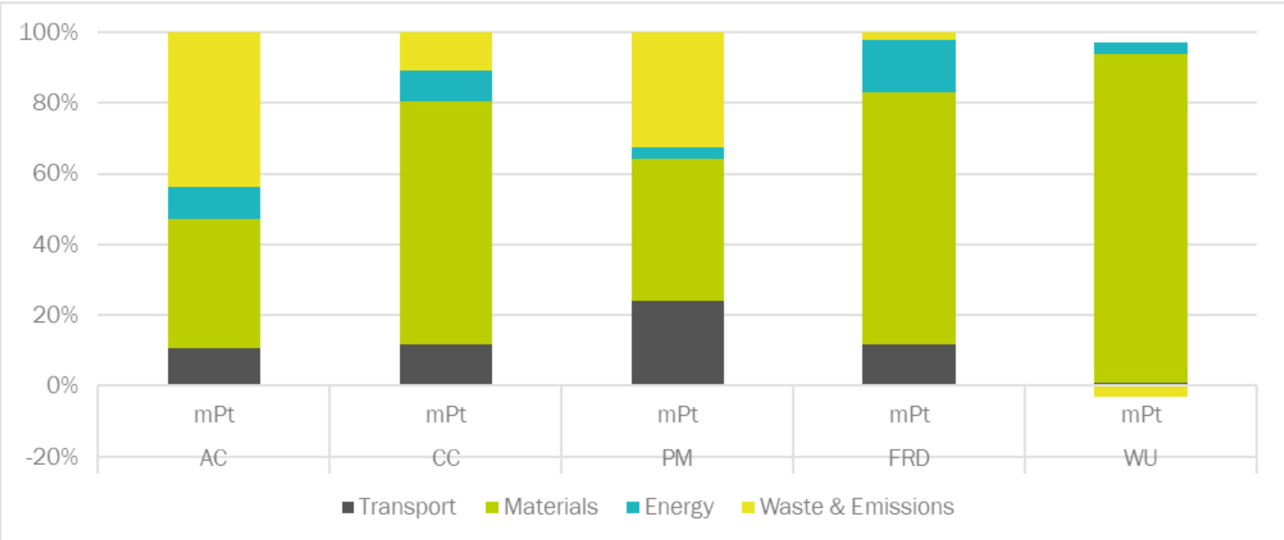

Figure 10. Environmental impacts weighted distribution (based on data from Cortés et al.[11])

As shown below, when looking in detail at each process related to the life cycle stages of the system, raw materials had the largest contribution due to the steam required for the production process for almost all relevant impact categories, except for the WU indicator, where the largest contribution came from the cooling water demand.

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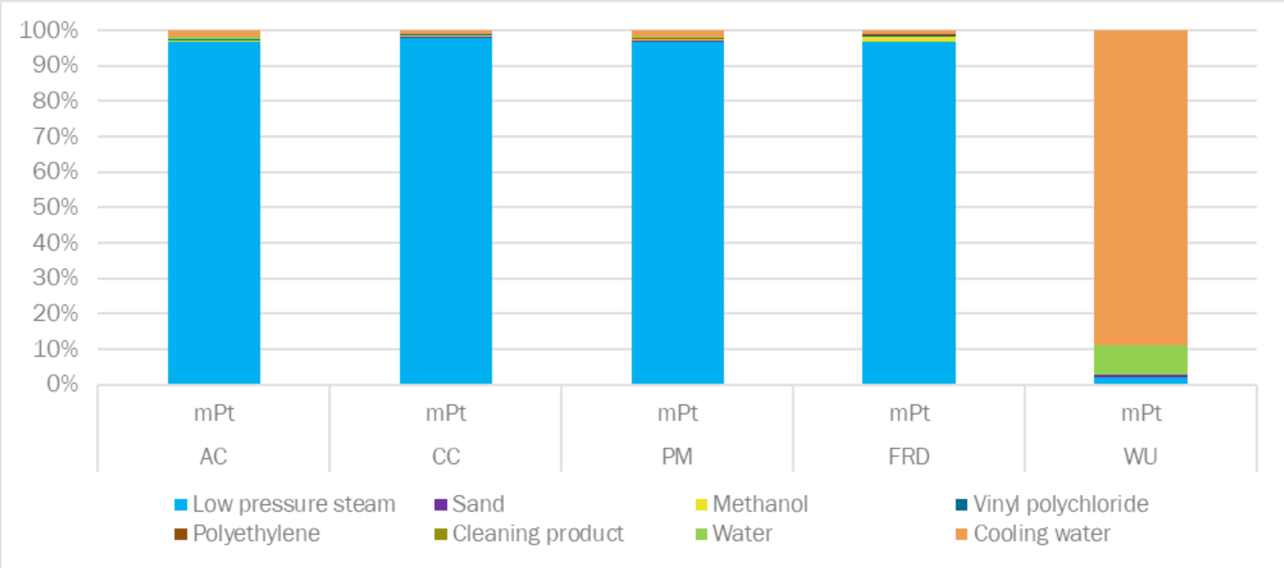

Figure 11. Materials flow weighted impact distribution (based on data from Cortés et al.[11])

In Figure 12, transportation stage weighted impact distribution is shown. The major contribution to this stage was due to the car transportation, bringing the exhausted grape marc from distillation sub-process to vermicomposting and seed oil extraction sub-processes.

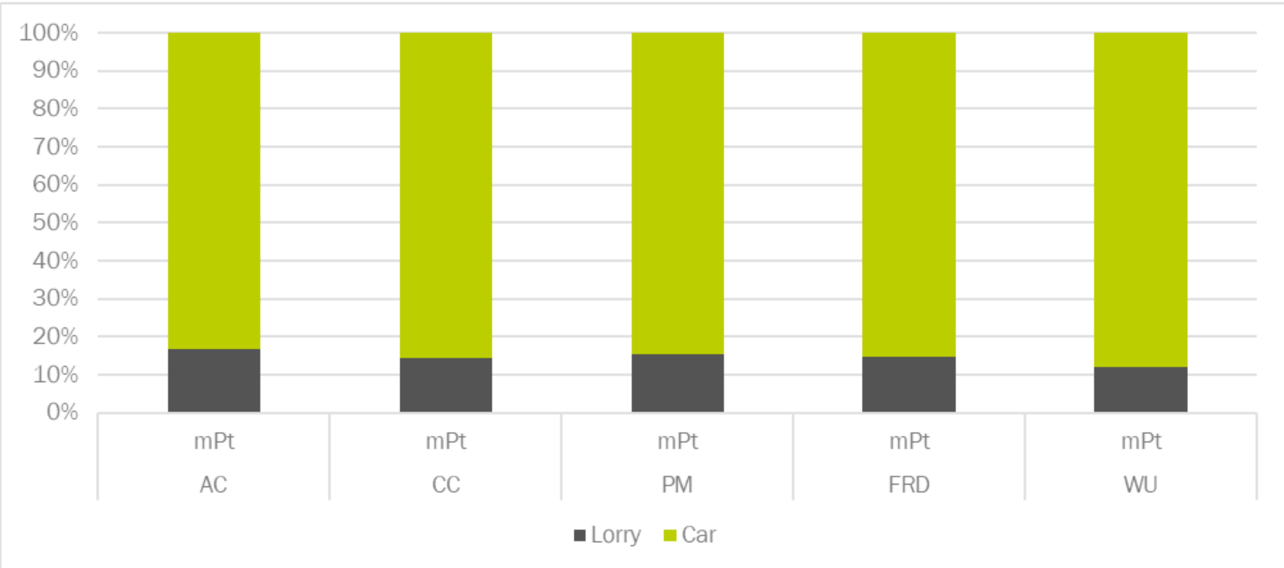

Figure 12. Transportation flow weighted impact distribution (based on data from Cortés et al.[11])

4.1.2 Citrus peel waste valorisation

Joglekar et al.[12] explored the use of fruit peel waste for producing various value-added products. In this specific case, they analysed the route of a citrus peel waste valorisation, and all the involved processes needed to obtain products such as ethanol (43 %), limonene (13.8 %) and methane (43.2 %). The prices

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these products were sourced from literature[3]: ethanol 0,6 €/kg, limonene at 9,81 €/kg and methane at 3,39 €/kg. Data for Indian market couldn't be found, so Spanish area has been considered.

Table 9. Case study of citrus peel waste valorisation based on Joglekar et al.[12]

Biomass input
Citrus peel waste
Output
Ethanol, limonene, methanol
Geography area
India
Paper
Process of fruit peel waste biorefinery: a case study of citrus waste biorefinery, its environmental impacts and recommendations
Author
Saurabh N. Joglekar, Pranav D. Pathak, Sachin A. Mandavgane, Bhaskar D. Kulkarni
Year
2019
Functional Unit
1 kg of citrus peel waste transported 100 km with a freight to a biorefinery plant, where it will be processed by hydrolysis, filtration, distillation and anaerobic digestion, in India.
Reference Flow
2500 kg of citrus peel waste

The environmental impacts related to 2.5 Ton of citrus peel waste valorisation are shown in Table 10, while the allocation of both approaches, economical and mass, are presented in Table 11.

Table 10. Damage assessment of citrus peel waste valorisation (based on data from Joglekar et al.[12]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	4.74E+00	1.90E-03
Climate change	**kg CO2 eq**	2.70E+03	1.08E+00
Ecotoxicity, freshwater	**CTUe**	2.82E+03	1.13E+00
Particulate matter	**disease inc.**	5.01E-05	2.00E-08
Eutrophication, marine	**kg N eq**	7.59E-01	3.04E-04
Eutrophication, freshwater	**kg P eq**	3.11E-02	1.24E-05
Eutrophication, terrestrial	**mol N eq**	8.39E+00	3.36E-03
Human toxicity, cancer	**CTUh**	1.56E-06	6.25E-10

[3] https://www.volza.com/p/limonene/import/

Damage category	Unit	Total	Per kg of feedstock
Human toxicity, non-cancer	**CTUh**	7.21E-06	2.89E-09
Ionising radiation	**kBq U-235 eq**	6.35E+00	2.54E-03
Land use	**Pt**	7.90E+03	3.16E+00
Ozone depletion	**kg CFC11 eq**	1.21E-05	4.83E-09
Photochemical ozone formation	**kg NMVOC eq**	3.08E+00	1.23E-03
Resource use, fossils	**MJ**	1.37E+04	5.50E+00
Resource use, minerals and metals	**kg Sb eq**	3.55E-03	1.42E-06
Water use	**m3 depriv.**	4.97E+02	1.99E-01

Table 11. Mass and economic allocation from Damage assessment (based on data from Joglekar et al.[12]).

Damage category	Unit	Mass Allocation			Economic allocation		
		Ethanol	Limonene	Methane	Ethanol	Limonene	Methane
AC	mol H+ eq	2.04E+00	6.54E-01	2.05E+00	4.22E-01	2.07E+00	2.25E+00
CC	kg CO2 eq	1.16E+03	3.72E+02	1.17E+03	2.40E+02	1.18E+03	1.28E+03
ECOTOX	CTUe	1.21E+03	3.88E+02	1.22E+03	2.51E+02	1.23E+03	1.34E+03
PM	disease inc.	2.15E-05	6.90E-06	2.16E-05	4.46E-06	2.19E-05	2.37E-05
MEU	kg N eq	3.26E-01	1.05E-01	3.28E-01	6.75E-02	3.32E-01	3.60E-01
FEU	kg P eq	1.34E-02	4.28E-03	1.34E-02	2.77E-03	1.36E-02	1.47E-02
TEU	mol N eq	3.61E+00	1.16E+00	3.63E+00	7.47E-01	3.67E+00	3.97E+00
HTOC_c	CTUh	6.72E-07	2.15E-07	6.76E-07	1.39E-07	6.83E-07	7.41E-07
HTOC_nc	CTUh	3.10E-06	9.94E-07	3.12E-06	6.42E-07	3.15E-06	3.42E-06
IR	kBq U-235 eq	2.73E+00	8.76E-01	2.75E+00	5.65E-01	2.78E+00	3.01E+00
LU	Pt	3.40E+03	1.09E+03	3.41E+03	7.03E+02	3.45E+03	3.74E+03
ODP	kg CFC11 eq	5.20E-06	1.67E-06	5.22E-06	1.08E-06	5.28E-06	5.72E-06
POF	kg NMVOC eq	1.32E+00	4.25E-01	1.33E+00	2.74E-01	1.35E+00	1.46E+00
FRD	MJ	5.91E+03	1.89E+03	5.94E+03	1.22E+03	6.01E+03	6.51E+03
MRD	kg Sb eq	1.53E-03	4.89E-04	1.53E-03	3.16E-04	1.55E-03	1.68E-03
WU	m3 depriv.	2.14E+02	6.84E+01	2.15E+02	4.42E+01	2.17E+02	2.35E+02

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The weight of the different environmental impacts categories is represented in Figure 13. The most relevant impact categories were climate change (60 %), particulate matter (14.03 %) and resource use (fossils) (6.01 %), since the total number of those indicators added up to 80.04 % of the total environmental impacts.

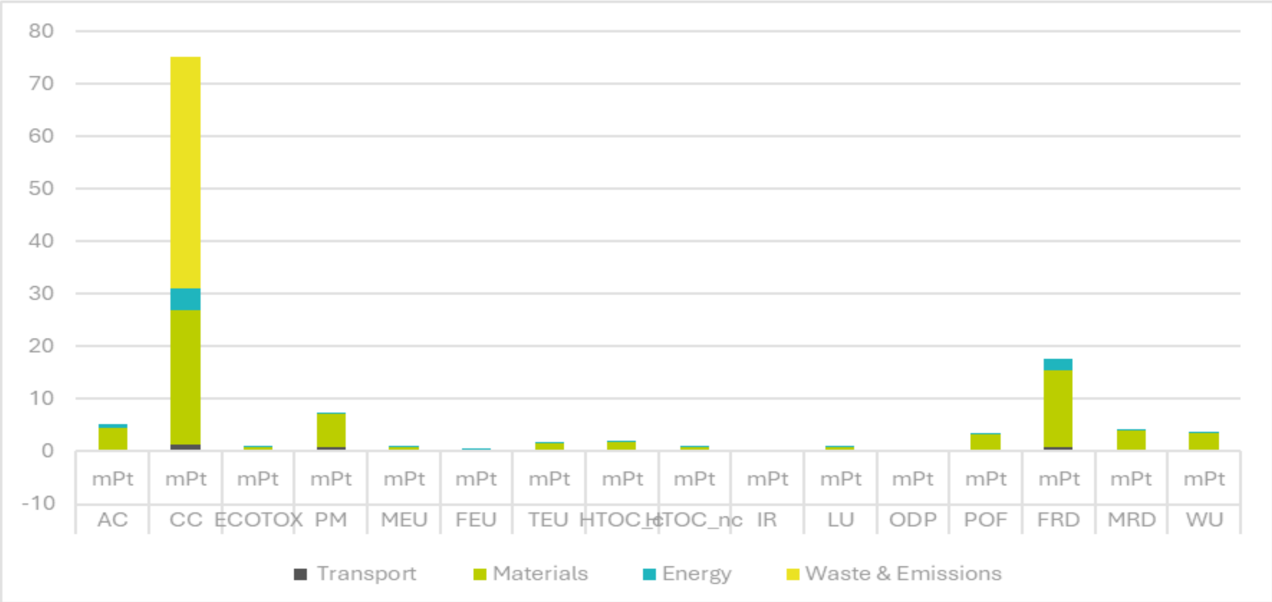

Figure 13. Citrus peel waste valorisation weighted impact category relevance (based on data from Joglekar et al.[12]).

As shown in Figure 14, regarding climate change, waste & emissions flows were the main contributors to this impact category, followed by materials, whereas for the particulate matter and resource use (fossils) indicators, the most relevant flow was the one related with materials.

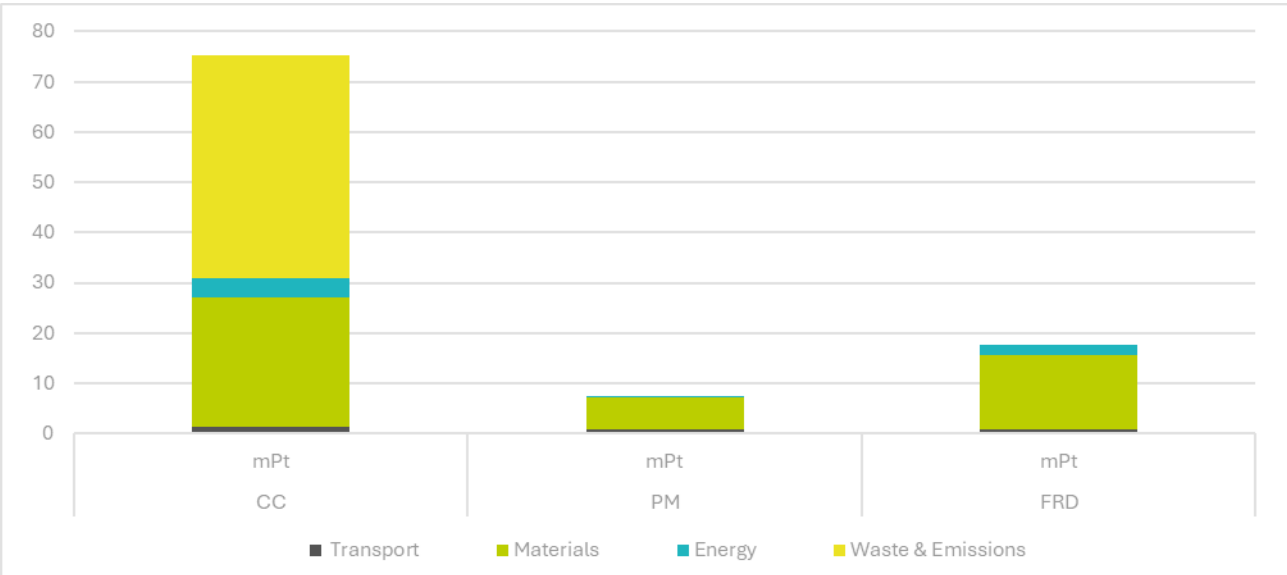

Figure 14. Environmental impacts weighted distribution (based on data from Joglekar et al.[12]).

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On one hand, (as shown in Figure 15) the great contribution of the waste and emissions flow over the climate change indicator was mostly attributed to the large amount of biogenic CO_2 emitted during the anaerobic digestion step. On the other hand, going thoroughly the materials flow, the major contribution to this flow in all the most relevant categories was associated with the steam requirement in the citrus peel waste valorisation.

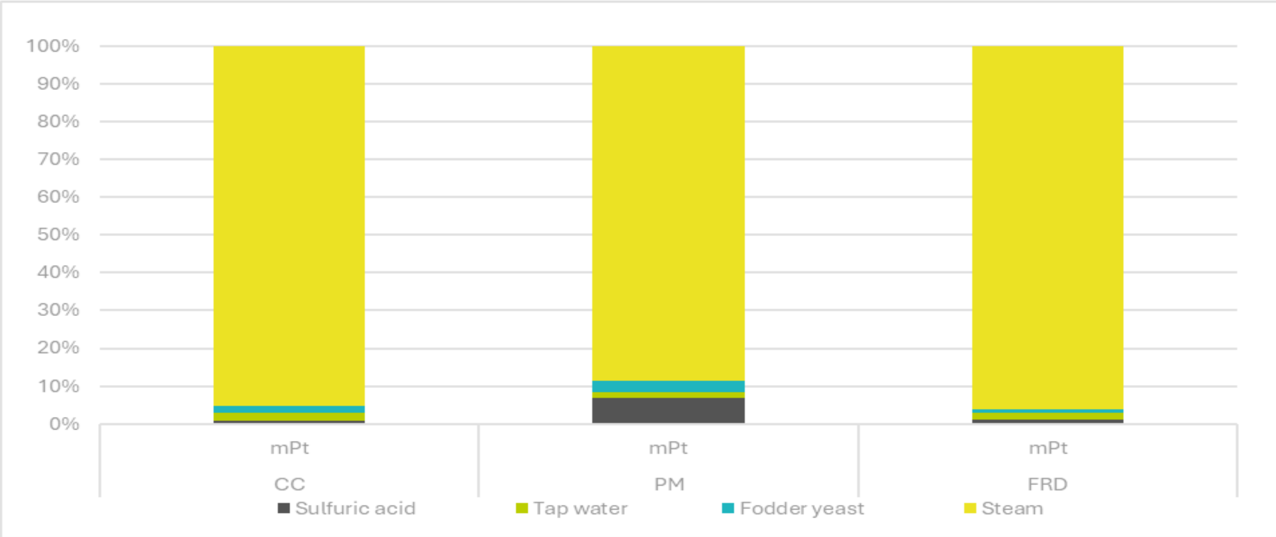

Figure 15. Materials flow impacts weighted distribution (based on data from Joglekar et al.[12]).

4.1.3 Almond shells valorisation

Sillero et al.[13] examined the environmental impacts derived from the conversion of residual almond shells into high added-value products, such as oligosaccharides (98 %), lignin (1 %) and cellulose nanocrystals (CNC) (1 %). They analysed six different scenarios, but this report is only centred on the transformation route with least environmental impacts contribution. According to different sources, the selling prices of the different final products are 0.67 €/kg for oligosaccharides[14], 10.86 €/kg for lignin and 6.56 €/kg for CNC[4].

Table 12. Case study of almond shells valorisation based on Sillero et al.[13]

Biomass input
Almond shells
Output
Oligosaccharides, lignin, cellulose nanocrystals (CNC)
Geography area
Spain
Paper

[4] https://www.indiamart.com/

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Life Cycle Assessment of various biorefinery approaches for the valorisation of almond shells
Author
Leyre Sillero, Amaia Morales, Rut Fernández-Marín, Fabio Hernández-Ramos, Izaskun Dávila, Xabier Erdocia, Jalel Labidi
Year
2021
Functional Unit
1 kg of dried almond shells processed in a biorefinery plant via autohydrolysis, alkaline delignification, bleaching process and multiple separation phases, in Spain.
Reference Flow
1 kg of almond shells

The environmental impacts related to 1 kg of residual almond shells valorisation are shown in the table below, while the allocation of impacts can be seen in Table 13.

Table 13. Damage assessment of almond shells valorisation (based on data from Sillero et al.[13]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	9.80E-02	9.80E-02
Climate change	**kg CO2 eq**	2.02E+01	2.02E+01
Ecotoxicity, freshwater	**CTUe**	1.99E+02	1.99E+02
Particulate matter	**disease inc.**	6.73E-07	6.73E-07
Eutrophication, marine	**kg N eq**	1.79E-02	1.79E-02
Eutrophication, freshwater	**kg P eq**	8.31E-04	8.31E-04
Eutrophication, terrestrial	**mol N eq**	1.97E-01	1.97E-01
Human toxicity, cancer	**CTUh**	2.61E-07	2.61E-07
Human toxicity, non-cancer	**CTUh**	3.97E-07	3.97E-07
Ionising radiation	**kBq U-235 eq**	5.84E+00	5.84E+00
Land use	**Pt**	1.01E+02	1.01E+02
Ozone depletion	**kg CFC11 eq**	4.92E-07	4.92E-07
Photochemical ozone formation	**kg NMVOC eq**	6.93E-02	6.93E-02
Resource use, fossils	**MJ**	5.46E+02	5.46E+02
Resource use, minerals and metals	**kg Sb eq**	2.89E-04	2.89E-04
Water use	**m3 depriv.**	5.36E+02	5.36E+02

Table 14. Mass allocation and economic allocation from Damage assessment (based on data from Sillero et al.[13]).

Damage category	Unit	Mass Allocation			Economic Allocation		
		Oligosaccharides	Lignin	CNC	Oligosaccharides	Lignin	CNC
AC	mol H+ eq	9.59E-02	1.23E-03	8.59E-04	9.00E-02	6.35E-05	7.89E-03

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Damage category	Unit	Mass Allocation			Economic Allocation		
		Oligosaccharides	Lignin	CNC	Oligosaccharides	Lignin	CNC
CC	kg CO2 eq	1.98E+01	2.53E-01	1.77E-01	1.86E+01	1.31E-02	1.63E+00
ECOTOX	CTUe	1.95E+02	2.49E+00	1.74E+00	1.83E+02	1.29E-01	1.60E+01
PM	disease inc.	6.59E-07	8.42E-09	5.90E-09	6.19E-07	4.37E-10	5.43E-08
MEU	kg N eq	1.75E-02	2.24E-04	1.57E-04	1.64E-02	1.16E-05	1.44E-03
FEU	kg P eq	8.13E-04	1.04E-05	7.29E-06	7.63E-04	5.39E-07	6.70E-05
TEU	mol N eq	1.92E-01	2.46E-03	1.72E-03	1.81E-01	1.27E-04	1.58E-02
HTOC_c	CTUh	2.56E-07	3.27E-09	2.29E-09	2.40E-07	1.69E-10	2.10E-08
HTOC_nc	CTUh	3.89E-07	4.97E-09	3.48E-09	3.65E-07	2.58E-10	3.20E-08
IR	kBq U-235 eq	5.72E+00	7.31E-02	5.12E-02	5.37E+00	3.79E-03	4.71E-01
LU	Pt	9.86E+01	1.26E+00	8.83E-01	9.25E+01	6.53E-02	8.11E+00
ODP	kg CFC11 eq	4.81E-07	6.15E-09	4.31E-09	4.52E-07	3.19E-10	3.96E-08
POF	kg NMVOC eq	6.79E-02	8.67E-04	6.08E-04	6.37E-02	4.50E-05	5.59E-03
FRD	MJ	5.34E+02	6.83E+00	4.78E+00	5.01E+02	3.54E-01	4.40E+01
MRD	kg Sb eq	2.82E-04	3.61E-06	2.53E-06	2.65E-04	1.87E-07	2.32E-05
WU	m3 depriv.	5.25E+02	6.70E+00	4.70E+00	4.93E+02	3.48E-01	4.32E+01

An environmental impacts weighted distribution from Sillero et al. permits the identification of the most relevant impact categories in the valorisation process (Figure 16). Water Use (61.36 %), resource use (fossils) (10.77 %) and climate change (8.70 %) are those to consider since their contribution comes to a total of 80.82%.

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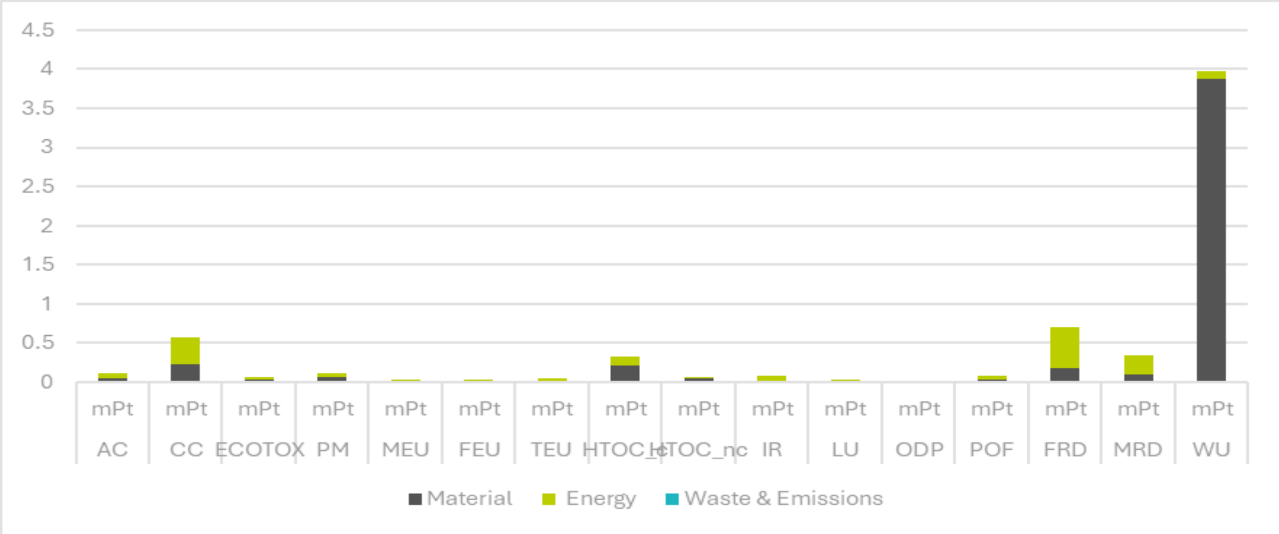

Figure 16. Almond shells valorisation weighted impact category relevance (based on data from Sillero et al.[13]).

The life cycle flows linked to this process were analysed considering that the most relevant impact categories regarding the scope of the study was limited to the processing of almonds shells. As it can be seen in Figure 17, the most relevant flow for all the impact categories was the one related to the energy demands, followed by materials flow.

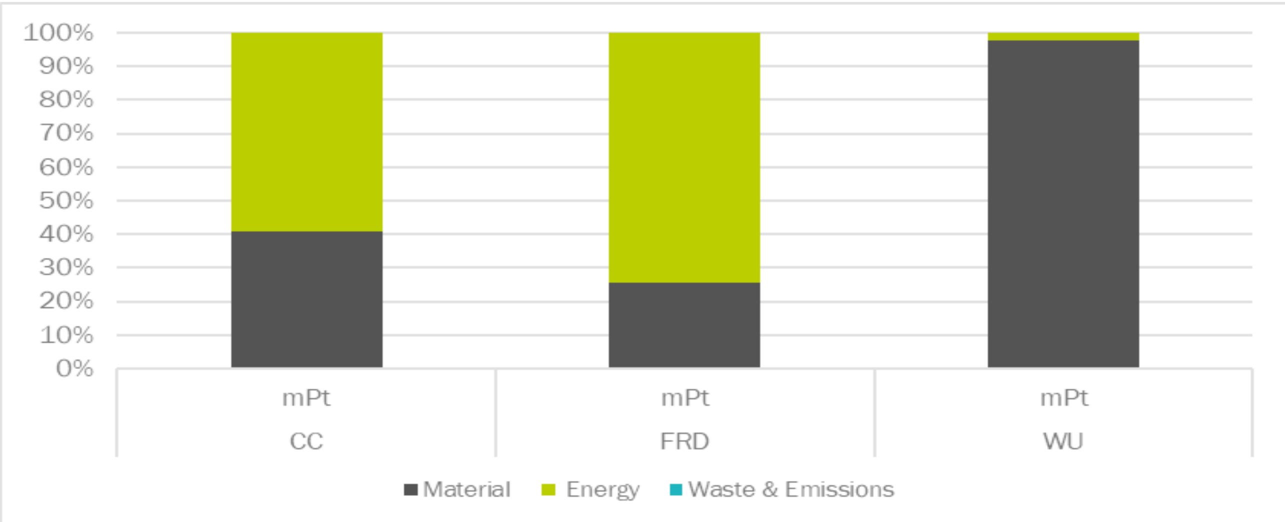

Figure 17. Environmental impacts weighted distribution from (based on data from Sillero et al.[13]).

The energy flow was only composed of the amount of electricity required during the whole production process. The impacts associated with this flow were associated to the coal consumption during the electricity production.

As it can be seen in Figure 18, the major contribution to the materials flow in every relevant impact category were due to the water requirements in every single process of the biorefinery route, specially throughout separation steps. The use of sodium hypochlorite ($NaClO_2$) during the bleaching process had also relevancy in the total impacts.

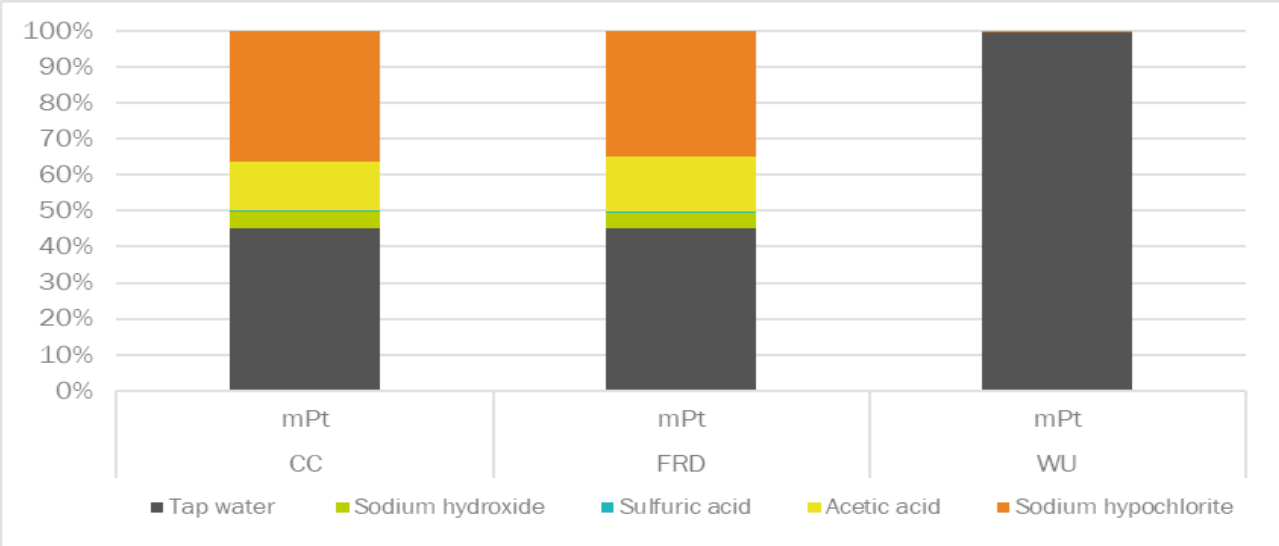

Figure 18. Materials flow weighted impact distribution (based on data from Sillero et al.[13]).

4.1.4 Pomegranate peels valorisation

Pomegranate peels were studied by Shinde et al.[15] to analyse their potential as a bioresource for various value-added products and the environmental impact of the valorisation process. The study detailed the route for sequential extraction of ellagic acid (22 %), lignin (32 %) and pectin (46 %) from pomegranate peels residue. In accordance with different sources, the market price of coproducts were 45,68 €/kg, 0,037 €//kg and 10,86 €/kg, respectively.

Table 15. Case study of pomegranate peels valorisation based on Shinde et al.[15]

Biomass input
Pomegranate peels
Output
Ellagic acid, lignin, pectin
Geography area
India
Paper
Process development and life cycle assessment of pomegranate biorefinery
Author
Pratik N. Shinde, Sachin A. Mandavgane, Vijay Karadbhajane
Year
2020
Functional Unit

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1 kg of dried pomegranate peels transported 100 km with a freight to a biorefinery plant, where it will be treated through NaOH digestion, centrifuge, filter filtration, acid hydrolysis and extraction processes, in India.
Reference Flow
1000 kg of pomegranate peels

The environmental impacts related to 1 ton of pomegranate peels valorisation are listed in Table 16, while the allocation of impacts is shown in Table 17.

Table 16. Damage assessment of pomegranate peels valorisation (based on data from Shinde et al.[15]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	1.20E+01	1.20E+01
Climate change	**kg CO2 eq**	3.28E+03	3.28E+03
Ecotoxicity, freshwater	**CTUe**	1.67E+04	1.67E+04
Particulate matter	**disease inc.**	1.01E-04	1.01E-04
Eutrophication, marine	**kg N eq**	2.35E+00	2.35E+00
Eutrophication, freshwater	**kg P eq**	1.43E+00	1.43E+00
Eutrophication, terrestrial	**mol N eq**	2.41E+01	2.41E+01
Human toxicity, cancer	**CTUh**	1.47E-05	1.47E-05
Human toxicity, non-cancer	**CTUh**	3.18E-05	3.18E-05
Ionising radiation	**kBq U-235 eq**	2.00E+02	2.00E+02
Land use	**Pt**	1.22E+04	1.22E+04
Ozone depletion	**kg CFC11 eq**	1.65E-04	1.65E-04
Photochemical ozone formation	**kg NMVOC eq**	1.96E+01	1.96E+01
Resource use, fossils	**MJ**	8.98E+04	8.98E+04
Resource use, minerals and metals	**kg Sb eq**	3.47E-02	3.47E-02
Water use	**m3 depriv.**	1.89E+03	1.89E+03

Table 17. Mass allocation and economic allocation from Damage assessment (based on data from Shinde et al.[15]).

Damage category	Unit	Mass Allocation			Economic allocation		
		Lignin	Pectin	Ellagic Acid	Lignin	Pectin	Ellagic Acid
AC	mol H+ eq	3.80E+00	5.46E+00	2.70E+00	9.2E-03	3.9E+00	8.1E+00
CC	kg CO2 eq	1.04E+03	1.50E+03	7.41E+02	2.5E+00	1.1E+03	2.2E+03
ECOTOX	CTUe	5.31E+03	7.63E+03	3.78E+03	1.3E+01	5.4E+03	1.1E+04
PM	disease inc.	3.21E-05	4.61E-05	2.28E-05	7.8E-08	3.3E-05	6.8E-05
MEU	kg N eq	7.45E-01	1.07E+00	5.30E-01	1.8E-03	7.6E-01	1.6E+00
FEU	kg P eq	4.54E-01	6.53E-01	3.23E-01	1.1E-03	4.6E-01	9.7E-01
TEU	mol N eq	7.66E+00	1.10E+01	5.45E+00	1.9E-02	7.8E+00	1.6E+01
HTOC_c	CTUh	4.68E-06	6.73E-06	3.33E-06	1.1E-08	4.8E-06	9.9E-06
HTOC_nc	CTUh	1.01E-05	1.45E-05	7.18E-06	2.4E-08	1.0E-05	2.1E-05
IR	kBq U-235 eq	6.36E+01	9.13E+01	4.52E+01	1.5E-01	6.5E+01	1.4E+02

Damage category	Unit	Mass Allocation			Economic allocation		
		Lignin	Pectin	Ellagic Acid	Lignin	Pectin	Ellagic Acid
LU	Pt	3.87E+03	5.57E+03	2.75E+03	9.4E+00	4.0E+03	8.2E+03
ODP	kg CFC11 eq	5.24E-05	7.53E-05	3.72E-05	1.3E-07	5.3E-05	1.1E-04
POF	kg NMVOC eq	6.24E+00	8.97E+00	4.44E+00	1.5E-02	6.4E+00	1.3E+01
FRD	MJ	2.85E+04	4.10E+04	2.03E+04	6.9E+01	2.9E+04	6.1E+04
MRD	kg Sb eq	1.10E-02	1.59E-02	7.85E-03	2.7E-05	1.1E-02	2.3E-02
WU	m3 depriv.	6.02E+02	8.65E+02	4.28E+02	1.5E+00	6.1E+02	1.3E+03

Considering cradle-to-gate approach, which includes the transport of raw materials, the manufacturing of raw materials and energy production, the most relevant impact categories were resource use (fossils) (30.32 %), climate change (24.15 %), resource use (minerals/metals) (10.88 %), eutrophication (freshwater) (6.58 %), photochemical ozone formation (6.07 %) and human toxicity (cancer) (4.80 %), representing 82.80 % of the total environmental impacts (Figure 19).

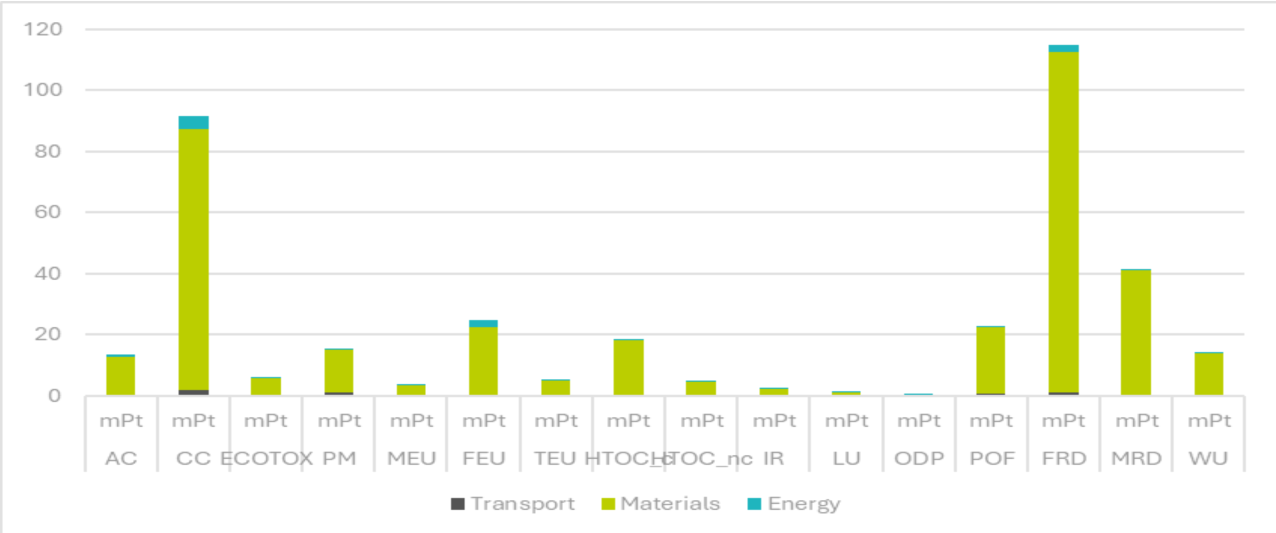

Figure 19. Pomegranate peels valorisation weighted impact category relevance (based on data from Shinde et al.[15]).

Additionally, the analysis of inputs revealed the contribution of the different life cycle flows in the overall. As it can be seen in the following figure, the materials flow was the most relevant one.

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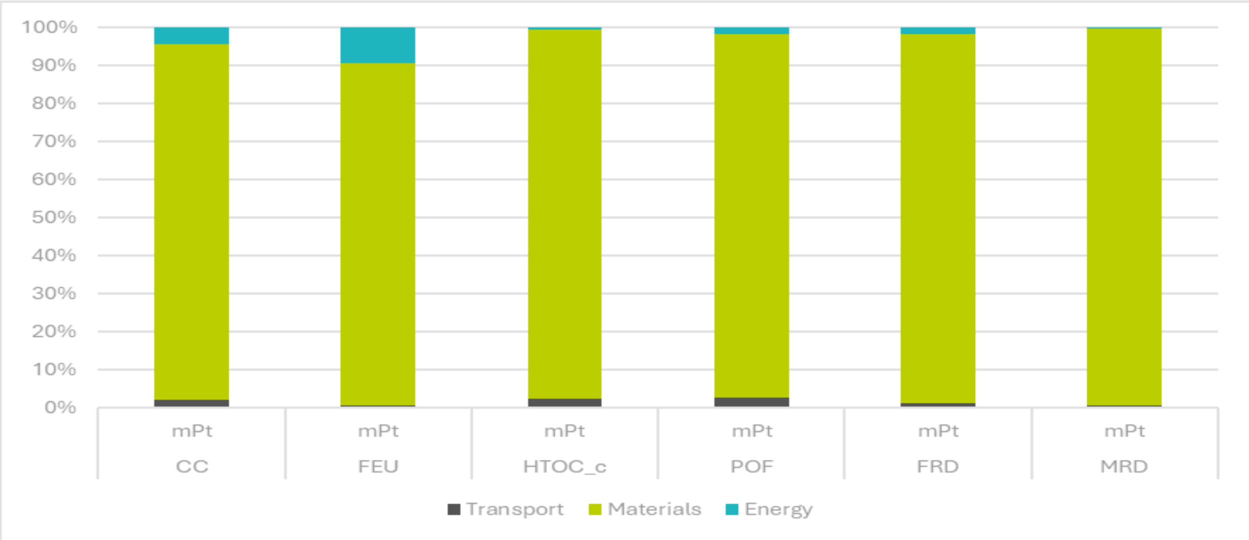

Figure 20. Environmental impacts weighted distribution (based on data from Shinde et al.[15])

Going deeper into the evaluation, the materials flow was analysed (Figure 21), observing that the larger contribution was due to the use of ethanol in the pectin extraction step. The high contribution was attributed to the indirect emissions during the production of the raw material (ethanol).

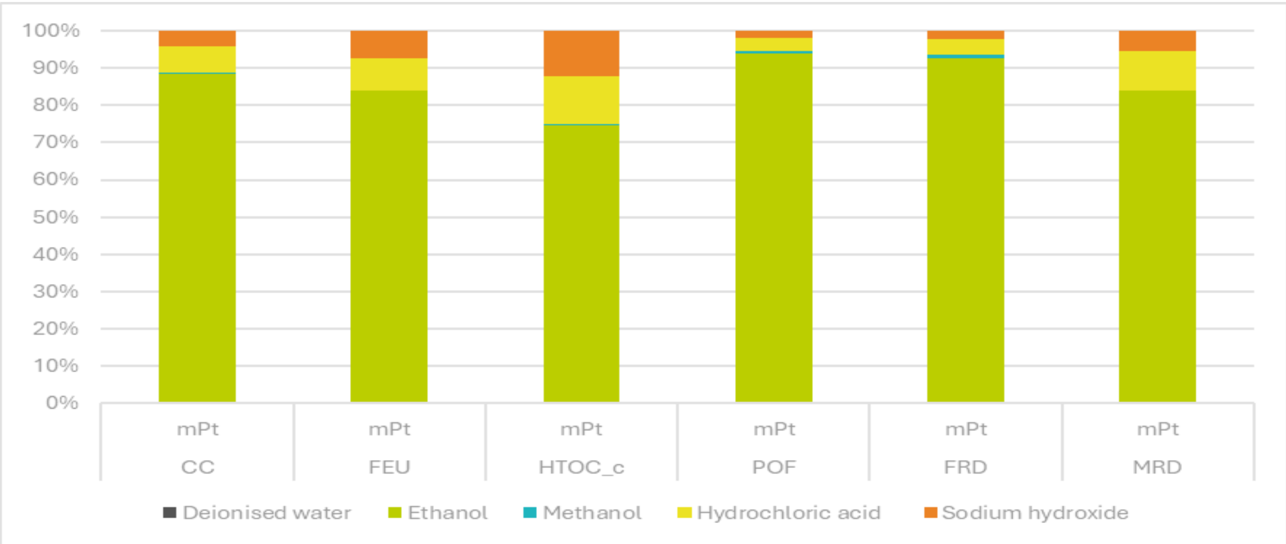

Figure 21. Materials flow weighted impact distribution (based on data from Shinde et al.[15]).

4.1.5 Brewery waste & Brewer's spent grain valorisation

González-García et al.[14] analysed the environmental performance of lignocellulosic residues, such as barley straw and brewer's spent grains, valorisation route to obtain bioethanol (51 %) and xylooligosaccharides (49 %), including all the steps involved in the production system. According to González-García et al.[14], the market price of both co-products were 0.64 €/kg and 0.67 €/kg, respectively.

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Table 18. Case study of barley straw and brewer's spent grains valorisation based on González-García et al.[14]

Biomass input
Barley straw, brewer's spent grain
Output
Xylooligosaccharides, bioethanol
Geography area
Spain
Paper
Estimating the environmental impacts of a brewery waste–based biorefinery: Bioethanol and xylooligosaccharides joint production case study
Author
Sara González-García, Pablo Comendador Morales, Beatriz Gullón
Year
2018
Functional Unit
1 kg of lignocellulosic matter (barley straw and brewer's spent grain) processed in a biorefinery plant via a valorisation route, including raw materials reconditioning, autohydrolysis, fermentation and final products purification, in Spain.
Reference Flow
74,220 kg of lignocellulosic residues (37,108 kg barley straw + 37,108 kg brewer's spent grain)

The environmental impacts were reported per production batch in Table 19 (where total column is referring to 37,108 kg of barley straw and brewer's spent grain each). The allocation of impacts is shown in Table 20.

Table 19. Damage assessment of barley straw and brewer's spent grains valorisation (based on data González-García et al.[14]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	1.00E+03	1.35E-02
Climate change	**kg CO2 eq**	2.37E+05	3.19E+00
Ecotoxicity, freshwater	**CTUe**	2.86E+07	3.85E+02
Particulate matter	**disease inc.**	1.07E-02	1.44E-07
Eutrophication, marine	**kg N eq**	1.04E+04	1.39E-01
Eutrophication, freshwater	**kg P eq**	4.75E+02	6.40E-03
Eutrophication, terrestrial	**mol N eq**	2.85E+03	3.84E-02
Human toxicity, cancer	**CTUh**	1.18E-03	1.59E-08
Human toxicity, non-cancer	**CTUh**	8.97E-03	1.21E-07
Ionising radiation	**kBq U-235 eq**	3.65E+04	4.92E-01
Land use	**Pt**	1.33E+06	1.79E+01
Ozone depletion	**kg CFC11 eq**	2.92E-03	3.93E-08

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Damage category	Unit	Total	Per kg of feedstock
Photochemical ozone formation	**kg NMVOC eq**	7.70E+02	1.04E-02
Resource use, fossils	**MJ**	2.78E+06	3.74E+01
Resource use, minerals and metals	**kg Sb eq**	1.06E+00	1.43E-05
Water use	**m3 depriv.**	-7.68E+05	-1.03E+01

Table 20. Mass allocation and economic allocation from Damage assessment (based on data from González-García et al.[14]).

Damage category	Unit	Mass Allocation		Economic allocation	
		Xylooligosaccharides	Bioethanol	Xylooligosaccharides	Bioethanol
AC	mol H+ eq	4.35E+02	5.68E+02	4.46E+02	5.57E+02
CC	kg CO2 eq	1.03E+05	1.34E+05	1.05E+05	1.32E+05
ECOTOX	CTUe	1.24E+07	1.62E+07	1.27E+07	1.59E+07
PM	disease inc.	4.62E-03	6.04E-03	4.74E-03	5.92E-03
MEU	kg N eq	4.49E+03	5.87E+03	4.60E+03	5.75E+03
FEU	kg P eq	2.06E+02	2.69E+02	2.11E+02	2.64E+02
TEU	mol N eq	1.23E+03	1.61E+03	1.27E+03	1.58E+03
HTOC_c	CTUh	5.11E-04	6.68E-04	5.24E-04	6.55E-04
HTOC_nc	CTUh	3.89E-03	5.09E-03	3.99E-03	4.98E-03
IR	kBq U-235 eq	1.58E+04	2.07E+04	1.62E+04	2.03E+04
LU	Pt	5.76E+05	7.54E+05	5.91E+05	7.39E+05
ODP	kg CFC11 eq	1.26E-03	1.65E-03	1.30E-03	1.62E-03
POF	kg NMVOC eq	3.34E+02	4.36E+02	3.42E+02	4.28E+02
FRD	MJ	1.20E+06	1.57E+06	1.23E+06	1.54E+06
MRD	kg Sb eq	4.59E-01	6.00E-01	4.71E-01	5.88E-01
WU	m3 depriv.	-3.33E+05	-4.35E+05	-3.41E+05	-4.27E+05

Since a cradle-to-gate approach was considered, the impacts were estimated from the raw materials, energy and waste flows directly involved in bioethanol and xylooligosaccharides processing.

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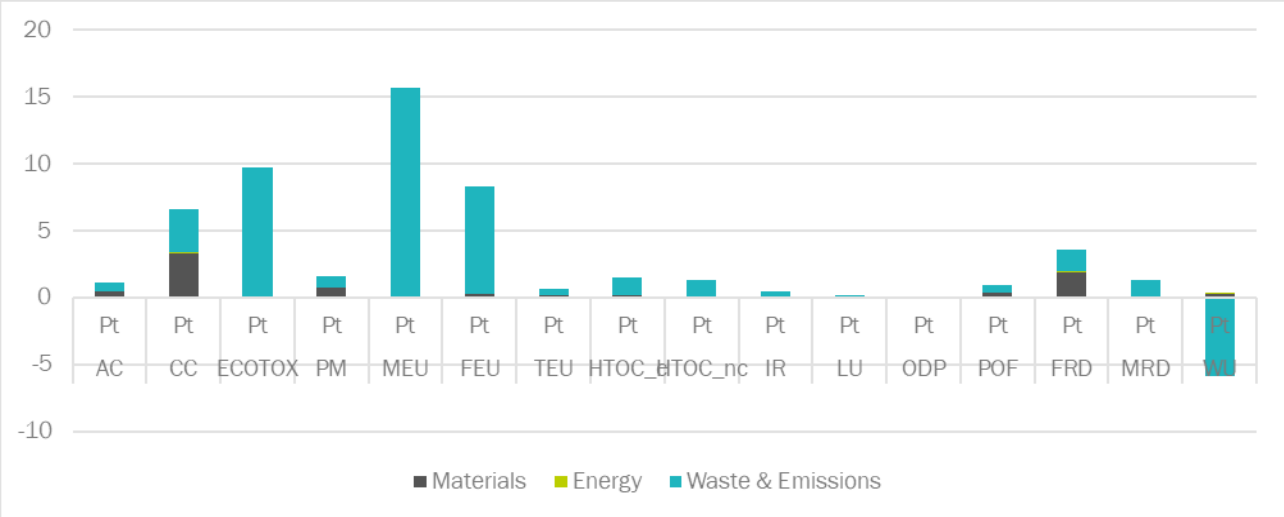

Figure 22. Brewery waste valorisation weighted impact category relevance (based on data from González-García et al.[14]).

The environmental impacts weighted distribution facilitates the identification of the most relevant impact categories (Figure 22). Within the valorisation process, eutrophication (marine) (26.69 %), ecotoxicity (freshwater) (14.09 %), eutrophication (terrestrial) (14.09 %), climate change (11.25 %), water use (10.48 %) and resource use (fossils) (6.05 %), were the impact categories with major relevancy (85.05 % of the total).

The fact that water use had a negative value means that there was a positive impact rather than a negative effect on the environment. Wastewater from the biorefinery were treated, through a wastewater treatment plant, increasing the amount of freshwater inside the system boundaries.

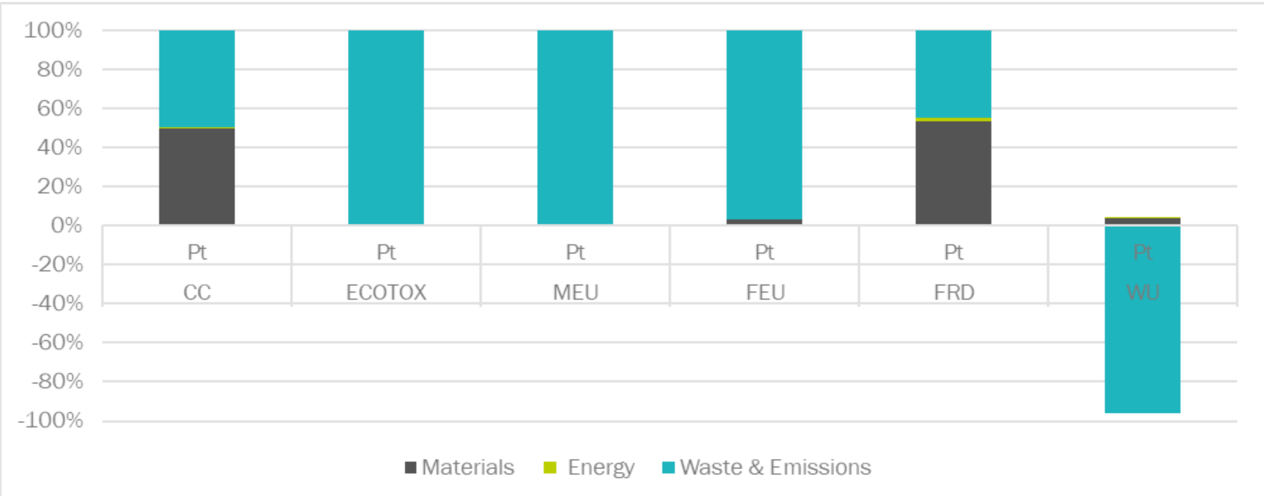

Figure 23. Environmental impacts weighted distribution (based on data from García-Gonzalez et al.[14]).

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As shown in Figure 24, the flow related with waste materials and emission to air during the valorisation process, had nearly its total contribution due to the existence of a wastewater treatment plant so water use indicator had a negative value, as it was mentioned before.

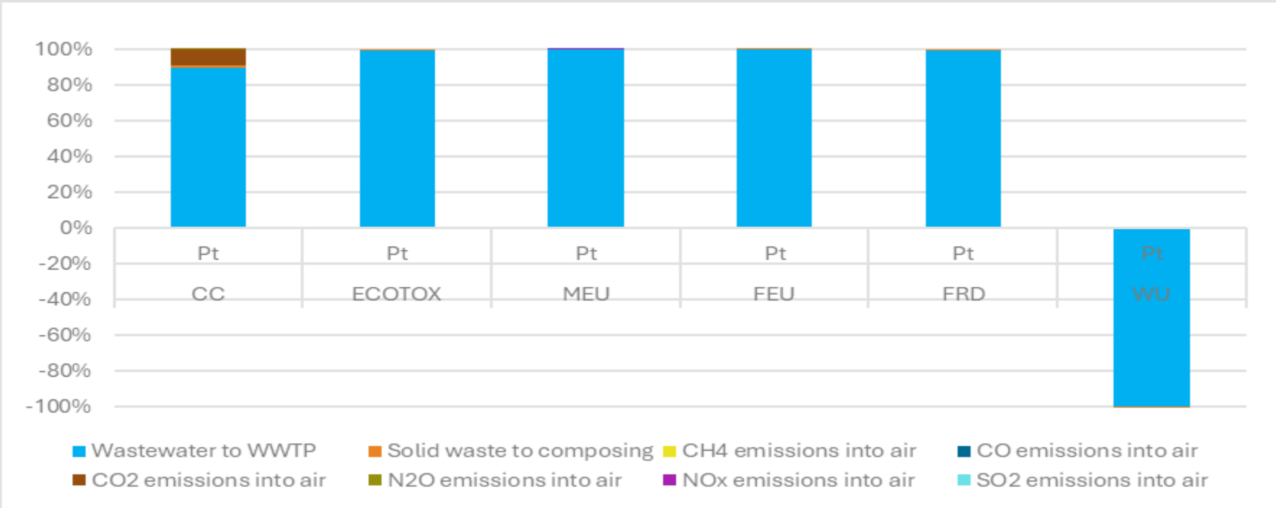

Figure 24. Waste & emissions flow weighted impact distribution (based on data from García-Gonzalez et al.[14]).

For almost all relevant categories, the largest contribution to the materials flow was associated with the steam consumption during the autohydrolysis reaction. The same reaction was associated with high water consumption, which was the reason for the impact on the water use category.

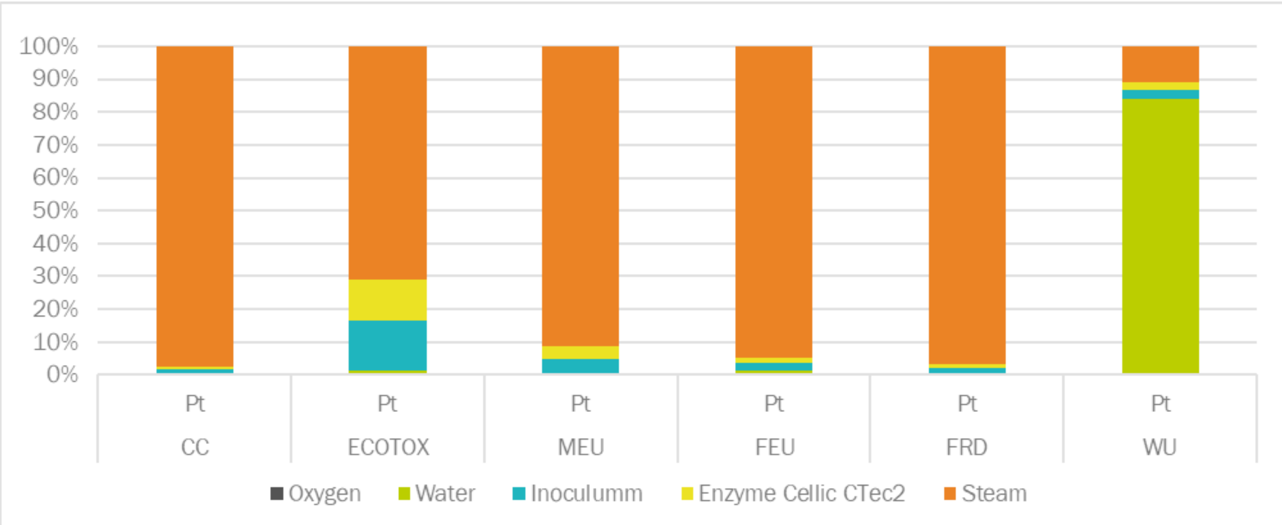

Figure 25. Materials flow weighted impact distribution (based on data from García-Gonzalez et al.[14]).

4.1.6 Rice straw valorisation

Sreekumar et al.[16] detailed the production process of converting rice straw to ethanol and all the environmental impacts associated with it. At the end of the biorefinery route not only ethanol was

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produced (41 %), but also other byproducts, such as food grade CO_2 (23 %), Silica (23 %), inorganics (10 %) and methanol (1 %). According to Sreekumar et al. [16] the prices of this products at the Indian market were: silica at 6,000 Rs/ton, methanol at 20,000 Rs/ton, food-grade CO_2 at 20,000 Rs/ton, ethanol at 60,000 Rs/ton and inorganics at 1,000 Rs/ton.

Table 21. Case study of rice straw valorisation based on Sreekumar et al.[16]

Biomass input
Rice straw
Output
Ethanol, food grade CO_2, methanol, silica, inorganics
Geography area
India
Paper
Life cycle assessment of ethanol production in a rice-straw-based biorefinery in India
Author
Arun Sreekumar, Yogendra Shastri, Prathamesh Wadekar, Mallikarjun Patil, Arvind Lali
Year
2019
Functional Unit
1 kg of rice straw transported 20 km with a freight to a biorefinery plant, for a valorisation process including the pretreatment of the feedstock, an enzyme hydrolysis, fermentation and ethanol distillation, in India.
Reference Flow
3,370 kg of rice straw

The environmental impacts related to the valorisation of 3,390 kg of rice straw as feedstock is shown in Table 22, and the allocation of impacts in Table 23 and Table 24.

Table 22. Damage assessment of rice straw valorisation (based on data from Sreekumar et al.[16])

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	1.37E-02	4.06E-06
Climate change	**kg CO2 eq**	3.00E+00	8.90E-04
Ecotoxicity, freshwater	**CTUe**	9.59E+00	2.85E-03
Particulate matter	**disease inc.**	6.39E-08	1.90E-11
Eutrophication, marine	**kg N eq**	2.89E-03	8.57E-07
Eutrophication, freshwater	**kg P eq**	2.63E-04	7.79E-08
Eutrophication, terrestrial	**mol N eq**	3.37E-02	9.99E-06
Human toxicity, cancer	**CTUh**	3.29E-09	9.76E-13
Human toxicity, non-cancer	**CTUh**	2.43E-08	7.22E-12

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Damage category	Unit	Total	Per kg of feedstock
Ionising radiation	**kBq U-235 eq**	4.67E-02	1.38E-05
Land use	**Pt**	1.07E+01	3.17E-03
Ozone depletion	**kg CFC11 eq**	2.22E-08	6.59E-12
Photochemical ozone formation	**kg NMVOC eq**	7.01E-03	2.08E-06
Resource use, fossils	**MJ**	2.91E+01	8.64E-03
Resource use, minerals and metals	**kg Sb eq**	4.22E-06	1.25E-09
Water use	**m3 depriv.**	8.85E-01	2.63E-04

Table 23. Mass allocation from Damage assessment (based on data from Sreekumar et al.[16])

Damage category	Unit	Mass Allocation				
		Ethanol	Food-grade CO_2	Methanol	Silica	Inorganics
AC	mol H+ eq	5.68E-03	3.19E-03	2.13E-04	3.19E-03	1.42E-03
CC	kg CO2 eq	1.24E+00	6.99E-01	4.66E-02	6.99E-01	3.11E-01
ECOTOX	CTUe	3.97E+00	2.24E+00	1.49E-01	2.24E+00	9.94E-01
PM	disease inc.	2.65E-08	1.49E-08	9.93E-10	1.49E-08	6.62E-09
MEU	kg N eq	1.20E-03	6.73E-04	4.49E-05	6.73E-04	2.99E-04
FEU	kg P eq	1.09E-04	6.12E-05	4.08E-06	6.12E-05	2.72E-05
TEU	mol N eq	1.40E-02	7.85E-03	5.24E-04	7.85E-03	3.49E-03
HTOC_c	CTUh	1.36E-09	7.67E-10	5.11E-11	7.67E-10	3.41E-10
HTOC_nc	CTUh	1.01E-08	5.67E-09	3.78E-10	5.67E-09	2.52E-09
IR	kBq U-235 eq	1.93E-02	1.09E-02	7.25E-04	1.09E-02	4.83E-03
LU	Pt	4.43E+00	2.49E+00	1.66E-01	2.49E+00	1.11E+00
ODP	kg CFC11 eq	9.20E-09	5.18E-09	3.45E-10	5.18E-09	2.30E-09
POF	kg NMVOC eq	2.90E-03	1.63E-03	1.09E-04	1.63E-03	7.26E-04
FRD	MJ	1.21E+01	6.79E+00	4.53E-01	6.79E+00	3.02E+00
MRD	kg Sb eq	1.75E-06	9.84E-07	6.56E-08	9.84E-07	4.37E-07
WU	m3 depriv.	3.67E-01	2.06E-01	1.38E-02	2.06E-01	9.17E-02

Table 24. Economic allocation from Damage assessment (based on data from Sreekumar et al.[16])

Damage category	Unit	Economic Allocation				
		Ethanol	Food-grade CO_2	Methanol	Silica	Inorganics
AC	mol H+ eq	1.09E-02	2.04E-03	1.36E-04	6.11E-04	4.53E-05
CC	kg CO2 eq	2.38E+00	4.46E-01	2.97E-02	1.34E-01	9.91E-03
ECOTOX	CTUe	7.61E+00	1.43E+00	9.51E-02	4.28E-01	3.17E-02
PM	disease inc.	5.07E-08	9.50E-09	6.34E-10	2.85E-09	2.11E-10
MEU	kg N eq	2.29E-03	4.30E-04	2.86E-05	1.29E-04	9.55E-06
FEU	kg P eq	2.08E-04	3.91E-05	2.60E-06	1.17E-05	8.68E-07
TEU	mol N eq	2.67E-02	5.01E-03	3.34E-04	1.50E-03	1.11E-04
HTOC_c	CTUh	2.61E-09	4.89E-10	3.26E-11	1.47E-10	1.09E-11
HTOC_nc	CTUh	1.93E-08	3.62E-09	2.41E-10	1.09E-09	8.05E-11

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Damage category	Unit	Economic Allocation				
		Ethanol	Food-grade CO_2	Methanol	Silica	Inorganics
IR	kBq U-235 eq	3.70E-02	6.94E-03	4.63E-04	2.08E-03	1.54E-04
LU	Pt	8.48E+00	1.59E+00	1.06E-01	4.77E-01	3.53E-02
ODP	kg CFC11 eq	1.76E-08	3.30E-09	2.20E-10	9.91E-10	7.34E-11
POF	kg NMVOC eq	5.56E-03	1.04E-03	6.95E-05	3.13E-04	2.32E-05
FRD	MJ	2.31E+01	4.33E+00	2.89E-01	1.30E+00	9.63E-02
MRD	kg Sb eq	3.35E-06	6.28E-07	4.19E-08	1.88E-07	1.40E-08
WU	m3 depriv.	7.02E-01	1.32E-01	8.78E-03	3.95E-02	2.93E-03

Climate change (43,10 %), resource use (fossils) (19,22 %), acidification (7,88 %), particulate matter (4,96 %), photochemical ozone formation (4,23 %) and eutrophication (terrestrial) (3,64 %) were the most relevant impact categories of the valorisation process (83,03 % of the total impacts).

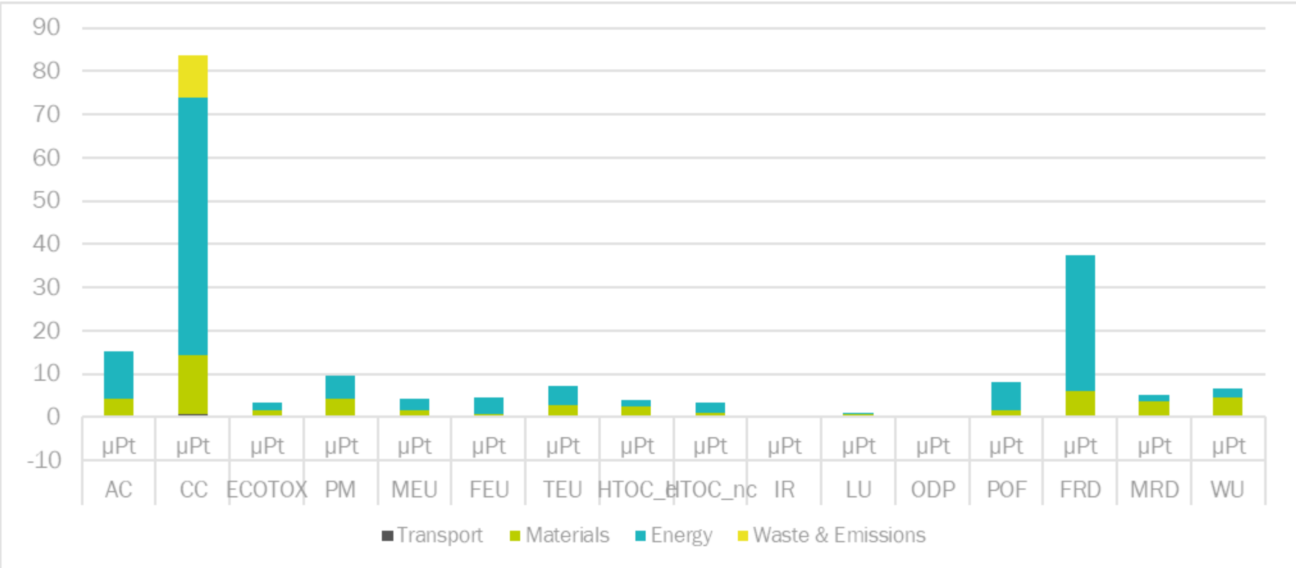

Figure 26. Rice straw valorisation weighted impact category relevance (based on data from Sreekumar et al.[16])

Considering only to the most relevant categories in Figure 27, energy consumption was the major contribution. However, the raw materials flow also had significant influence. Energy elementary flow contributed 70 % of the total impacts while materials contribution reaches the 25 % of the overall.

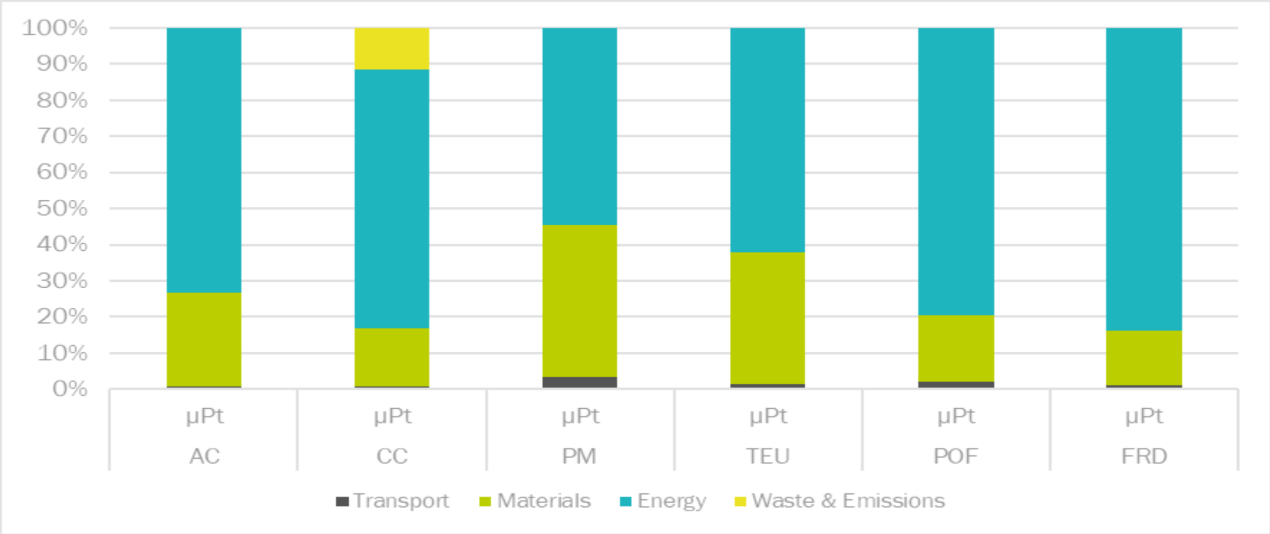

Figure 27. Environmental impacts weighted distribution (based on data from Sreekumar et al.[16])

The total contribution of the energy flow was related to the great amount of electricity requirements throughout the biorefinery process, due to the coal consumption during the electricity production. As shown in Figure 28, the major contribution to the materials flow in all the most relevant categories was attributed to the use of enzymes, followed by the production of nitric acid and the manufacturing of sodium hydroxide. Steam and water requirements contributions were almost illegible.

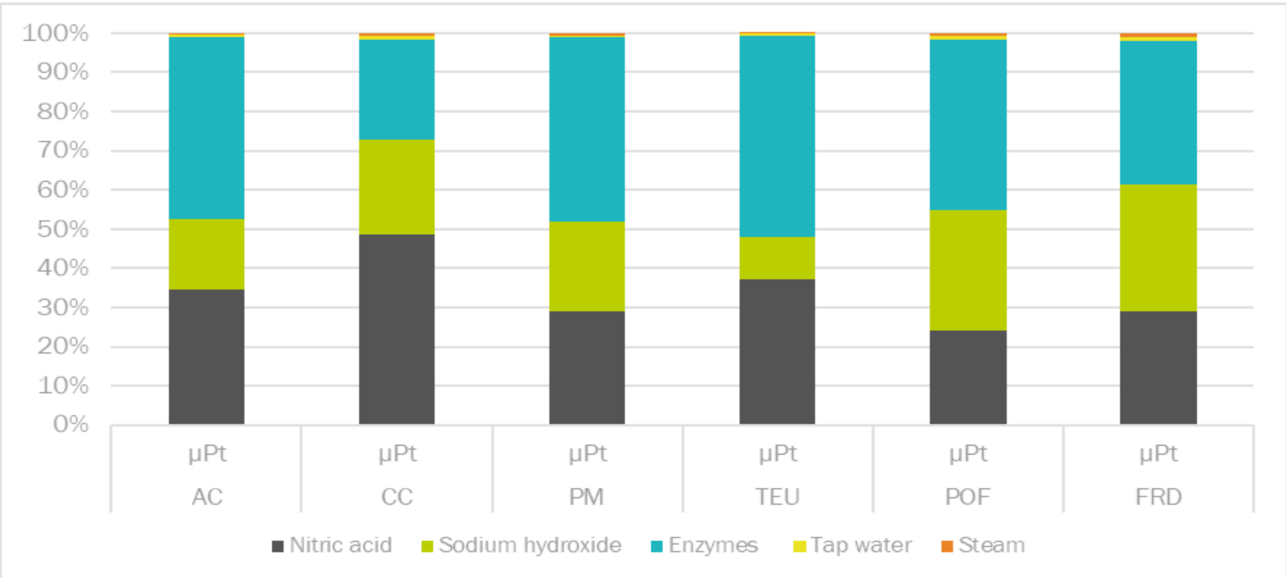

Figure 28. Materials flow weighted impact distribution (based on data from Sreekumar et al.[16]).

4.1.7 Poplar biomass valorisation

Budsberg et al.[17] studied the life cycle impacts of producing acetic acid from poplar biomass using a bioconversion process. It is a complex study as they analysed four different biorefinery methods to

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produce acetic acid, nevertheless this report was only centred on two of them. The scenarios chosen were those with the lowest contribution to the global warming potential of the refinery, according to the author.

The methods were denominated as Method A and Method B. Method A involved burning lignin (poplar biomass by-product) and natural gas onsite to meet heat and electricity demands, whereas method B used only natural gas onsite to meet heat demands, with electricity from the country mix to meet biorefinery needs and selling lignin as a co-product.

Method A only produced acetic acid, whereas Method B generated acetic acid (69 %) together with lignin (31 %). According to Budsberg et al.[17] the selling price of co-products were 819 $/ton of acetic acid and 39 $/ton of lignin.

Table 25. Case poplar biomass valorisation based on Budsberg et al.[17]

Biomass input
Poplar biomass
Output
Acetic acid (Method A & B), Lignin (Method B)
Geography area
United States of America (USA)
Paper
Production routes to bio-acetic acid: life cycle assessment
Author
Erik Budsberg, Rodrigo Morales-Vera, Jordan T. Crawford, Renata Bura and Rick Gustafson
Year
2020
Functional Unit
1 kg of poplar biomass transported 100 km to a biorefinery plant and processed in a valorisation system, including the pretreatment of the feedstock, enzymatic hydrolysis, fermentation and alamine/diisobutyl ketone extraction, in USA.
Reference Flow
1.9 ton of poplar

The environmental impacts per production batch are shown in Table 26 and Table 27, both associated to the input (1.9 ton of poplar biomass). Table 28 shows the allocation basing the impact interpretation on the output (acetic acid and lignin).

Table 26. Damage assessment of poplar biomass valorisation (Method A) (based on data from Budsberg et al.[17]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	1.76E+00	9.26E-04
Climate change	**kg CO2 eq**	3.28E+03	1.73E+00

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Damage category	Unit	Total	Per kg of feedstock
Ecotoxicity, freshwater	CTUe	2.21E+03	1.16E+00
Particulate matter	disease inc.	1.51E-05	7.92E-09
Eutrophication, marine	kg N eq	3.06E-01	1.61E-04
Eutrophication, freshwater	kg P eq	6.19E-02	3.26E-05
Eutrophication, terrestrial	mol N eq	3.17E+00	1.67E-03
Human toxicity, cancer	CTUh	2.46E-06	1.30E-09
Human toxicity, non-cancer	CTUh	4.06E-06	2.13E-09
Ionising radiation	kBq U-235 eq	1.23E+01	6.48E-03
Land use	Pt	6.30E+04	3.32E+01
Ozone depletion	kg CFC11 eq	1.99E-05	1.04E-08
Photochemical ozone formation	kg NMVOC eq	2.86E+00	1.50E-03
Resource use, fossils	MJ	2.40E+04	1.26E+01
Resource use, minerals and metals	kg Sb eq	3.17E-03	1.67E-06
Water use	m3 depriv.	1.77E+02	9.31E-02

Table 27. Damage assessment of poplar biomass valorisation (Method B) (based on data from Budsberg et al.[17]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	mol H+ eq	2.35E+00	1.23E-03
Climate change	kg CO2 eq	2.15E+03	1.13E+00
Ecotoxicity, freshwater	CTUe	3.24E+03	1.71E+00
Particulate matter	disease inc.	1.88E-05	9.92E-09
Eutrophication, marine	kg N eq	4.54E-01	2.39E-04
Eutrophication, freshwater	kg P eq	1.65E-01	8.68E-05
Eutrophication, terrestrial	mol N eq	4.54E+00	2.39E-03
Human toxicity, cancer	CTUh	3.94E-06	2.08E-09
Human toxicity, non-cancer	CTUh	5.45E-06	2.87E-09
Ionising radiation	kBq U-235 eq	7.00E+01	3.69E-02
Land use	Pt	6.37E+04	3.35E+01
Ozone depletion	kg CFC11 eq	2.69E-05	1.41E-08
Photochemical ozone formation	kg NMVOC eq	4.18E+00	2.20E-03
Resource use, fossils	MJ	3.63E+04	1.91E+01
Resource use, minerals and metals	kg Sb eq	3.41E-03	1.80E-06
Water use	m3 depriv.	2.25E+02	1.19E-01

Table 28. Mass allocation and economic allocation from Damage assessment (based on data from Budsberg et al.[17]).

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Damage category	Unit	Mass Allocation		Economic allocation	
		Acetic acid	Lignin	Acetic acid	Lignin
AC	mol H+ eq	1.63E+00	7.17E-01	2.24E+00	1.07E-01
CC	kg CO2 eq	1.50E+03	6.58E+02	2.06E+03	9.79E+01
ECOTOX	CTUe	2.25E+03	9.91E+02	3.10E+03	1.47E+02
PM	disease inc.	1.31E-05	5.76E-06	1.80E-05	8.56E-07
MEU	kg N eq	3.15E-01	1.39E-01	4.33E-01	2.06E-02
FEU	kg P eq	1.15E-01	5.04E-02	1.57E-01	7.50E-03
TEU	mol N eq	3.15E+00	1.39E+00	4.33E+00	2.06E-01
HTOC_c	CTUh	2.74E-06	1.20E-06	3.76E-06	1.79E-07
HTOC_nc	CTUh	3.78E-06	1.66E-06	5.20E-06	2.48E-07
IR	kBq U-235 eq	4.86E+01	2.14E+01	6.69E+01	3.18E+00
LU	Pt	4.42E+04	1.95E+04	6.08E+04	2.89E+03
ODP	kg CFC11 eq	1.87E-05	8.21E-06	2.56E-05	1.22E-06
POF	kg NMVOC eq	2.91E+00	1.28E+00	3.99E+00	1.90E-01
FRD	MJ	2.52E+04	1.11E+04	3.47E+04	1.65E+03
MRD	kg Sb eq	2.37E-03	1.04E-03	3.26E-03	1.55E-04
WU	m3 depriv.	1.57E+02	6.89E+01	2.15E+02	1.02E+01

Observing the results, Method A had lower values in every impact category except for climate change since this Method had no energy input and the demand of natural gas was lower than Method B. However, climate change indicator was higher in Method A than in Method B because of the CO_2 emitted during the combustion of lignin.

Since a cradle-to-gate boundary was considered the environmental impacts were estimated from the raw materials, energy and waste flows directly used in bio- acetic acid manufacturing process (shown in Figure 29 and Figure 30).

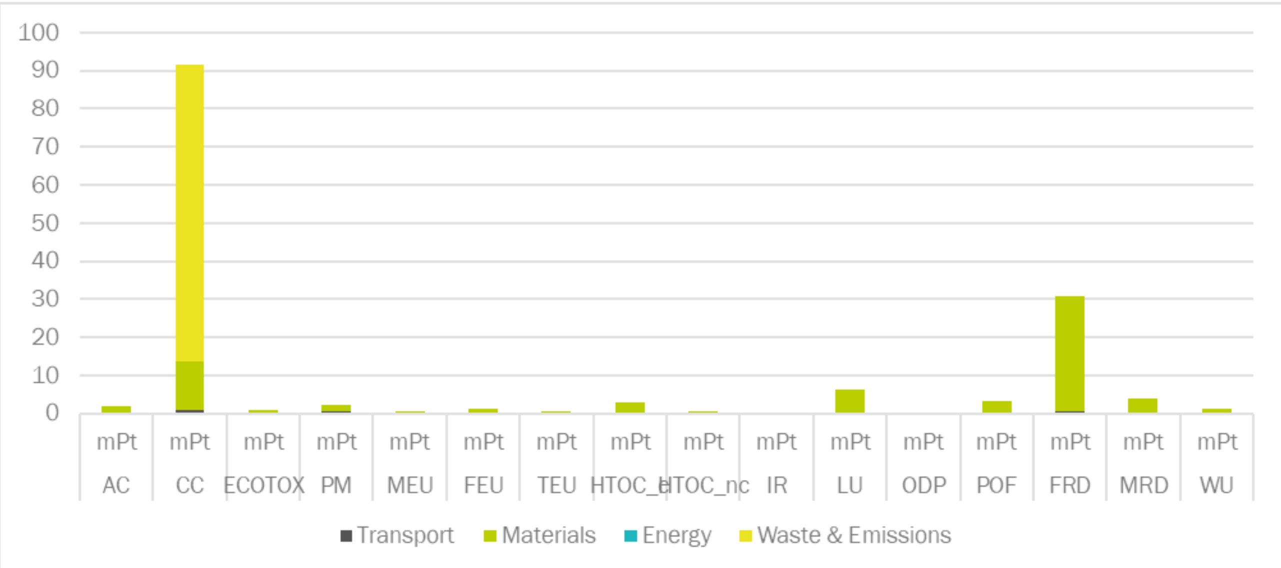

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Figure 29. Poplar biomass valorisation (Method A) weighted impact category relevance (based on data from Budsberg et al.[17]).

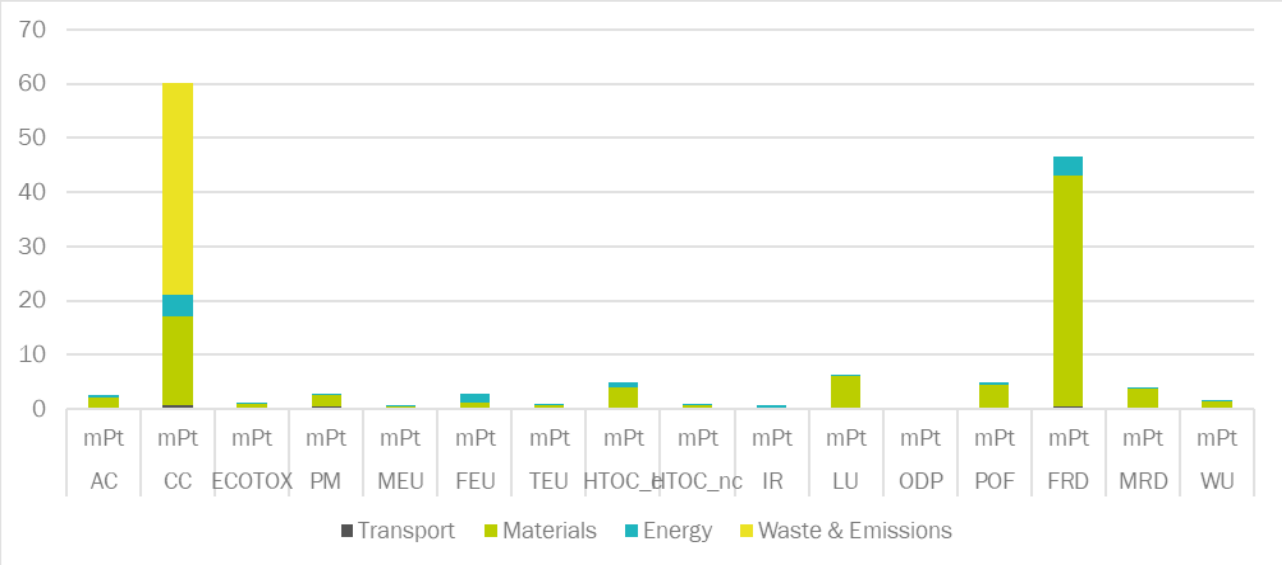

Figure 30. Poplar biomass valorisation (Method B) weighted impact category relevance (based on data from Budsberg et al.[17]).

Both synthesis routes, A and B, had similar results in terms of the most relevant impact categories. The impact categories with major relevancy in Method A (Figure 31) were climate change (61.97 %) and resource use (Fossils) (20.76 %) (82.74 % of the total). In case of Method B (Figure 32), climate change (42.62 %), resource use (fossils) (33.00 %) and land use (4.38 %) (80.00 % of the total impacts). Focusing on those relevant impact categories, mass and waste & emissions flows were the main contributors in both systems.Figure 31Figure 31. Environmental impacts weighted distribution (Method A) (based on data from Budsberg et al.[17]).

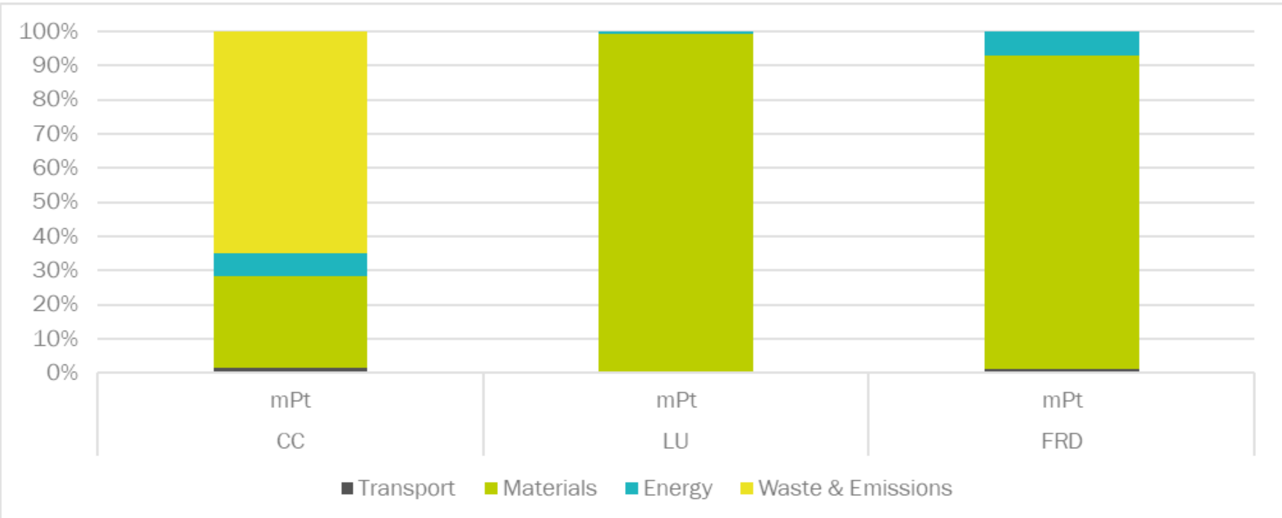

Figure 32. Environmental impacts weighted distribution (Method B) (based on data from Budsberg et al.[17]).

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The total contribution of waste and emissions flow of both processes was related to the emissions of carbon dioxide during the combustion of natural gas or lignin to produce steam and electricity.

The major contribution to materials flow in Method A as well as in Method B was associated with the use of natural gas to produce the necessary steam to operate the biorefinery. Sodium hydroxide, ammonia and enzymes were also important contributors. In Method B, land use category was dominated by the use of enzymes.

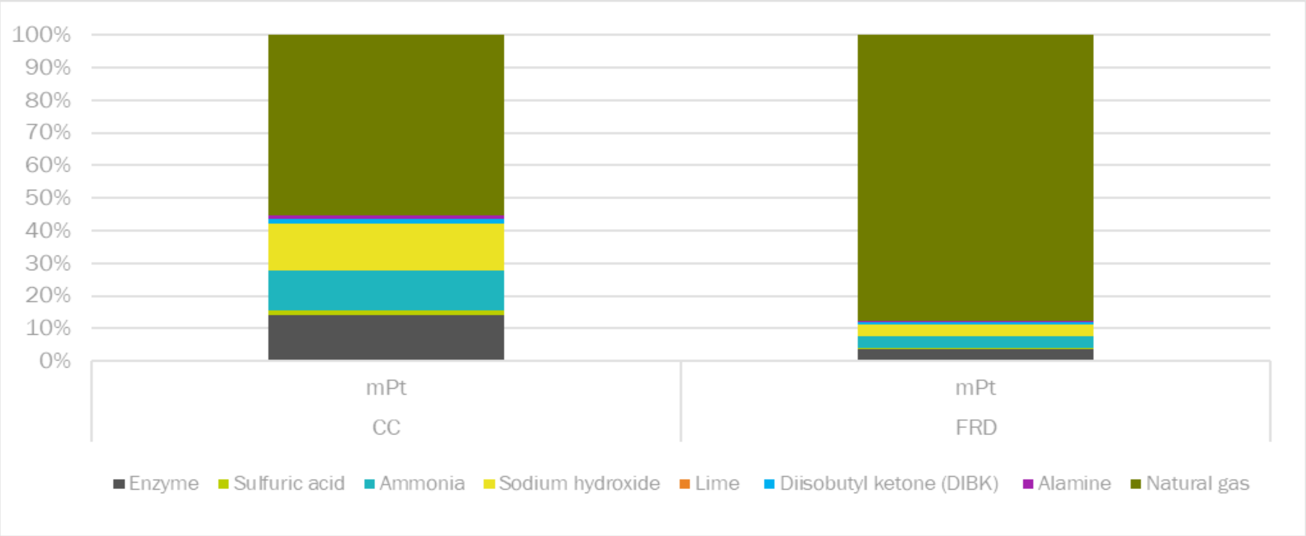

Figure 33. Materials flow weighted impact distribution (Method A) (based on data from Budsberg et al.[17]).

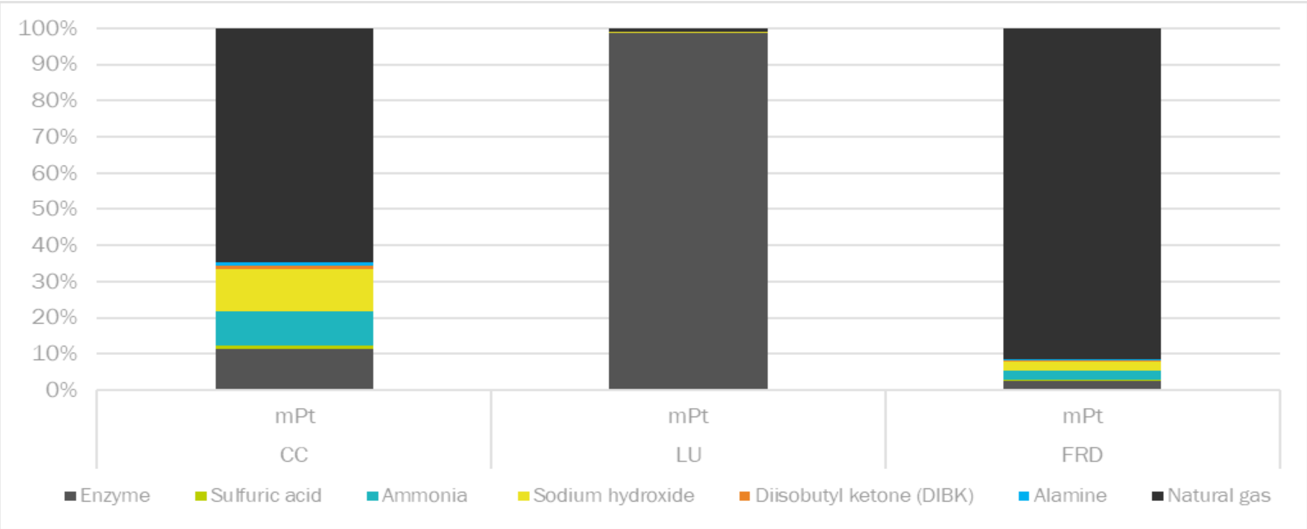

Figure 34. Materials flow weighted impact distribution (Method B) (based on data from Budsberg et al.[17]).

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4.1.8 Wheat straw and Alfalfa valorisation

Parajuli et al.[18] evaluated and compared two standalone biorefineries with an integrated biorefinery plant using a LCA method. The aim of the study was to combine the two standalone systems based on the possible synergy between them. However, this report will focus only on the biorefineries routes and their environmental impacts.

4.1.8.1 Wheat straw valorisation

In this scenario, wheat straw was converted to bioethanol only so there were no other co-products.

Table 29. Case study wheat straw valorisation based on Parajuli et al.[18]

Biomass input
Wheat straw
Output
Bioethanol
Geography area
Denmark
Paper
Environmental impacts of producing bioethanol and biobased lactic acid from standalone and integrated biorefineries using a consequential and an attributional life cycle assessment approach
Author
Ranjan Parajuli, Marie Trydeman Knudsen, Morten Birkved, Sylvestre Njakou Djomo, Andrea Corona, Tommy Dalgaard
Year
2017
Functional Unit
1 kg of wheat straw transported 200 km with a freight to a biorefinery plant, where it will be treated via pretreatment of the feedstock, hydrolysis, saccharification and fermentation, in Denmark.
Reference Flow
1 ton of wheat straw (85 % dry matter)

The environmental impacts related to 1000 kg of wheat straw are shown in Table 30.

Table 30. Damage assessment of wheat straw valorisation (based on data from Parajuli et al.[18]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	6.31E+00	6.31E-03
Climate change	**kg CO2 eq**	6.82E+02	6.82E-01
Ecotoxicity, freshwater	**CTUe**	1.13E+04	1.13E+01
Particulate matter	**disease inc.**	4.88E-05	4.88E-08

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Damage category	Unit	Total	Per kg of feedstock
Eutrophication, marine	kg N eq	2.81E+00	2.81E-03
Eutrophication, freshwater	kg P eq	1.18E-01	1.18E-04
Eutrophication, terrestrial	mol N eq	2.28E+01	2.28E-02
Human toxicity, cancer	CTUh	3.14E-06	3.14E-09
Human toxicity, non-cancer	CTUh	1.70E-05	1.70E-08
Ionising radiation	kBq U-235 eq	2.54E+01	2.54E-02
Land use	Pt	1.83E+04	1.83E+01
Ozone depletion	kg CFC11 eq	2.04E-05	2.04E-08
Photochemical ozone formation	kg NMVOC eq	2.63E+00	2.63E-03
Resource use, fossils	MJ	9.39E+03	9.39E+00
Resource use, minerals and metals	kg Sb eq	3.43E-03	3.43E-06
Water use	m3 depriv.	1.54E+03	1.54E+00

No mass allocation nor economic allocation were performed since this route only produces acetic acid as the principal product, so all the impacts were allocated to it. Considering cradle-to-gate approach, starting with the manufacturing and transport of the raw materials, energy generation and including all chemicals and inputs required for biorefinery operations, the manufacturing of the biochemicals and the emissions or waste treatments at the end of the biorefinery, the life cycle flows related to this process were evaluated. Thus, the most relevant impact categories were climate change (21.78 %), resource use (fossils) (13.77 %), water use (13.07 %), particulate matter (8.41 %), acidification (8.06 %), eutrophication (terrestrial) (5.49 %), eutrophication (marine) (4.88 %) and resource use (minerals/metals) (4.66 %), meaning 80.11 % of the total environmental impacts.

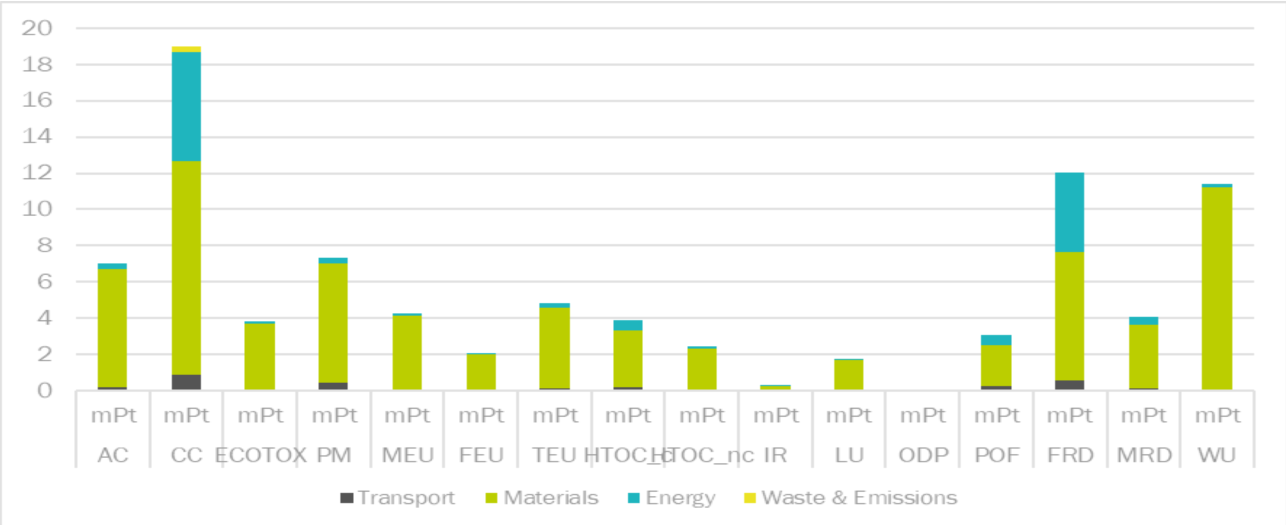

Figure 35. Wheat straw valorisation weighted impact category relevance (based on data from Parajuli et al.[18]).

The weight of the most relevant environmental impacts categories is represented in Figure 36, where materials flows are shown as the most relevant contributor.

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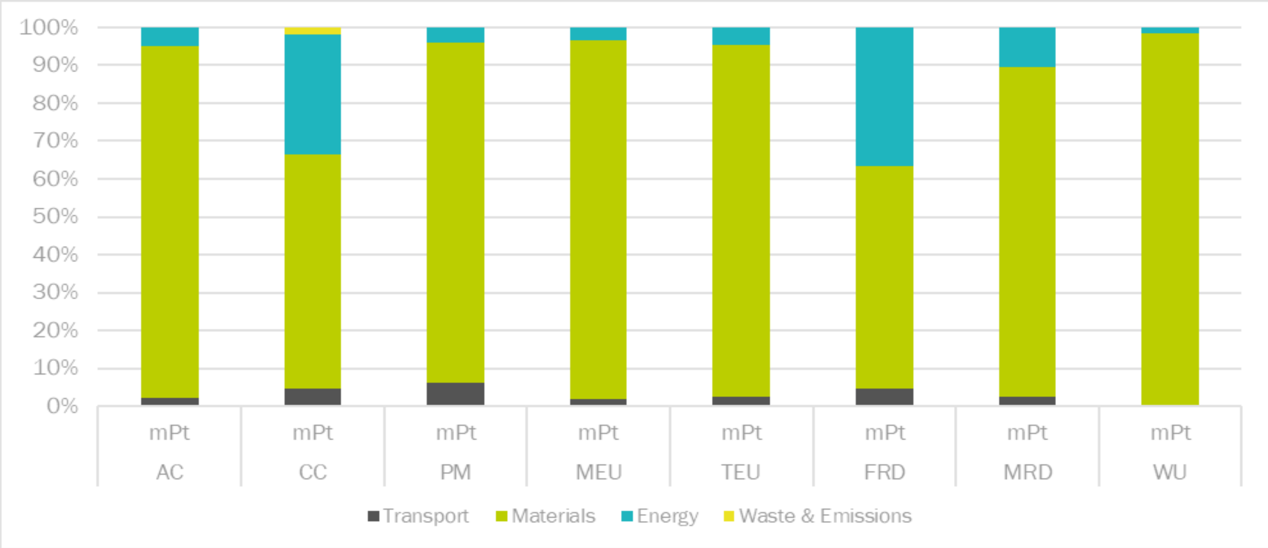

Figure 36. Environmental impacts weighted distribution (based on data from Parajuli et al.[18]).

Looking in detail to the materials flow, its largest contribution was linked to the enzymes used in every relevant impact category, due to large quantities of enzymes required-

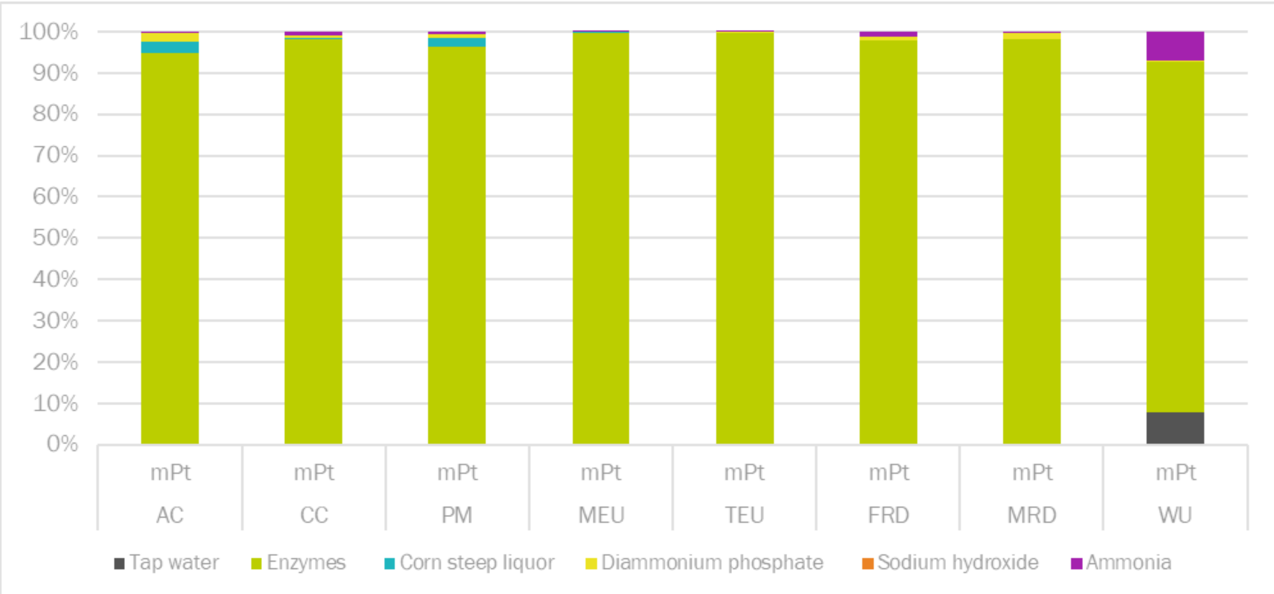

Figure 37. Materials flow impacts weighted distribution (based on data from Parajuli et al.[18]).

4.1.8.2 Alfalfa valorisation

In this scenario, alfalfa biomass was converted to lactic acid (24 %), as the main product, feed protein (7 %) and fodder silage (69 %). According to Parajuli et al.[18] the selling price of final products were 1.36 €/kg of lactic acid, 0.33 €/kg of feed protein and 0.02 €/kg of fodder silage.

Table 31. Case study alfalfa biomass valorisation based on Parajuli et al.[18]

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Biomass input
Alfalfa biomass
Output
Lactic acid, feed protein, fodder silage
Geography area
Denmark
Paper
Environmental impacts of producing bioethanol and biobased lactic acid from standalone and integrated biorefineries using a consequential and an attributional life cycle assessment approach
Author
Ranjan Parajuli, Marie Trydeman Knudsen, Morten Birkved, Sylvestre Njakou Djomo, Andrea Corona, Tommy Dalgaard
Year
2017
Functional Unit
1 kg of wheat straw transported 200 km with a freight to a biorefinery plant, where it will be processed via pretreatment of the feedstock, enzymatic hydrolysis, fermentation and final extraction of products, in Denmark.
Reference Flow
1 ton of alfalfa biomass (35 % dry matter)

The environmental impacts related to 1000 kg of alfalfa are shown in Table 32.

Table 32. Damage assessment of alfalfa biomass valorisation (based on data from Parajuli et al.[18]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	2.86E+00	2.86E-03
Climate change	**kg CO2 eq**	2.85E+02	2.85E-01
Ecotoxicity, freshwater	**CTUe**	5.70E+03	5.70E+00
Particulate matter	**disease inc.**	2.37E-05	2.37E-08
Eutrophication, marine	**kg N eq**	1.33E+00	1.33E-03
Eutrophication, freshwater	**kg P eq**	5.36E-02	5.36E-05
Eutrophication, terrestrial	**mol N eq**	1.09E+01	1.09E-02
Human toxicity, cancer	**CTUh**	1.47E-06	1.47E-09
Human toxicity, non-cancer	**CTUh**	7.73E-06	7.73E-09
Ionising radiation	**kBq U-235 eq**	1.00E+01	1.00E-02
Land use	**Pt**	1.43E+04	1.43E+01
Ozone depletion	**kg CFC11 eq**	9.01E-06	9.01E-09
Photochemical ozone formation	**kg NMVOC eq**	1.21E+00	1.21E-03
Resource use, fossils	**MJ**	3.80E+03	3.80E+00
Resource use, minerals and metals	**kg Sb eq**	1.54E-03	1.54E-06

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Damage category	Unit	Total	Per kg of feedstock
Water use	**m3 depriv.**	6.17E+02	6.17E-01

Table 33. Mass allocation and economic allocation from Damage assessment (based on data from Parajuli et al.[18]).

Damage category	Unit	Mass Allocation			Economic Allocation		
		Lactic acid	Feed protein	Fodder silage	Lactic acid	Feed protein	Fodder silage
AC	mol H+ eq	6.78E-01	1.98E-01	1.99E+00	2.57E+00	1.82E-01	1.11E-01
CC	kg CO2 eq	6.75E+01	1.97E+01	1.98E+02	2.56E+02	1.81E+01	1.10E+01
ECOTOX	CTUe	1.35E+03	3.94E+02	3.96E+03	5.12E+03	3.63E+02	2.21E+02
PM	disease inc.	5.60E-06	1.64E-06	1.64E-05	2.12E-05	1.51E-06	9.16E-07
MEU	kg N eq	3.16E-01	9.22E-02	9.26E-01	1.20E+00	8.49E-02	5.16E-02
FEU	kg P eq	1.27E-02	3.71E-03	3.72E-02	4.81E-02	3.41E-03	2.07E-03
TEU	mol N eq	2.59E+00	7.57E-01	7.60E+00	9.82E+00	6.96E-01	4.24E-01
HTOC_c	CTUh	3.47E-07	1.01E-07	1.02E-06	1.32E-06	9.32E-08	5.67E-08
HTOC_nc	CTUh	1.83E-06	5.35E-07	5.37E-06	6.94E-06	4.92E-07	2.99E-07
IR	kBq U-235 eq	2.38E+00	6.95E-01	6.98E+00	9.02E+00	6.39E-01	3.89E-01
LU	Pt	3.39E+03	9.89E+02	9.93E+03	1.28E+04	9.11E+02	5.54E+02
ODP	kg CFC11 eq	2.13E-06	6.23E-07	6.26E-06	8.09E-06	5.73E-07	3.49E-07
POF	kg NMVOC eq	2.86E-01	8.37E-02	8.40E-01	1.09E+00	7.70E-02	4.68E-02
FRD	MJ	8.99E+02	2.63E+02	2.64E+03	3.41E+03	2.42E+02	1.47E+02
MRD	kg Sb eq	3.65E-04	1.07E-04	1.07E-03	1.39E-03	9.82E-05	5.98E-05
WU	m3 depriv.	1.46E+02	4.27E+01	4.28E+02	4.91E+02	1.19E+02	7.22E+00

Within a cradle-to-gate approach, the impacts of processing alfalfa were estimated. Using the environmental impacts weighted distribution from Parajuli, et al. the most relevant impact categories of the valorisation process were identified. The main impact categories were climate change (20.38 %), resource use (fossils) (12.46 %), water use (11.74 %), particulate matter (9.13 %), acidification (8.19 %), eutrophication (terrestrial) (5.89%), eutrophication (marine) (5.18 %), ecotoxicity (freshwater) (4.95 %) and resource use (minerals/metals) (4.70 %), representing 82.62 % of the total environmental impacts.

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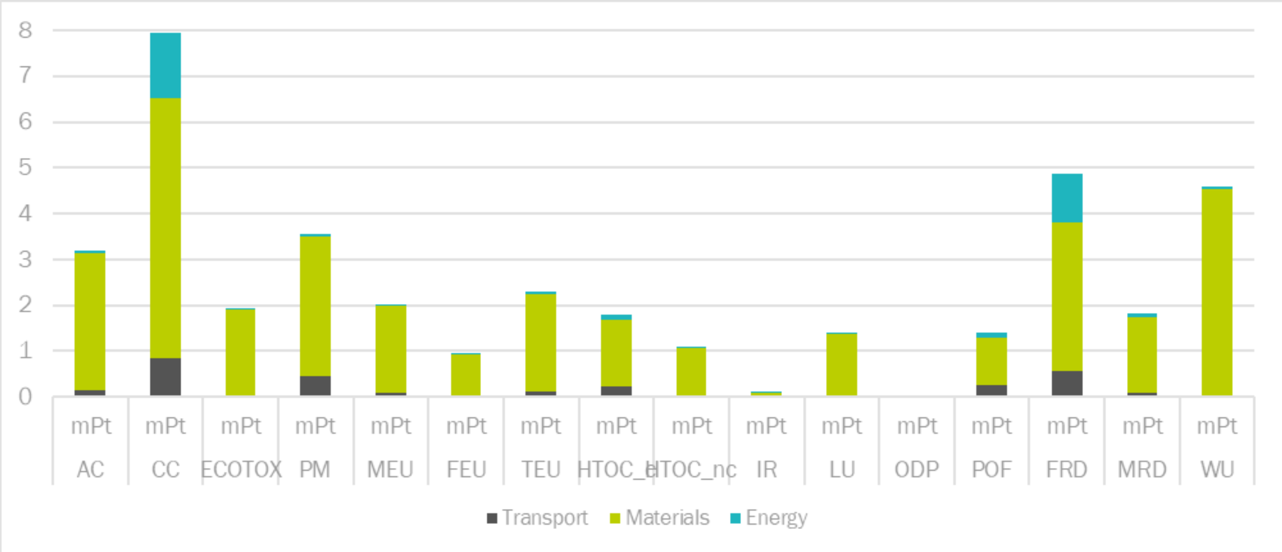

Figure 38. Alfalfa biomass valorisation weighted impact category relevance (data from Parajuli et al.*[18]).*

The weight of the most relevant environmental impacts categories is represented in Figure 39. As it can be seen, the major contribution in every indicator were due to the materials flow.

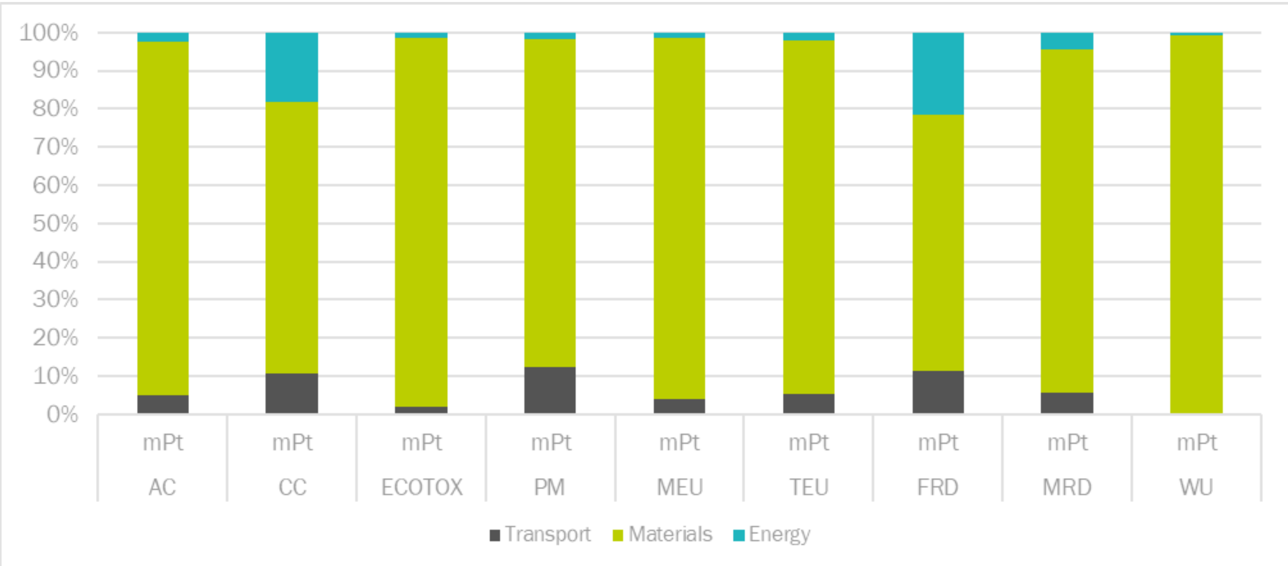

Figure 39. Environmental impacts weighted distribution (data from Parajuli et al.[18]).

Looking materials flow into detail, enzymatic hydrolysis and the related consumption of enzymes were the most relevant contributor to the material flows impacts.

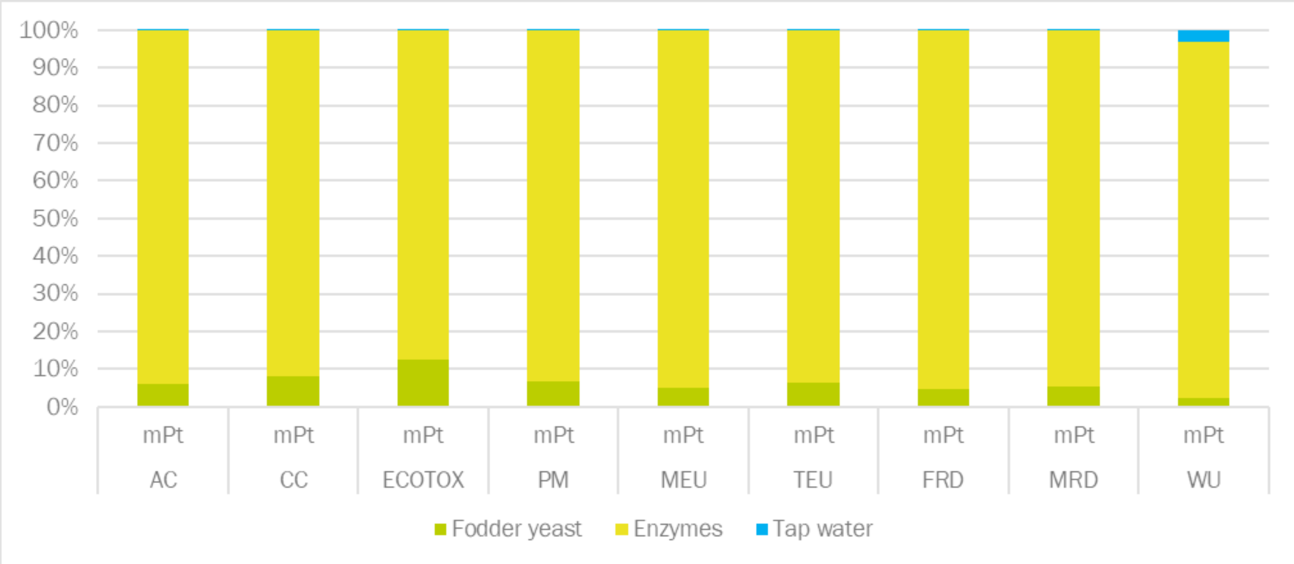

Figure 40. Materials flow impacts weighted distribution (data from Parajuli et al.[18]).

4.1.9 Red microalgae biomass valorisation

Saadia et al.[19] analysed the environmental impacts of three different scenarios for producing polysaccharides from red microalgae biomass. This section is only centred on the route that has the minor carbon footprint associated to the electricity demand.

Originally the study was focused on the cultivation of algae to polysaccharides production. Although the biomass is considered a dedicated-feedstock, the present study did not include the assessment of the cultivation and harvesting process, so the impacts had a gate-to-gate approach.

Table 34. Case study of red microalgae biomass valorisation based on Saadia et al.[19]

Biomass input
Red microalgae
Output
Polysaccharides
Geography area
Israel
Paper
The carbon footprint of polysaccharide production from red microalgae
Author
Karin Saadia, Antionio Dominguez, Selene Cobo
Year
2017
Functional Unit

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1 kg of red algae biomass for valorisation to produce polysaccharides via centrifuge separation, ultrafiltration and dry freezing lyophilization, in Israel.	
Reference Flow	
1,5 kg of red algae biomass	

The environmental impacts associated to the valorisation of 1.5 kg of red algae biomass are shown in Table 35.

Table 35. Damage assessment of red algae biomass valorisation (based on data from Saadia et al.[19]).

Damage category	Unit	Total	Per kg of feedstock
Acidification	**mol H+ eq**	3.59E+00	2.39E-03
Climate change	**kg CO2 eq**	6.97E+02	4.64E-01
Ecotoxicity, freshwater	**CTUe**	1.24E+03	8.28E-01
Particulate matter	**disease inc.**	6.22E-06	4.15E-09
Eutrophication, marine	**kg N eq**	5.22E-01	3.48E-04
Eutrophication, freshwater	**kg P eq**	1.68E-02	1.12E-05
Eutrophication, terrestrial	**mol N eq**	5.78E+00	3.85E-03
Human toxicity, cancer	**CTUh**	8.68E-07	5.79E-10
Human toxicity, non-cancer	**CTUh**	2.70E-06	1.80E-09
Ionising radiation	**kBq U-235 eq**	1.07E+00	7.11E-04
Land use	**Pt**	6.78E+02	4.52E-01
Ozone depletion	**kg CFC11 eq**	1.27E-05	8.48E-09
Photochemical ozone formation	**kg NMVOC eq**	2.21E+00	1.47E-03
Resource use, fossils	**MJ**	9.19E+03	6.13E+00
Resource use, minerals and metals	**kg Sb eq**	6.82E-04	4.55E-07
Water use	**m3 depriv.**	-1.30E+03	-8.64E-01

No mass nor economic allocation were performed since the biorefinery route had just polysaccharides as final product.

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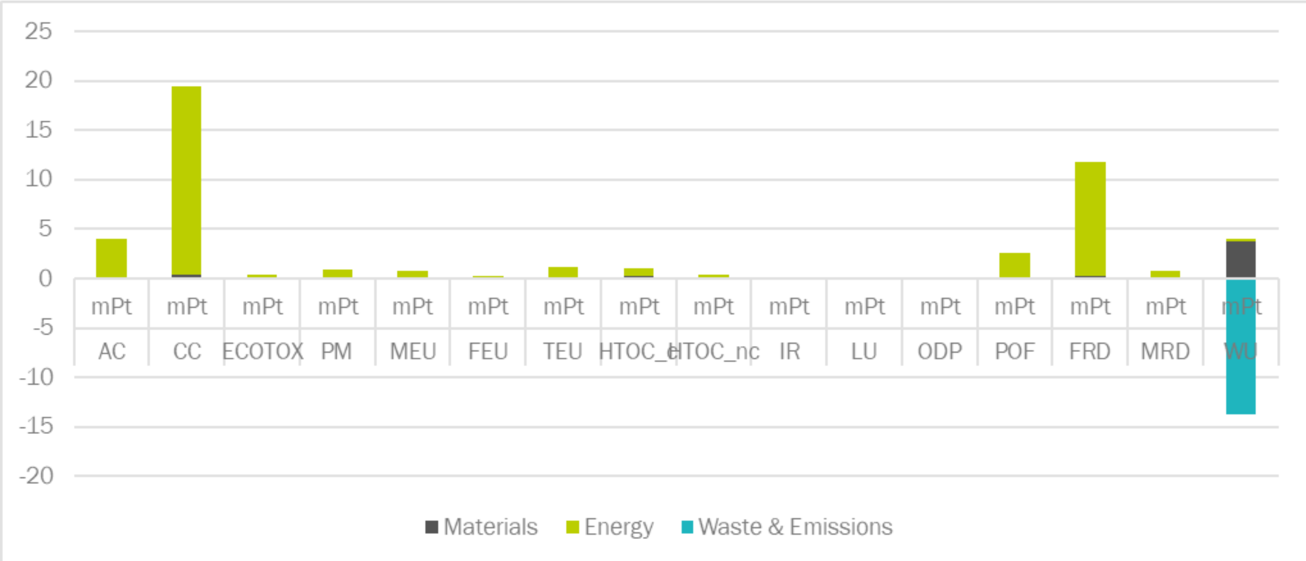

Figure 41. Red microalgae biomass valorisation weighted impact category relevance (data from Saadia et al.[19]).

Considering a cradle to gate scope, the most relevant environmental impact categories were selected from the life cycle assessment of the processing of algae biomass. The most relevant categories from Saadia et al. were climate change (31.56 %), water use (28.85 %), resource use (fossils) (19.11 %) and acidification (6.51 %), since they account the 86.03 % of the total impact.

Focusing on the contribution of the different life cycle flows in each relevant category, it can be seen in Figure 42 that the energy flow was the most significant one, followed by the waste& emissions, and materials. Transport was not considered.

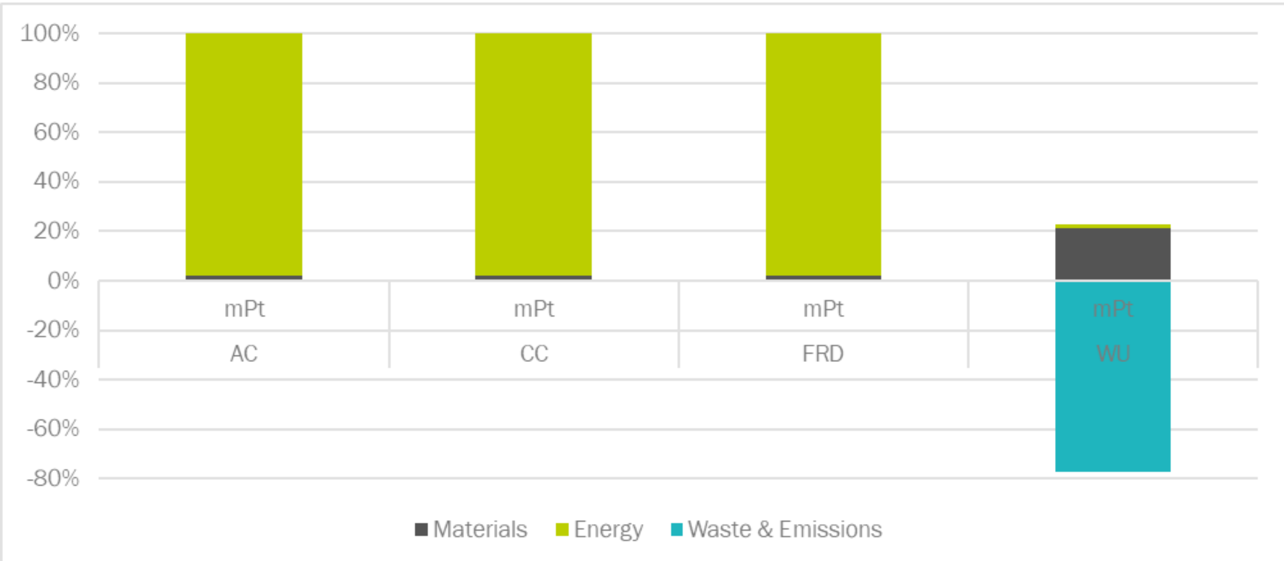

Figure 42. Environmental impacts weighted distribution (data from Saadia et al.[19]).

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In the overall, the greatest contribution was the energy demands of the process since every stage of the biorefinery was energy intensive. Waste and emissions flow represented a benefit to Water Use impact category, mainly due to water recovered by sublimation during the lyophilization stage.

4.2 Overview of the environmental performance of bioprocesses

The principal aim of literature review was to identify the main environmental hotspots of different biobased refineries industries following the LCA methodology. The studies reviewed described various routes of transformation of biomass feedstocks and final products. All studies detailed valorisation processes which were designed to fraction biomass integrally or to obtain the highest conversion as possible, as well as to perform efficiently and at the same time be sustainable, minimizing waste and emissions of the processing.

LCA is a useful methodology to identify the potential environmental impacts of the biorefinery routes and then indicate the direct elementary flows involved in the process, such as resources and emissions, whose contribution influences the most to the sustainability. To conduct LCA studies, the availability of inventory data is key. In general, LCA in scientific literature present detailed inventories but in some cases, they were quite unspecific, for example transport of the raw material to the biorefinery gate or waste flows. The lack of detail on flows (quantities and qualities) may affect the results since several assumptions are needed.

All the studies considered cradle-to-gate approach, starting with the manufacturing and transport of the raw materials and energy required for biorefinery operations, including emissions and waste leaving the system and treated downstream. Saadia, et al.[19] included also the production of the bio-based feedstock. The contribution of the feedstock generation was not accounted to the overall environmental impacts as the authors considered the feedstock as a waste of a previous process, therefore free of environmental impacts. Differences on the scope made comparison between studies difficult.

Focusing on the results of the environmental impacts estimations, the most relevant environmental impact categories are climate change (CC), eutrophication (freshwater) (FEU), resource use (fossil) (RFD), water use (WU) and particulate matter (PM). Their average contributions to the total were CC (28.77 %), FEU (14.97 %), RFD (14.09 %), WU (10.48 %) and PM (8.41 %).

In the overall, the most relevant elementary flows were raw materials manufacturing and energy systems required for processing feedstocks, since their contribution to the total impacts are the most noticeable in all the biotransformation routes studied.

Steam was the main contributor of the material flows and the use of enzymes, and the consumption of ethanol had major relevancy in materials flows, caused by their obtention process and the substantial quantity needed. Replacing fossil fuels with renewable sources or biobased products would reduce environmental impacts, as well as the reduction of the supply's consumption or its reutilization.

Electricity was the biggest contributor within the energy consumption, due to the highly dependence on non-renewable resources for some electricity country mixes. Every studied modelled in the present work, considered electricity grid mix (medium voltage) from the country where the biorefineries were located.

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Substituting non-renewable-electricity-produced with electricity produced from a renewable source could improve the environmental performance of the biorefineries routes.

The use of ethanol was a major contributor to the impact categories, so biobased substitutes could potentially improve the environmental footprint (i.e. study from Shinde, et al.[15]). From the biorefineries studied, four described the obtention route of bioethanol from different feedstock: Barley straw (González-Garcia, et al.[14]), Citrus peel waste (Joglekar, et al.[12]), Rice straw (Sreekumar, et al.[16]) and Wheat straw (Parajuli, et al.[18]). Comparing environmental assessment results in terms of CC through the whole life cycle of the production of bioethanol, Parajuli, et al. biorefinery was identified as the best strategy within the studies reviewed.

Practically all the reviewed processes produced coproducts (considered as value-added marketable). Mass and economic allocations showed that the impacts associated with the production of only one final product was higher than producing coproducts, due to the distributions of burdens. However, economic allocation should be based on accurate information of selling prices.

5 Coming steps: integration and validation

During the proposal phase of BioINSouth, it was anticipated that, in order to achieve the project's objectives—particularly the analysis of ecological limits in implementing a circular bioeconomy as a driver for local development—datasets would be employed to evaluate the environmental sustainability of bioeconomy processes across the targeted regions. Once the implementation phase began, the complexity of methodological choices prompted a review of approaches adopted by several European projects focused on bioeconomy methodologies. Feedback gathered from seven such projects revealed a lack of consensus yet identified a number of shared elements that should be considered in any life cycle assessment (LCA) related to bioeconomy. In particular, a thorough analysis of raw materials and energy inputs in biorefinery processes is essential before drawing robust conclusions on the sustainability of biobased products. At the current stage of implementation, BioINSouth includes the development of nine simplified LCAs for selected bioprocesses. The LCA data resented in chapter 4 will be integrated into the BioINSouth toolkit for Hubs consultation in line with the diagram shows in

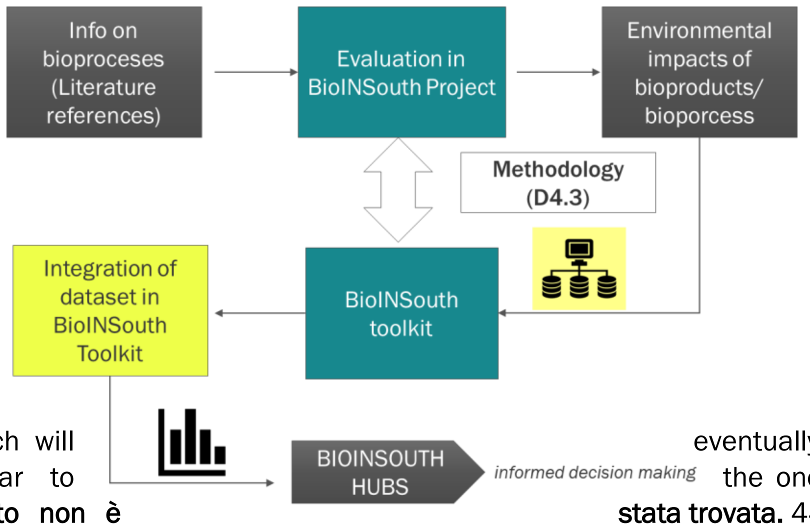

Figure 43, and which will eventually result in a visualisation similar to the one shown in **Errore. L'origine riferimento non è stata trovata.** 44.

Figure 43 LCA Data integration into BioINSouth Toolkit

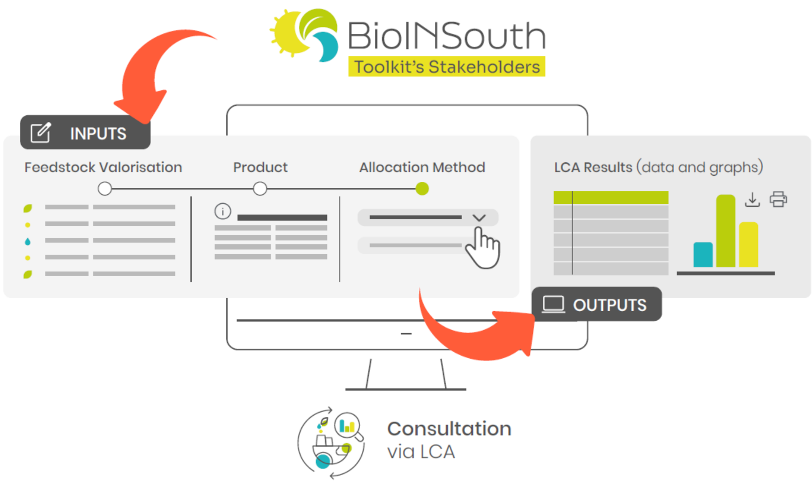

Figure 44 LCA Data integration into BioINSouth Toolkit

For an efficient validation process, in the context of WP4, the MARGs and future members of the BioINSouth HUBs were asked to provide insights on the main areas of action for each region, which was essential information for the identification of specific LCA dataset that would be integrated in the toolkit. Under this goal, a questionnaire was developed to explore potential actions (education, legislation, ...), the scale, the biomass preferences and the target audience that would benefit most by the HUBs. MARGs coordinators gathered the feedback during the KOMs, and the following section graphically represents the feedback received region by region.

A sum of 77 people participated in the questionnaire. The following questions were the ones the MARGs, and future members of the HUBs answered to:

- What do you think will be the main area of action of the BioINSouth Hub in your region?
- At which level the BioINSouth HUB action will have the greatest impact?
- To which biomass (sectors) do you think the HUB's action will be more oriented?

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- Which stakeholders will benefit most from the HUB's actions?

Table 36 shows the results of the questionnaire region by region. Based on the preferences received, it is recommended that the validation process to prioritize the specific regions more oriented to the biomass exploitation (Slovenia, Centro Region and Andalucia). Through the toolkit, regional HUBs could check and compare the environmental footprint of different bio-based processes to evaluate the environmental impacts of their activities. Looking into the potential biomass for these cases, LCA data for agricultural feedstock, industrial bio-waste and forestry biomasses could be prioritized.

Table 36. Graphical representation of the feedback received from the MARGs and future members of the HUBs.

BioINSouth Region	Main area	Level of impact	Most oriented biomass sector	Most benefitted stakeholders
Chart legend	Education/Engagement Legislation/Policy Biomass exploitation R&D projects	Regional Local Industry Market (products)	Agriculture Aquaculture Forestry Livestock Municipal waste Industry biowaste	Industry Citizens Local government Academic/research institutions
Slovenia				
Centro Region				

BioINSouth Region	Main area	Level of impact	Most oriented biomass sector	Most benefitted stakeholders
Chart legend	■ Education/Engagement ■ Legislation/Policy ■ Biomass exploitation ■ R&D projects	■ Regional ■ Local ■ Industry ■ Market (products)	■ Agriculture ■ Aquaculture ■ Forestry ■ Livestock ■ Municipal waste ■ Industry biowaste	■ Industry ■ Citizens ■ Local government ■ Academic/research institutions
Andalusia[5]				
Cyprus				
Campania				
Peloponnese				

[5] Andalusia MARG members marked more than one answer per question.

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Asturias				
Nouvelle-Aquitaine				

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6 Conclusions

This deliverable gatherer the main methodological approaches available for the implementation of environmental assessment of bioeconomy processes. Taking the European environmental footprint initiative as reference, the principal aspects for the Life cycle studies are explored and exemplified. In addition to this, the SSBD is also presented as a useful framework for innovation processes where the principles of the sustainability are embedded from design phases.

The diverse approaches for modelling environmental impacts are recognised as the main principal challenge for the development of LCAs. On the one hand, differences between results from CLCA and ALCA studies emerges with the example provided for ethanol. CLCA considers marginal changes and market-driven shifts, making it difficult to track specific cause-effect relationships, especially when multiple industries are interconnected, as opposed to the more direct, static data-driven approach of ALCA. On the other hand, prospective LCA is a powerful approach for guiding sustainable innovation by integrating future environmental challenges and opportunities into decision-making, but it faces challenges due to the static condition of datasets, being notable the uncertainties in future projections. Tools like premise offer significant potential to enhance the robustness of prospective LCA by integrating projections of future energy systems, material flows, and industrial transformations by the use of Integrated Assessment Models.

Due to the complexity of the methodological decisions, this work also collects feedback from several European projects focused on methodological developments within the bioeconomy. Results received from 7 projects highlight the lack of consensus but some common aspects that should be discussed in any LCA study in bioeconomy. Raw materials and energy consumed in the biorefinery process need to be analysed in detail before robust conclusions can be drawn about the sustainability of biobased products.

The present work also incorporates the development of 9 simplified LCA for selected bioprocesses. From this analysis, it can be concluded that LCA is a useful tool that provides relevant information on hotpots and environmental performance of the bioeconomy. The interpretation of results can become as wide as the complexity of the systems studied and other deeper considerations, such as bio-carbon flows or territorial aspects are not considered. Likewise, technologies with low TRL can be potentially better studied through prospective LCA, which entail the study of future scenarios addressing variation on market variations. Those aspects make the application of LCA more complex and would require the involvement of LCA practitioners on the decision-making process.

For all above-mentioned, BioINSouth foresee the incorporation of life cycle assessment as a decision support system for the BioINSouth HUBs but based on LCA results so it is expected that environmental information on different bioproducts could help guide the work of the HUBs more focused on actions related to the exploitation of biomass.

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BioINSouth Info Box

The BioINSouth project aims to support decision-makers to incorporate considerations of ecological limits into their regional bioeconomy strategies and roadmaps relevant to circular bio-based activities. We aim to develop guidelines and digital tools, considering the safe and sustainable by design (SSbD) assessment framework, to support the adoption of innovative methodologies to assess environmental impacts in multiple industrial bio-based systems, increasing regional competitiveness and innovation capacity, and contributing to the EU fair & green transition.

Find out more:

Website: https://www.bioinsouth.eu/
LinkedIn: https://www.linkedin.com/company/104361906/
YouTube: https://www.youtube.com/@BioINSouth
Contact coordinator:
SPRING the Italian Circular Bioeconomy Cluster info@clusterspring.it

Authors: Inma Sanchez, Daniel Checa, Carmen Sala (LEITAT), Andrea Cavallaro (PNO Innovation Digital)

Review by: Francesco Caracciolo (UNINA), Cristina Viera Bardon (ASINCAR), Pierluigi Argoneto, Lara Carlet (SPRING)

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