EnXylaScope

Unleashing Xylan's Potential with Enzymes
for a Scope of Consumer Products

D7.3

Environmental implications of an innovative enzyme-based process for the production of xylan products

DELIVERABLE 7.3	FINAL REPORT ON ENVIRONMENTAL ASSESSMENT
DELIVERABLE TYPE: REPORT	WORK PACKAGE: WP 7
DISSEMINATION LEVEL: PUBLIC	MONTH AND DATE OF DELIVERY: M45 | 31 JANUARY 2025
LEADER: IFEU	**AUTHORS:**
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PROGRAMME H2020 **|** **CONTRACT NUMBER** 101000831 **|** **DURATION** 48 MONTHS **|** **START** MAY 1ST, 2021

PREPRINT

This version represents the status at the time of submission.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000831

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Revision history

Version	Date	Reviewer	Modifications
1.0	13/12/2024	Internal	First draft
2.0	30/01/2025	All partners	Final

Suggested citation

Breyer, M., Keller, H., Gärtner, S., Rettenmaier, N. (2025): Environmental implications of an innovative enzyme-based process for the production of xylan products (D7.3). In: EnXylaScope project reports, supported by the EU's Horizon 2020 research and innovation programme under grant agreement No 101000831, IFEU - Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany. https://www.ifeu.de/projekt/enxylascope.

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1 Summary

A novel lignocellulose biorefinery concept following a so-called xylan-first approach was developed in the EU-funded project EnXylaScope. Enzyme-assisted alkali extraction designed for wet biomass was found to be suitable for extracting polymeric to oligomeric decolourised xylan as the main product from several lignocellulosic biomass feedstocks. This xylan can optionally be functionalised by enzymes. The potential for high value use of the extracted xylan has been demonstrated in several tested applications. In addition, the biorefinery concept allows high-value use of the co-products cellulose, which can optionally be enzymatically hydrolysed, and several different lignin fractions. While the fermentability of glucose from hydrolysed cellulose has been shown to be similar to that of pure glucose, the recovered lignin is suitable for fractionation and/or uniformisation/depolymerisation which is increasingly found necessary for most types of lignin in high-value applications.

The project is accompanied by an integrated life cycle sustainability assessment covering environmental, economic and social sustainability aspects using a common set of scenarios based on mass and energy balances from detailed process models representing potential future industrial-scale biorefinery variants. The scenarios comprise the use of modified and unmodified xylan as an ingredient in cosmetics and as a health-improving feed additive for pigs. The co-products glucose and lignin are valorised, too.

This report by IFEU covers the environmental assessment. It assesses the potential environmental impacts that can be associated with the future implementation of the biorefinery concept and derives recommendations for their improvement.

Comparison with existing alternatives

If modified xylan is used in cosmetics instead of conventional palm oil-and sugar-based products, deforestation risks and land use weighted by the distance to its natural state can be substantially reduced. Most other environmental impacts show a moderate improvement compared to this conventional, equally bio-based reference. However, disadvantages in terms of summer smog (photochemical ozone creation potential) are possible unless the emission of ethanol vapours from the biorefinery can be largely avoided. Negligible to substantial climate benefits can be achieved mainly depending on land use and land use change associated with biomass provision for the biorefinery and for palm oil-based products in the reference system, respectively. Substantial greenhouse gas emission reductions of around 50% can be achieved if straw-based xylan replaces conventional cosmetics ingredients made using average palm oil. The lower the emissions associated with palm oil provision and the higher the emissions from European arable land on drained peatlands (associated with the cultivation of biorefinery feedstocks such as poplar), the lower the resulting benefits.

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In a second analysed application scenario, the use of xylan as a feed additive has the potential to reduce the pig feed demand by up to forty times the mass of the additive, due to improvements in health and feed conversion efficiency. If this scenario can be realised in practice, the environmental benefits of the xylan produced would be enormous, including more than 80 % and 95 % reduction in climate change and land use, respectively. In this case, at least part of the produced xylan should be used as a feed additive to release enough European arable land for the cultivation of the required biomass feedstock due to the lower feed demand.

The analysed biorefinery concept has the potential to deliver considerable overall environmental benefits compared to conventional, mostly bio-based products that provide the same functionality. This is remarkable at this early stage of development, as the use of co-products has not yet been optimised. In the future, improvements in the integrated biorefinery processes and (co-)product uses beyond the evaluated scenarios could further increase these benefits.

Optimisation levers

The largest contributors to the carbon footprint and other environmental impact categories are the provision of heat followed by biomass and enzyme production and, to a lesser extent, the chemicals required such as hydrogen peroxide or sodium hydroxide. They can be reduced in the following ways:

- The impacts of heat provision can be reduced by two main measures: First, the production of modified water-insoluble xylan results in lower overall impacts compared to unmodified xylan, despite of the additional modification step. This is because modified xylan precipitates easily and therefore energy demand for its purification is lower. If both unmodified and modified xylan can be used in the final consumer product formulations, the latter should hence be preferred from an environmental point of view. Second, electrification of the processes, such as using vapour recompression and heat pumps instead of natural gas boilers, could significantly reduce the environmental footprint of the process heat used and make it largely climate-neutral if renewable electricity is used in the future.
- Both wheat straw and poplar chips have been modelled as biomass feedstocks in EnXylaScope. In a direct comparison, the use of wheat straw as a biomass residue is more favourable from an environmental point of view, as poplar cultivation requires additional land and efforts. Therefore, if suitable for an application, surplus straw should be used as long as sufficient amounts are left on the fields to maintain soil organic carbon levels. Otherwise, poplar from short rotation coppice is acceptable if high-impact products are replaced and no drained peatlands are used. Wherever possible, it should be cultivated in strips on larger fields or adjacent to water bodies to provide benefits in terms of reduced wind erosion and reduced nutrient leaching, respectively.

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- For the internal production of enzymes, optimisation potentials can be found in the electrification of the processes and in the replacement of chemical lysis agents by a mechanical disruption of the cells.
- Efficiency measures such as increasing yields or reducing the required amounts of hydrogen peroxide or sodium hydroxide in the main process or lactose for enzyme production would also be beneficial, as far as technically possible.
- In addition, ethanol vapours released into the atmosphere can be a substantial contributor to summer smog. These specific process emissions should be reduced by appropriate measures.
- The biorefinery should be built on disused industrial sites (“brownfield”) rather than on agricultural land (“greenfield”).

Another way to improve the environmental performance is to replace higher volumes of products with greater environmental burdens: The scenarios evaluated represent initial ideas for lignin valorisation via the METNIN™ fractionation process from project partner MetGen, which could enable high-value material use of lignin fractions in the future. However, it was not part of the technical research and development during the EnXylaScope project and could therefore not be optimised for the application in this biorefinery concept. According to available preliminary datasets, lignin products therefore replace more bio-based commodities than high-value fossil-based products. Further process development or other lignin use options could therefore substantially increase the environmental benefits. In addition, produced 2nd generation glucose provides certain environmental advantages over 1st generation glucose, which is set to be replaced in the scenarios assessed. If it were additionally produced and converted into products that replace fossil-based products, this could lead to greater environmental benefits. Therefore, the next step should be to develop and/or integrate more environmentally beneficial applications of lignin and glucose.

Outlook

Reducing the environmental impacts compared to current products is important but climate neutrality must be reached during the expected lifetime of newly built plants, such as those according to the EnXylaScope concept, if the climate goals of the Paris Agreement are to be met. We have studied the extent to which it is possible to provide the required external inputs in a climate-neutral manner and what internal measures need to be taken. The most important design step towards climate neutrality is the full electrification of the plant. Together with the sourcing of inputs from emerging decarbonised production described in the report, the EnXylaScope concept could come close to climate neutrality. However, biomass provision, even from residues such as straw, will remain a source of emissions, as emissions such as nitrous oxide from the soil cannot be avoided.

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2 Introduction

Hemicellulosic xylan is one of the most abundant polymers in plants. If appropriately modified by enzymes, xylan polymers have unique properties and can be incorporated in various consumer products. However, the biobased sector has focused on cellulose and lignin as further lignocellulose polymers, and existing enzyme treatments often results in monomeric xylan. Hence, xylan is often considered as a side-stream of low value. The EU-funded project EnXylaScope aimed to develop a new biorefinery concept with a xylan-first approach. This includes an effective xylan extraction from various wet biomass feedstocks, optional enzymatic modifications of the extracted xylan, and recovery of the co-products cellulose and lignin for high-value applications.

One main motivation for the EnXylaScope project is to improve the technology, economics as well as environmental and social sustainability impacts of advanced pre-treatment, separation and conversion technologies for complex lignocellulosic biomass. The sustainability assessment within this project ensures that process and product improvements lead to a more sustainable performance over the whole life cycle.

Work package 7 of the EnXylaScope project conducts an integrated life cycle sustainability assessment analysing the three main pillars of sustainability: environment, economy and society. This document contains the environmental assessment of the scenarios commonly defined for all parts of the integrated sustainability assessment [Bedzo et al. 2022].

3 Methodology

In order to achieve reliable and robust sustainability assessment results, it is inevitable that the principles of comprehensiveness and life cycle thinking (LCT) are applied. Life cycle thinking means that all life cycle stages for products are considered, i.e. the complete supply or value chains, from the production of biomass, through processing in the biorefinery and production of the end user products, to product use and end-of-life treatment / final disposal (see section 3.1.2). Through such a systematic overview and perspective, the unintentional shifting of environmental burdens, economic benefits and social well-being between life cycle stages or individual processes can be identified and possibly avoided or at least minimised. The performance of each product and co-product is compared to alternative reference products.

This assessment is based on the methodology of Integrated Life Cycle Sustainability Assessment (ILCSA) [Keller et al. 2015]. The structure of WP 7 that implements this integrated life cycle sustainability assessment is depicted in Figure 1.

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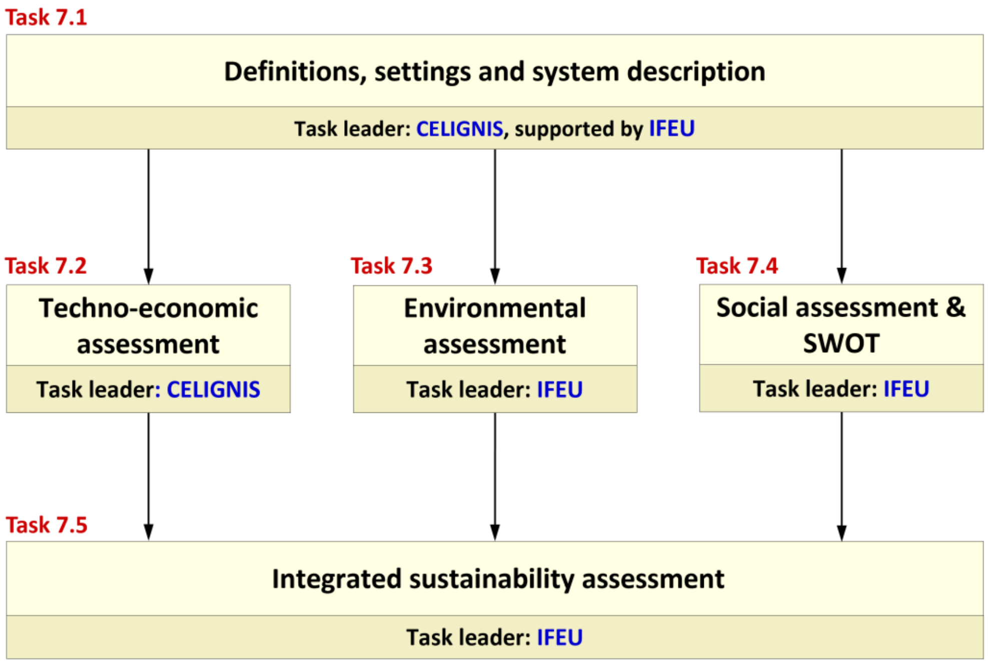

Figure 1: Structure of the work package on sustainability assessment in EnXylaScope.

Common definitions and settings such as goal and scope of the assessment are described in section 3.1 and the specific methodologies and settings applied for the environmental assessment are described in section 3.2 for life cycle assessment and section 3.3 for the assessment of local impacts.

3.1 Common definitions and settings

A well-founded sustainability assessment requires common definitions and settings on which the environmental, techno-economic and social assessment will be based. Thus, general definitions and settings lead to an efficient professional communication between the project partners in WP 7 and ensure consistent data and results for the integrated sustainability assessment. The goal and scope definition is the first phase of any sustainability assessment and is relevant for all three sub-analyses on the environmental, economic and social impacts.

3.1.1 Goal definition

The comprehensiveness and depth of detail of the sustainability assessment can differ considerably depending on its goal. Therefore, the intended applications, the reasons for carrying out the study, the decision context as well as the target audiences and the commissioner have to be described within the goal definition.

Intended applications

The aim of the sustainability assessment within the EnXylaScope project is to support decision-making:

- Project-internal decision support of ongoing process development. Thus, this study is an ex-ante assessment, as the systems to be assessed have not yet been implemented in this particular form on a relevant scale and for a sufficiently long period of time.
- Provide a basis for communicating the findings of the EnXylaScope project to external decision makers, i.e. academia, industry, policy makers and the general public.

Target audience

Defining the target audience helps to identify the appropriate form and technical level of reporting. The target audience is divided into

- Project partners and
- External stakeholders
    - Scientists
    - Decision makers in industry
    - Political decision makers
    - Interested laypersons

Guiding questions

The following key research questions guide the sustainability assessment.

Main question:

To what extent and under which conditions can the EnXylaScope biorefinery concept contribute to a more sustainable supply of the targeted xylan-based products?

This main question leads to the following sub-questions:

- How does the studied EnXylaScope concept compare from a sustainability perspective to equivalent conventional fossil- and/or bio-based products?
- How does the studied EnXylaScope concept compare from a sustainability perspective to other use options of the same biomass or land, in particular by other competing xylan extraction processes?[1]

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[1] This question identified at the beginning of the project was decided not to follow-up further because no relevant competing xylan extraction process with sufficient data availability or other alternative biomass/land use option with particular relevance for the biorefinery concept to be assessed could be identified.

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- Which unit processes and (co-)product uses determine the results significantly and what are the optimisation potentials?
- Do conflicts exist between the different sustainability indicators or perspectives on sustainability (such as environmental, economic, social)? If yes, how could they be resolved or managed?

3.1.2 Scope definition

With the scope definition, the object of the sustainability assessment (i.e. the exact product or other system(s) to be analysed) is identified and described. The scope should be sufficiently well defined to ensure that the comprehensiveness, depth and detail of the study are compatible and sufficient to address the stated goal. Resulting definitions and settings are used in the subsequent analyses (tasks) to guarantee the consistency between the different assessments of environmental, economic and social implications.

System boundaries

System boundaries specify which unit processes are part of the production system and thus included into the assessment.

The sustainability assessment of the EnXylaScope system considers the products' entire value chain (life cycle) from cradle to grave, i.e. from resource extraction to the utilisation and end of life of the products (Figure 2). For the equivalent conventional reference products, the entire life cycle is considered, too.

This setting was chosen, because the concept of life cycle thinking integrates existing consumption and production strategies, preventing a piece-meal approach. Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium or protection target to another.

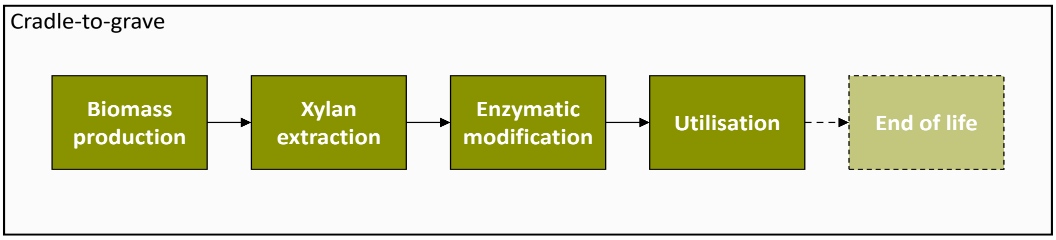

Figure 2: System boundary (cradle-to-grave) applied within the EnXylaScope project.

Geographical coverage

Geography determines several background datasets used such as on prices of materials, feedstocks and logistics or electricity generation systems.

Decision:

- Priority 1: EU (all calculations are based on generic European datasets), because this makes the results most valuable for European decision-makers to evaluate the performance and consider next steps.
- Priority 2: If more specific datasets are required, a country in the EU has to be selected as exemplary location. The country and region of commercial plant location influences the feedstock choice, availability, financial benefits in terms of support from the EU and local government, local wages, energy prices etc. Exemplarily, Ireland was chosen as location for a future EnXylaScope plant.

Technical reference

The technical reference describes development status, maturity and scale.

A mature technology on industrial scale ('nth plant') is considered in the sustainability assessment. The technologies developed by the various partners is at the lab or pilot scale. The data generated is extrapolated and supplemented with expert opinion and other reliable sources to model the realistic industrial scale equivalents of such technologies in order to allow for a fair comparison with already existing mature technologies.

Plant scale

A large-scale plant for hemicellulose extraction processes that is currently reported to be operational by a Swedish company is about 15 000 tonnes of biomass dry matter input per year which corresponds to approximately 45 tonnes per day which is relatively small scale compared to large 2nd generation ethanol biorefineries (150 000 - 250 000 tonnes of biomass per year). The scale of 15 000 tonnes/year processing was adopted as a sufficient baseline scale for the xylan production facility.

Timeframe

Like geography, the timeframe of the assessment determines background datasets used, e.g. for impacts related to power generation and labour costs.

2030 was selected as the first realistic year in which the technology could be mature and available as establishing the routine, learning from pilot plants, improving technology and products, implementing a steady state commercial scale production will take a considerable amount of time.

Settings for system modelling

A scenario-based assessment is applied. Each analysed scenario represents a realistic potential future implementation of the assessed technologies. When deriving the mass and energy flow data for these generic scenarios, data obtained from project partners' experiments, databases and literature were taken into consideration, but were not used directly (i.e. only after extrapolation). Uncertainty and future freedom of choice are covered by applying ranges of values from 'conservative' via 'typical' to 'optimistic'.

Each scenario represents a complete life cycle from cradle to grave, i.e. one specific combination of options for each processing step.

3.2 Specific definitions and settings for life cycle assessment (LCA)

The screening life cycle assessment (LCA) is based on international standards such as [ISO 2006a; b] and the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012]. In the following, specific settings and methodological choices are detailed.

3.2.1 Introduction to LCA methodology

Life cycle assessment (LCA) is structured, comprehensive and internationally standardised through ISO standards 14040:2006 and 14044:2006 [ISO 2006a; b]. The LCA within the EnXylaScope project is carried out largely following these ISO standards on product life cycle assessment. According to the ISO standards, a LCA consists of four iterative phases):

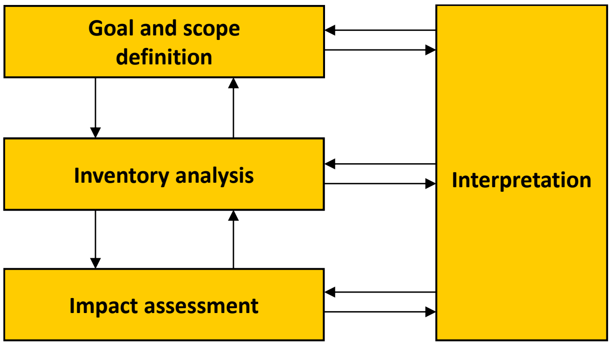

Figure 3: Phases of an LCA[ISO 2006a; b].

- Goal and scope definition (see section 3.1.1 and 3.1.2)
- Inventory analysis (see section 3.2.2),
- Impact assessment (see section 3.2.3), and
- Interpretation (see chapter 5).

The ISO standards 14040 and 14044 provide the indispensable framework for life cycle assessment. This framework, however, leaves the individual LCA analysts with a range of choices, which can affect the legitimacy of the results of an LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance.

The International Reference Life Cycle Data System (ILCD) Handbook [JRC-IES 2012] has therefore been developed to provide guidance and specifications that go beyond the ISO standards 14040 and 14044, aiming at consistent and quality-assured life cycle assessment data and studies. The screening LCA study carried out within the EnXylaScope project takes into account the major requirements of the ILCD Handbook following these considerations of flexibility and strictness. The analyses in this study are so-called screening LCAs which follow the above-mentioned ISO standards except for a)

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the level of detail of documentation, b) the quantity of sensitivity analyses and c) the mandatory critical review. Still, the results of these screening LCAs are suitable to answer the goal questions reliably due to the close conformity with the ISO standards.

3.2.2 Settings for Life Cycle Inventory (LCI)

Settings for Life Cycle Inventory include the following aspects:

I Data sources

II Attributional vs. consequential modelling

III Co-products handling

IV Infrastructure

I Data sources

Primary data on mass and energy balances is provided by task 7.1 on definitions, settings and system description, which has collected inputs from all technology development partners in the project. Modelling with Aspen plus was used by Celignis to integrate all data into consistent biorefinery scenarios. Further secondary data such as on background processes were taken from IFEU's internal database [IFEU 2024], from the ecoinvent database [ecoinvent database] and from literature data where necessary.

II Attributional vs. consequential modelling

The sustainability assessment can follow a consequential or attributional approach, which has implications for the methodological approach to co-products, indirect effects, etc., especially in LCA. Consequential modelling is more extensive and 'aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy' according to the ILCD Handbook [JRC-IES 2010]. Consequential modelling is recommended for decision-contexts where influential impacts are expected on a meso/macro-level [JRC-IES 2010]. This is the case for the EnXylaScope systems. Hence, a consequential modelling approach is applied in this assessment.

III Co-products handling

As explained in section 3.1.2, the system boundary includes all products and co-products. For each usable co-product produced, the environmental burdens of the main product need to be reduced. The general alternatives concerning this procedure of co-product handling are exemplarily illustrated in Figure 4. System expansion is applied, which according to ISO standards for LCA [ISO 2006a; b] is preferred over allocation: the impacts of a multi-output system are balanced with the avoided impacts of the reference products that are replaced by the products of the multi-output system.

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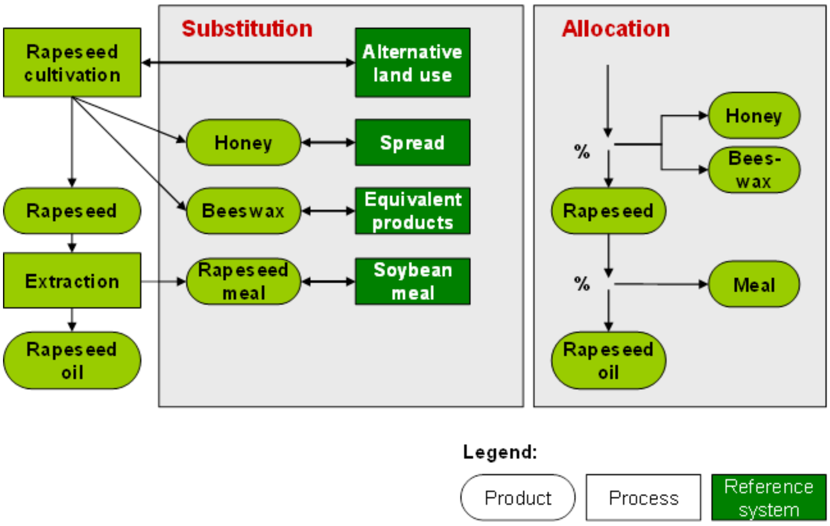

Figure 4: Exemplary illustration of methodological approaches for co-product accounting.

IV Infrastructure

Infrastructure is not included in the inventory of the foreground system at the current state of development. This applies to production and processing equipment, buildings and streets.

3.2.3 Settings for Life Cycle Impact Assessment (LCIA)

According to ISO standard 14040 [ISO 2006a], life cycle impact assessment (LCIA) includes the mandatory steps of classification and characterisation as well as the optional steps of normalisation and weighting. Classification and characterisation depend on the chosen impact categories and LCIA methods. Regarding the optional elements, only the normalisation step is applied within the EnXylaScope project. The corresponding specifications of these LCIA elements are described in the following sections including

I Impact categories and LCIA methods

II Normalisation

III Weighting.

I Impact categories and LCIA methods

All main environmental issues related to the EnXylaScope value chain should be covered within the impact categories of the screening life cycle assessment in a comprehensive way. Furthermore, the impact categories must be consistent with the goal of the study and the intended applications of the results. Potential environmental impacts can be analysed at midpoint or at endpoint level. For environmental assessments within technology development projects such as EnXylaScope, the midpoint level is considered

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as more suitable than the endpoint level because the impacts are analysed in a more differentiated way and the results are more accurate. This project assesses the midpoint indicators listed in Table 1. The LCIA methods follow the recommendations in [Detzel et al. 2016].

Table 1: Overview on included midpoint impact categories.

Midpoint impact category	LCIA method
Non-renewable energy use (NREU)	[Borken et al. 1999; VDI (Association of German Engineers) 2012]
Climate change	[IPCC 2021]
Acidification	[CML 2016]
Eutrophication, terrestrial	[CML 2016]
Ozone depletion	[Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010]
Photochemical ozone formation (summer smog)	[van Zelm et al. 2008]
Particulate matter formation (winter smog)	[de Leeuw 2002]
Land use (weighted; Distance-to-Nature-Potential [DNP])	[Fehrenbach et al. 2019]
Phosphate rock use	[Reinhardt, Rettenmaier, & Vogt 2019]

This set of methods also includes two long-neglected impact categories covering environmental issues: phosphate rock footprint and land use footprint:

The phosphate rock demand is dominated by phosphorus requirements of agricultural processes or fermentation processes and but other life cycle stages may also play an important role. The associated impacts on phosphorus resources are covered by the impact category ‘phosphate rock footprint’ [Reinhardt, Rettenmaier, & Vogt 2019].

Impacts on natural land use are addressed by the hemeroby approach according to [Fehrenbach et al. 2019]. This approach includes both the degree of human influence on a natural area and the distance of that area to the undisturbed state.

Impact categories that are irrelevant for the EnXylaScope value chains are excluded from this study. This is the case for ionising radiation, for example. Furthermore, impact categories are excluded (i) that are still too immature to provide conclusive results or (ii) that cannot ensure sufficient LCI data quality for the reference year 2030 (i.e. impact categories on toxicity). Specific issues on human health are nevertheless covered by the categories particulate matter formation and photochemical ozone formation.

II Normalisation

Normalisation in LCA is an optional step to better understand the relative magnitude of the results for the different environmental impact categories. To this end, the category indicator results are set into relation with reference information. Normalisation transforms an indicator result by dividing it by a selected reference value, e.g. a certain

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emission caused by the system is divided by this emission per capita in a selected country.

Within the EnXylaScope project, the value chains are characterised for Europe. Therefore, the resource demand and emissions per capita in the European region are chosen as reference for normalisation. Last available data from [Sala et al. 2015] are taken. These values refer to the year 2010 and the EU 28 countries.

III Weighting

Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis. Weighting is not applied in this study.

3.3 Settings and methodology for the assessment of local impacts

There are a number of environmental management tools that differ both in terms of subject of study (product, production site or project) and in their potential to address environmental impacts occurring at different spatial levels. Environmental life cycle assessment (LCA), for example, addresses potential environmental impacts of a product system (see section 3.2). However, for a comprehensive picture of environmental impacts, also local/site-specific impacts on environmental factors like e.g. biodiversity, water and soil have to be considered. Although methodological developments are under way, these local/site-specific impacts are not yet covered in standard LCA studies. Thus, for the time being, LCA has to be supplemented by elements borrowed from other tools.

The methodology applied in this project borrows elements from environmental impact assessment (EIA) [and partly from strategic environmental assessment (SEA)] and is therefore called life cycle environmental impact assessment (LC-EIA) [Keller et al. 2014; Kretschmer et al. 2012].

3.3.1 Introduction to EIA methodology

Environmental impact assessment (EIA) is a standardised methodology for analysing proposed projects, notably major building or development projects, regarding their potential to affect the local environment. It is based on the identification, description and estimation of the project's environmental impacts and is usually applied at an early planning stage, i.e. before the project is carried out. EIA primarily serves as a decision support for project management and authorities which have to decide on approval. Moreover, it helps decision makers to identify more environmentally friendly alternatives as well as to minimise negative impacts on the environment by applying mitigation and compensation measures.

The environmental impacts of a planned project depend on both the nature/ specifications of the project (e.g. a biorefinery plant housing a specific production process and requiring specific raw materials which have to be delivered) and on the

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specific quality of the environment at a certain geographic location (e.g. occurrence of rare or endangered species, air and water quality etc.). Thus, the same project probably entails different environmental impacts at two different locations. EIA is therefore usually conducted at a site-specific/local level. These environmental impacts are compared to a situation without the project being implemented ("no-action alternative").

Regulatory frameworks related to EIA

Within the European Union, it is mandatory to carry out an environmental impact assessment (EIA) for projects according to the Council Directive 85/337 EEC "on the assessment of the effects of certain public and private projects on the environment" [CEC 1985]. This Directive has been substantially amended several times. In the interests of clarity and rationality the original EIA Directive and its subsequent amendments has been codified into a single new act (Directive 2011/92/EU) [European Parliament & Council of the European Union 2011] which is still in force today. The latter has once again been amended in 2014 through Directive 2014/52/EU [European Parliament & Council of the European Union 2014].

EIA methodology

An EIA covers direct and indirect effects of a project on certain environmental factors. The list of factors has been substantially altered with the 2014 amendment (addition and deletion of factors) [European Parliament & Council of the European Union 2014] and currently covers the following ones:

- population and human health
- biodiversity (previously: fauna and flora)
- land (new), soil, water, air and climate
- material assets, cultural heritage and the landscape
- the interaction between these factors

Please note: the relatively new factor "land" is indirectly addressed in the conflict matrices (via the factors "soil" and "landscape") since implementing rules for the new factor "land" are lacking or under development. Moreover, we continue to address the two factors "fauna" and "flora" separately, since we think that "biodiversity" alone wouldn't cover all aspects that were previously addressed under "fauna" and "flora" (e.g. the conservation/Red List status of species). This way, more specific recommendations can be derived.

An EIA generally includes the following steps:

- Screening
- Scoping
- EIA report

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  - Project description and consideration of alternatives
  - Description of environmental factors
  - Prediction and evaluation of impacts
  - Mitigation measures
- Monitoring and auditing measures

Screening

Usually, an EIA starts with a screening process to find out whether a project requires an EIA or not. According to Article 4 (1) and Annex 1 (6) of the EIA Directive, an EIA is mandatory for *"Integrated chemical installations, i.e. those installations for the manufacture on an industrial scale of substances using chemical conversion processes, in which several units are juxtaposed and functionally linked to one another and which are"*

- *"for the production of basic organic chemicals"* (6a).

Annex 1 (6) makes reference to manufacture on an industrial scale using 'chemical conversion processes'. 'Chemical conversion processes' imply that transformation by one or several chemical reactions takes place during the production process. This also holds for a biotechnological or biological process that is mostly associated with a chemical conversion (e.g. fermentation). This and further guidance is found in [DG Environment 2024]

Thus, referring to Annex 1 (6) of the EIA Directive, an EIA would be required if one of the studied facilities was implemented.

Scoping

Scoping is to determine what should be the coverage or scope of the EIA study for a project as having potentially significant environmental impacts. It helps in developing and selecting reasonable alternatives to the proposed action and in identifying the issues to be considered in an EIA. The main objectives of the scoping are:

- Identify concerns and issues for consideration in an EIA.
- Identify the environmental impacts that are relevant for decision-makers.
- Enable those responsible for an EIA study to properly brief the study team on the alternatives and on impacts to be considered at different levels of analysis.
- Determine the assessment methods to be used.
- Provide an opportunity for public involvement in determining the factors to be assessed, and facilitate early agreement on contentious issues.

EIA report

An EIA report consists of a project description, a description of the status and trends of relevant environmental factors and a consideration of reasonable alternatives including against which predicted changes can be compared and evaluated in terms of importance.

- Impact prediction: a description of the likely significant effects of the proposed project on the environment resulting from:
    - The construction/installation of the project; temporary impacts expected, e.g. by noise from construction sites.
    - The existence of the project, i.e. project-related installations and buildings; durable impacts expected e.g. by loss of soil on the plant site.
    - The operation phase of the project; durable impacts expected, e.g. by emission of gases.

Prediction should be based on the available environmental project data. Such predictions are described in quantitative or qualitative terms considering e.g.:

- Quality of impact
- Magnitude of impact
- Extent of impact
- Duration of impact

Mitigation measures are recommended actions to avoid, prevent, reduce or offset the potential adverse environmental consequences of development activities. The objective of mitigation measures is to maximise project benefits and minimise undesirable impacts.

Monitoring and auditing measures

Monitoring and auditing measures are post-EIA procedures that can contribute to an improvement of the EIA procedure.

Monitoring is used to compare the predicted and actual impacts of a project, so that action can be taken to minimise environmental impacts. Usually, monitoring is constrained to either potentially very harmful impacts or to impacts that cannot be predicted very accurately due to lack of baseline data or methodological problems.

Auditing is aimed at the improvement of EIA in general. It involves the analysis of the quality and adequacy of baseline studies and EIA methodology, the quality and precision of predictions as well as the implementation and efficiency of proposed mitigation measures. Furthermore, the audit may involve an analysis of public participation during the EIA process or the implementation of EIA recommendations in the planning process.

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3.3.2 The LC-EIA approach in this project

Within this project, several integrated scenarios for a new xylan-extracting lignocellulose biorefinery concept are analysed. Each scenario is defined by the utilised biomass feedstock, the biorefinery inputs, the modification level of xylan, the downstream processes and the final products. This is also reflected in the objectives and common definitions and settings of the sustainability assessment (section 3.1): the aim is to qualitatively assess the impacts associated with each of the potential future investigated concepts (in the sense of technological concepts) at a generic level. The assessment is not meant to be performed for a planned facility at a certain geographic location.

Environmental impact assessment (EIA), however, is usually conducted specifically for a planned (actual) project (see previous section 3.3.1). For the purpose of the EnXylaScope project, which neither encompasses the construction of an actual industrial-scale facility, it is therefore not appropriate to perform a full-scale EIA according to the regulatory frameworks. Monitoring and auditing measures, for example, become redundant if a project is not implemented, as they are post-project procedures. Consequently, monitoring and auditing measures are omitted within this project. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the systems investigated in this project at a generic level. The elements of EIA used in this project are shown in Figure 5.

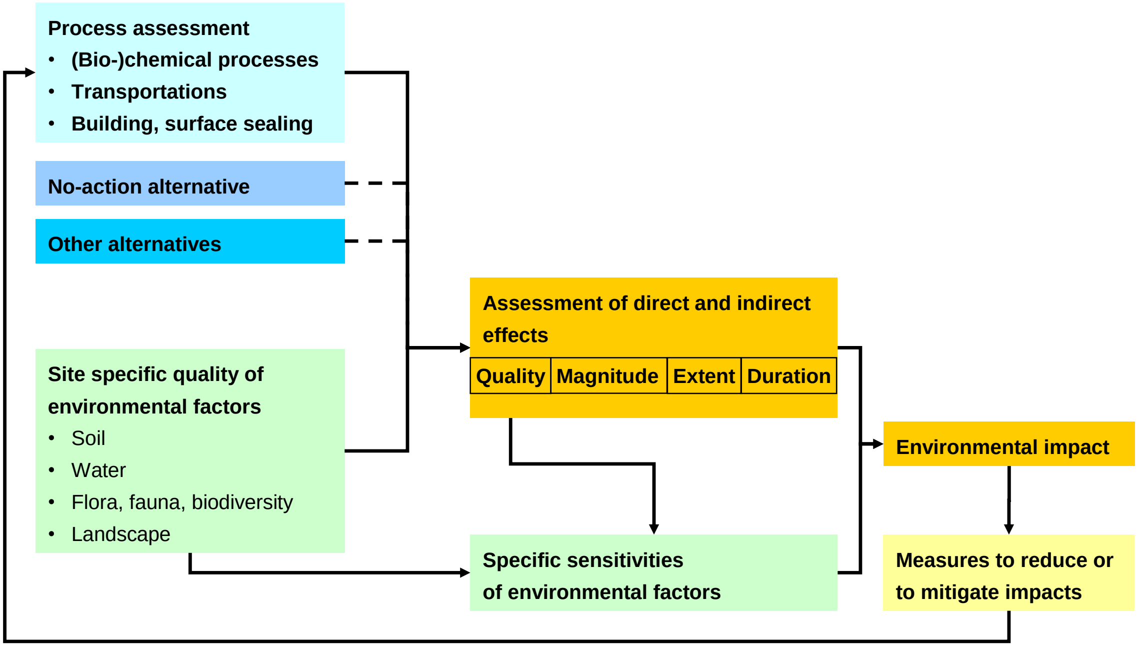

Figure 5: Structure of an LC-EIA.

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Reference systems

Generally, an EIA compares a planned project to a so-called “no-action alternative” (a situation without the project being implemented) in terms of environmental impacts. This assessment is restricted to one specific project or site such as a processing facility. Production sites for raw material inputs (e.g. biomass) and/or the impacts associated with the end use of the manufactured products are usually not considered.

Within this life cycle-based sustainability assessment, the scope, and therefore also the reference system, of the LC-EIA was chosen to encompass all life cycle stages from resource extraction though conversion to the utilisation and end of life of the final products. This corresponds to a life cycle perspective and goes beyond the regulatory frameworks for EIA.

Impact assessment

The assessment of local environmental impacts along the life cycle is carried out as a qualitative benefit and risk assessment. This is useful if no certainty exists regarding the possible future location of biomass production sites and biorefinery facilities.

For this qualitative impact assessment, so-called conflict matrices are used. These present in an aggregated manner the types of risk associated with each of the scenarios including a ranking of the impacts into five categories from A (low risk) to E (high risk). An example is given in the following Table 2.

Table 2: Comparison of scenarios regarding the risks associated with their implementation.

Type of risk	Scenario 1	Scenario 2	Scenario 3	Scenario 4	...
Soil erosion					
Soil compaction					
Eutrophication					
Accumulation of pesticides					
Depletion of groundwater					
Pollution of groundwater					
Pollution of surface water					
Loss of landscape elements					
Loss of habitat/biodiversity					

Categories (A = low risk, E = high risk): A B C D E

For lignocellulosic biomass from residues or dedicated crops, which are the targeted biomass feedstocks for the EnXylaScope concept, crop-specific conflict matrices are used. An example is provided in the following Table 3.

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In these crop-specific conflict matrices, the environmental impacts of biomass cultivation are compared to a reference system (relative evaluation) and evaluated as follows:

- "positive": compared to the reference system, biomass cultivation is more favourable
- "neutral": biomass cultivation shows approximately the same impacts as the reference system
- "negative": compared to the reference system, biomass cultivation is less favourable.

Finally, mitigation measures could be deducted from these conflict matrices. However, since the sustainability assessment within this project is not targeting a specific location, mitigation measures are omitted.

Table 3: Risks associated with the cultivation of a specific annual/perennial crop.

Type of risk	Affected environmental factors								
	Ground water	Surface water	Soil	Plants/Biotopes	Animals	Climate/Air	Landscape	Human health/ recreation	Biodiversity
Soil erosion									
Soil compaction									
Eutrophication									
Accumulation of pesticides									
Pollution of groundwater									
Pollution of surface water									
Loss of landscape elements									
Loss of habitat/biodiversity									

Categories: positive - neutral – negative

4 System description

This chapter provides a description of the EnXylaScope processes as well as the assessed variants, reference systems, and final scenarios

4.1 Overview of the EnXylaScope concept

Figure 6 below provides an overview of the EnXylaScope value chain assessed in this report as it could be implemented on industrial scale based on its present state of

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conception. The value chains include the provision of biomass, processing in the biorefinery and production of the end user products, to product use and end-of-life treatment or final disposal.

The process begins with the collection or cultivation and transportation of selected lignocellulosic biomasses (wheat straw and poplar woodchips) to the process facility where the feedstock is subjected to a series of size reduction and milling processes to generate biomass of the desired particle size. The biomass is subjected to pretreatment to remove the extractives and other monomeric compounds together with a fraction of lignin. The process then employs aqueous alkaline treatment under specified conditions to facilitate the liberation and dissolution of the hemicellulosic content of the biomass, followed by a series of separation and purification processes to ultimately generate unmodified or modified xylans. Selected valorisation pathways for the cellulose- and lignin-rich side streams are also modelled. Finally, the various combinations of feedstock type, xylan modification and xylan consumer product application result in six EnXylaScope biorefinery scenarios, each with three sub-scenarios depicting a range of process efficiencies, that are assessed for economic, environmental and social impacts.

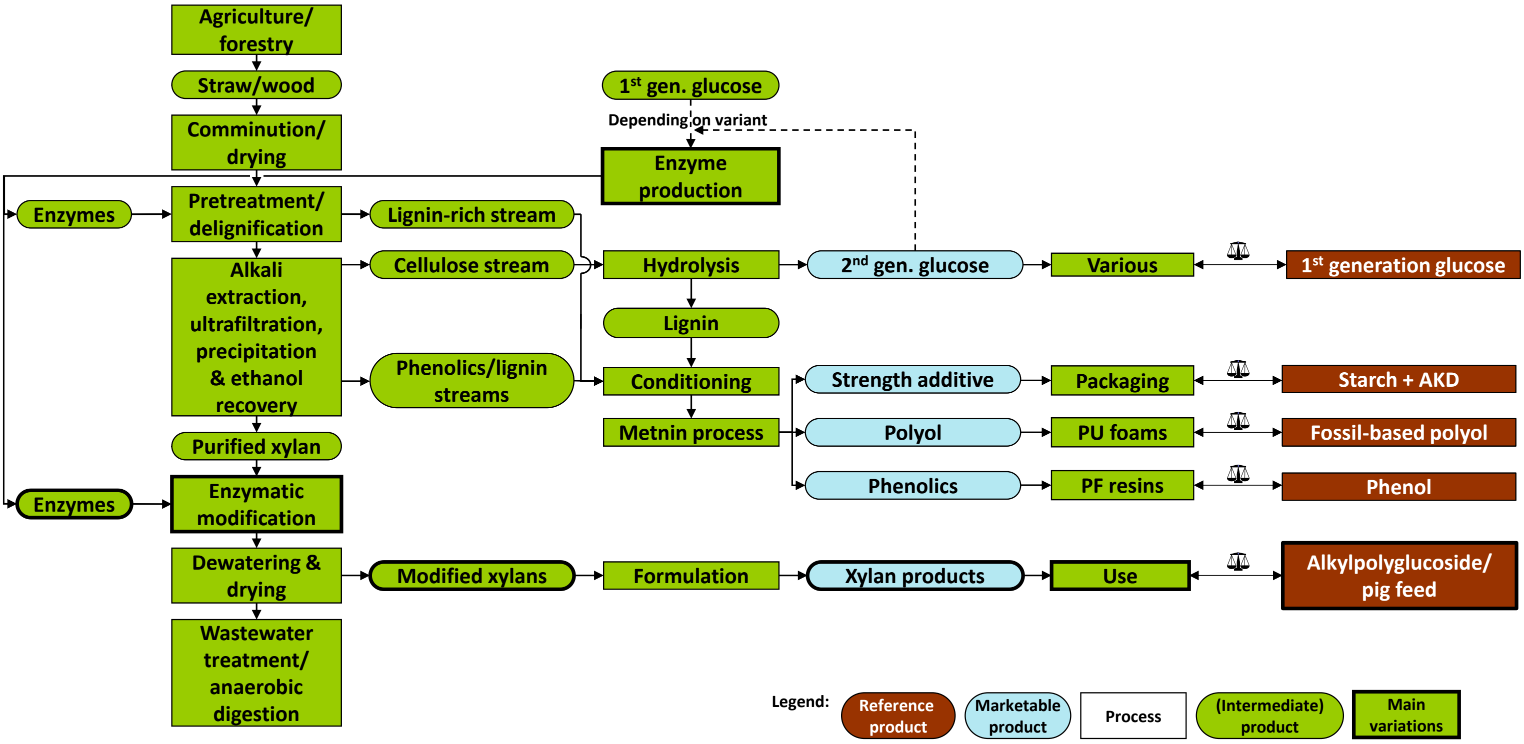

Figure 6: Simplified diagram showing the xylan extraction process in a biorefinery concept.

4.2 Process description

The xylan production process described here is principally based on a technology demonstrated at small scale by CELIGNIS. The performance values and outcomes from the small-scale experiments were supplemented with additional data from literature

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and expert communication to develop a conceptually scaled-up process. In a first step, the feedstock provision and the production of unmodified xylan (shown in Figure 7) are described in sections 4.2.1 to 4.2.6. Differences in the production of modified xylan are described in section 4.2.7.

4.2.1 Feedstock provision

Two feedstocks (wheat straw, poplar woodchips) were found to be suitable candidates for a sustainable production of xylan. The xylan in wheat straw mainly exists in the form of Glucurono(arabino)xylans (GAX), whereas the predominant xylan in the poplar woodchip is the O-acetyl-(4-O methyl-glucurono)xylan (GX). The feedstocks further differ with regard to the relative share of xylan/C5, cellulose/C6, and lignin. While poplar woodchips yield higher amounts of cellulose and lignin than wheat straw, xylan output is lower. The xylan type produced from the poplar woodchips so far generated the most favourable outcomes for the consumer product applications. However, wheat straw has the potential for improved performance with the implementation of certain optimisation steps. Therefore, both feedstocks are considered.

Poplar short rotation coppice

This feedstock represents an example of a dedicated perennial crop used to produce lignocellulosic biomass on agricultural land. It can be cultivated in several ways on whole fields or in strips between annual crops using fertiliser and low amounts of pesticides. A plantation is usually used for about 20 years and harvested every 3-7 years. The wood is chipped on the fields, directly transported to the biorefinery and used after optional short-term storage without drying.

Cereal straw (wheat)

This residue is extracted from wheat fields after the harvest. Depending on soil properties, straw is extracted around every third year to preserve soil organic carbon levels. Removed nutrients are supplemented by additional fertiliser in the next crop rotation.

4.2.2 Feedstock preparation

The unmodified xylan production process begins with the delivery of the feedstock at the gate of the production plant. Size reduction before the treatment of the biomass is of utmost importance for the maximisation of xylan recovery from the biomass. The particle size influences the kinetics of the hydrolytic processes, the efficiency of heat and mass transfer and the physical modification of the biomass. Conventionally, a smaller particle size provides a larger surface area for heat and mass transfer and product recovery. However, this impacts the milling power requirements as well as the overall cost of the process. Generally, the energy consumption of grinding a biomass is a function of the initial particle size, moisture content, properties of the material, the feed rate of the material as well as the machine variables. The poplar woodchips or wheat straw biomass when delivered to the plant is milled to the desired particle size.

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A hammer mill was identified as a suitable equipment for the milling process as it is cheap to operate and has the tendency to deliver a wide range of particle sizes.

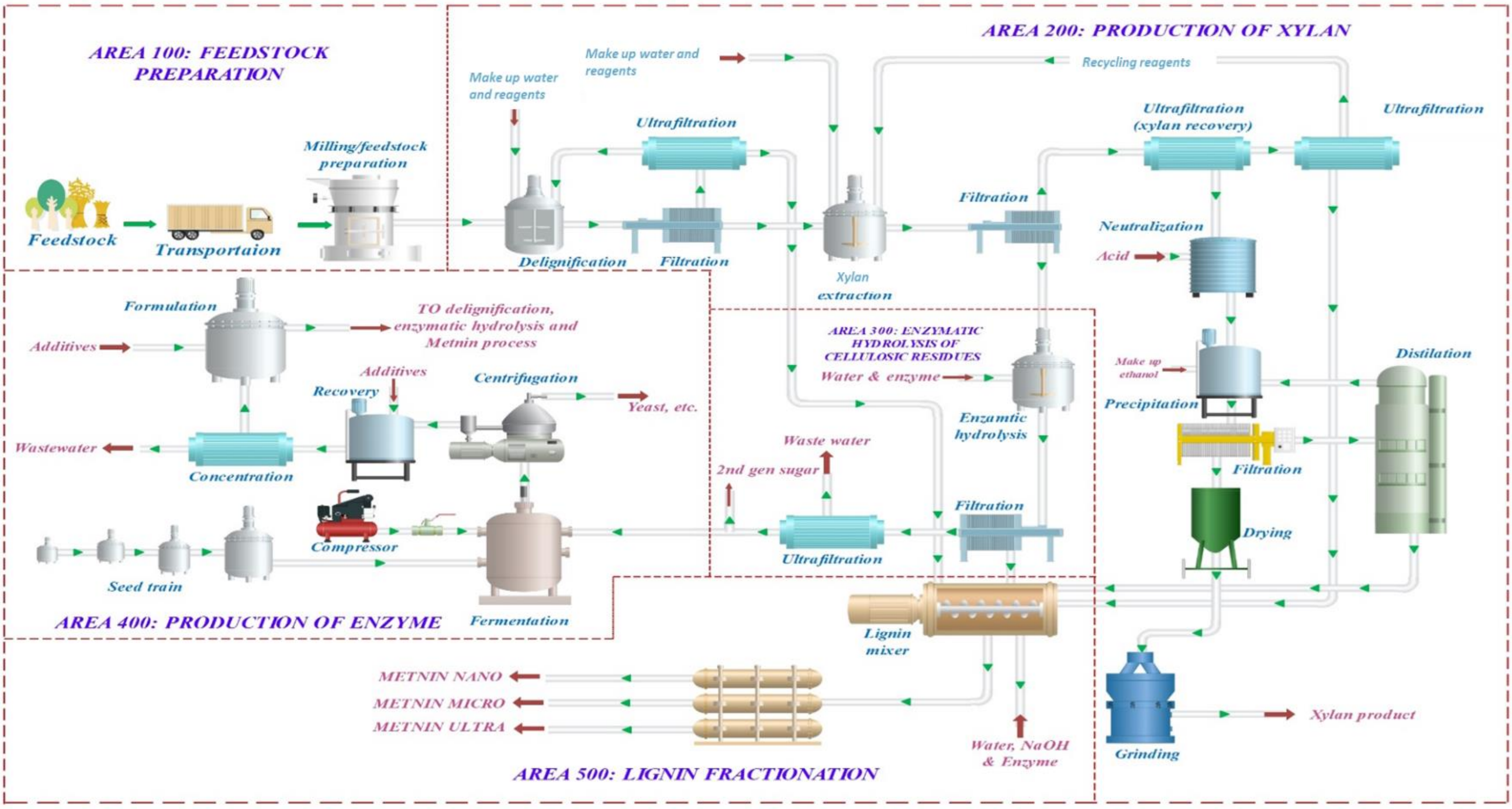

Figure 7: Simplified process flow of unmodified xylan production in a biorefinery concept.

4.2.3 Production of unmodified xylan

Delignification

Due to the generally recalcitrant nature of the wheat straw and poplar chips feedstock, a delignification pretreatment process is carried out to remove some lignin and certain other extractives which interfere with the hemicellulose liberation and solubilisation during the alkaline treatments to extract xylan.

Here, the milled biomass is loaded into a jacketed continuously stirred tank reactor with heating. This is followed by adjusting the pH and addition of catalysts for carrying out delignification. After the reaction, the slurry is channelled to a plate and frame filter where the extractives and lignin rich supernatant is separated from the solid cake. The solid cake is transferred to the second reactor for xylan extraction.

Alkali treatment

The solid cake from the delignification pretreatment process is loaded into the xylan extraction reactor and the reagents are added to the vessel. After the reaction is completed, the reactor effluents are discharged and filtered through a plate and frame

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filter to separate the xylan rich supernatant from the solid cake (cellulosic rich residues), followed by ultrafiltration to separate the low molecular weight materials (salts, pigments and phenolics) from the xylan product. The ultrafiltration leads to the concentration and purification of the xylan rich stream to obtain a more purified final product and the significantly reduced supernatant volume leads to the requirement of a significantly reduced ethanol for precipitation in the subsequent steps. The permeate from xylan concentration and purification is subjected additional step of ultrafiltration, where the reagents are recovered leaving the phenolics and other low molecular weights material which are channelled to lignin valorisation.

Neutralisation

The purified xylan rich supernatant is fed to stirred tank where the pH is adjusted slowly by the addition of HCl. A quantity of ethanol is then added to the mixture to allow precipitation of xylan.

Filtration

The resulting suspension mixture from the neutralisation is then subjected to a membrane filtration, to separate the precipitated xylan from the rest of the supernatant (mostly ethanol and water with salts, phenolics and monomeric sugars).

Vacuum drying and milling

The filtered xylan cake is vacuum dried at a temperature of 40 ^{o}C to obtain the solid xylan with a moisture content of 10% - 12%. This method has been tested in the lab scale and delivers xylan of good quality. The dried xylan is milled to deliver the material in powdered form.

It must be noted that several drying approaches (convection oven drying, vacuum drying, air drying and freeze drying) were tested. The freeze-drying process delivers a product with the best texture and appearance. But the expensive nature of the freeze-drying process may have economic implications during scale up. The vacuum drying appears as the ideal drying method as it limits exposure of the xylan to atmospheric air and also expedites the drying process due to the decreased pressure.

Ethanol recovery

A significant amount of ethanol is consumed in the precipitation of the xylans. The filtration processes that are designed to separate the precipitated xylans from the supernatants generates liquid waste streams which contain at least 50% ethanol and the rest being water with a small amount of dissolved and suspended solids. The distillation process was simulated with rigorous vapour-liquid equilibrium calculations in Aspen Plus using a RADFRAC model. As per the Aspen model, the aqueous ethanol waste stream is fed above stage 9 of the distillation column containing 20 stages. The required molar reflux ratio is 3. This ensures that the vapour overhead is a mixture containing 90% ethanol, resulting in least 90% recovery of the ethanol. The regenerated stream containing 90 % ethanol is removed as the vapour overhead which is condensed and recycled to areas requiring the use of ethanol.

In order to maximize the recovery of ethanol from the bottoms, the reboiler of the column should be maintained at a temperature that ensures a good compromise between the ethanol recovery and energy usage. The distillation bottom, mainly water containing phenolics, sugars, salts and suspended solids is channelled to lignin valorisation. Considering that the precipitation is carried out in a medium of aqueous ethanol (50 % v/v), a 100 % pure ethanol is not necessarily required. A single distillation column which generated an ethanol recycle stream of 90 % is sufficient for the ethanol recovery. The 90 % ethanol steam would be supplemented with make-up ethanol to reach the desired concentration for xylan precipitation. This design circumvents the additional capital and operating costs requirements of regenerating a 100 % pure ethanol by introducing a rectification column together with a vapour-phase molecular sieves adsorption. Future works would consider the use of vapour recompression system to further make the ethanol recovery process more sustainable and energy efficient.

4.2.4 Enzymatic hydrolysis of cellulosic residues

The cellulose rich residue from the xylan production is mixed with water in a jacketed CSTR vessel and cellulases are added. The reaction is allowed to proceed for 48 hours at 50 ^{o}C. After the reaction is completed, the reaction is briefly heated to 90 ^{o}C to stop the enzyme activity. The mixture is then cooled and filtered to separate the hydrolysate from the lignin rich solid residues. The filtered hydrolysate is further taken through a series of ultrafiltration steps to purify the stream and to also concentrate the solution to a glucose concentration of about 13 % (w/w). A portion of the glucose is allocated to enzyme production on site and the rest is sold for revenue generation. It is assumed that the downstream processing plant that purchases the glucose is in close proximity and would utilise the stream for fermentation processes that generally only require a glucose concentration of approximately 10 % (w/w). Hence a further concentration of the glucose solution to a syrup was not carried out.

4.2.5 Production of enzyme

All enzymes produced for utilisation in the EnXylaScope process are set to be produced on-site via the MetGen’s E. coli production platform that uses glucose as the carbon source. After the enzyme production, the cells lysis to obtain the enzyme is achieved with MetGen’s proprietary formulation. The broth is centrifuged to recover the enzyme liquor which is applied directly in the other areas.

4.2.6 Lignin fractionation (METNIN process)

This area is not an integral part of the EnXylaScope biorefinery, but it was introduced as an example of how to achieve sufficient valorisation of the lignin streams emanating from the xylan production process. The lignin and phenolic rich streams from the various

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areas (pretreatment of the feedstock, xylan extraction ethanolic bottoms, permeate from ultrafiltration of xylan supernatant and residues from enzymatic hydrolysis of cellulosic residues) are pooled together and taken through the MetGen's proprietary lignin valorisation process, which is seen as promising technology for this purpose. Used models of this process are based on initial estimates of performance for the given lignin characteristics. Since lignin valorisation via this process was not developed in this project, details could not be adapted and optimised. The enzymes and chemicals used in the process are recycled via a reverse osmosis (RO) filtration system.

METNIN™ Lignin Refining Technology enables the circumvention of the complexity of the lignin molecule. With the power of biotechnology, METNIN™ breaks down any type of lignin gently and affordably into specific fractions. These METNIN™ fractions are tailored to end-user needs to possess the chemical characteristics desired for the specific applications. For a list of products and the respective conventional equivalent products please see section 4.3.2.

4.2.7 Process variant: modified xylan

The production of the modified xylan is similar to that of the production of the unmodified xylan with a few modifications (Figure 8). In this case, the neutralized xylan rich supernatant is treated with enzymes and filtered to recover the xylan. Because of the reduced consumption of ethanol in the production of the modified xylan, the ethanol recovery section is significantly scaled down. All other unit operations and processes are the same as the unmodified xylan. The side stream from the process is combined with other lignin rich streams for energy generation or valorisation via the METNIN process.

Depending on the applied enzymes, the modification can yield either water-insoluble (WIS) or low molecular weight (LMW) xylan. Both modification processes are so similar taking uncertainty regarding upscaling into account that identical mass and energy balances were used.

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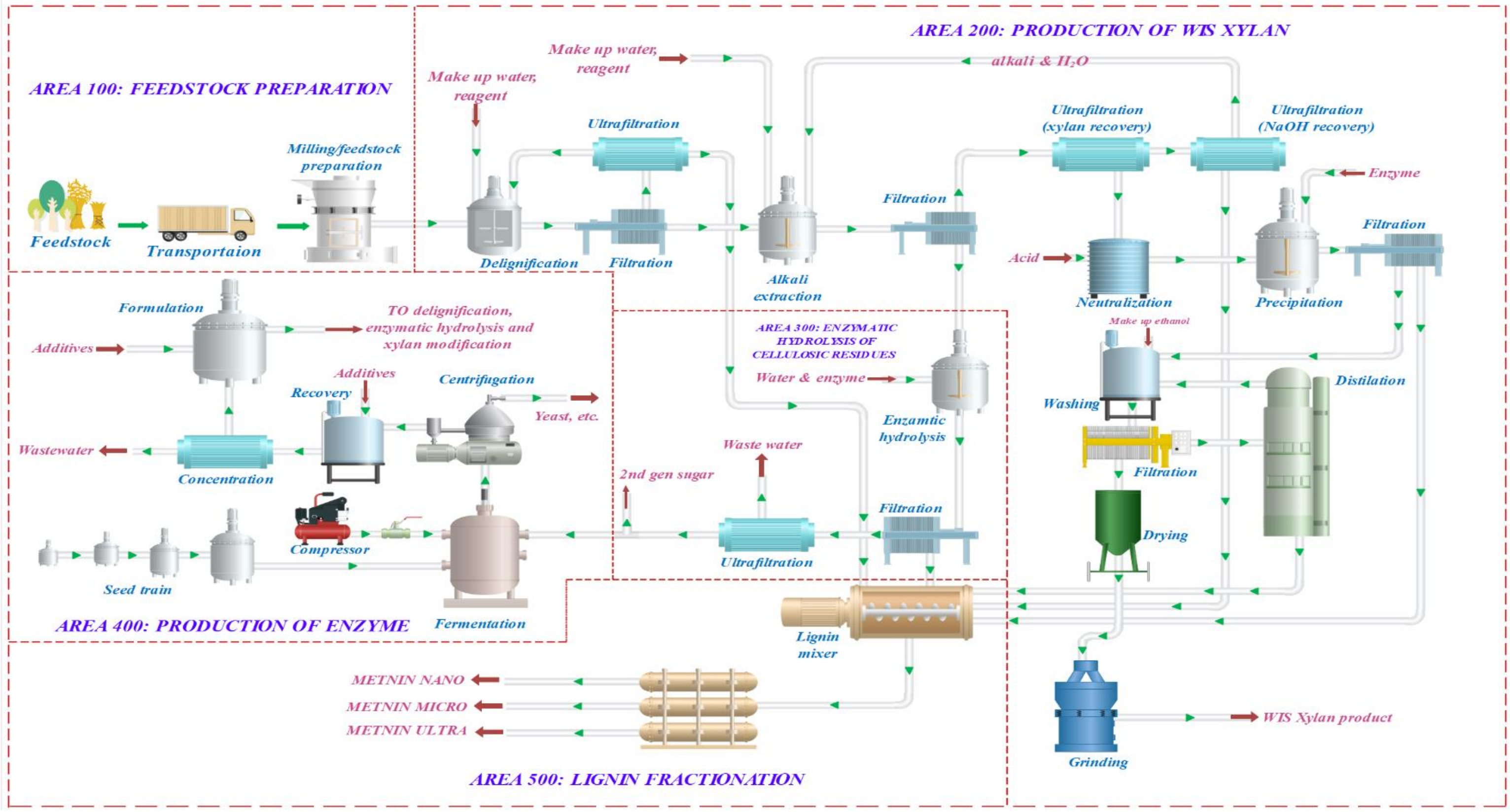

Figure 8: Simplified process flow of modified xylan production in a biorefinery concept.

4.3 Reference system

To assess if future implementation of the developed biorefinery concept leads to environmental benefits, sustainability impacts of products and co-products of the biorefinery are compared to those of conventional reference products that serve the same purpose and would be used instead. This section specifies the respective reference systems for the main product xylan (section 4.3.1) as well as the co-products 2nd generation glucose and lignin-based products (section 4.3.2).

4.3.1 Xylan reference systems

Within EnXylaScope, two different use options for the produced xylan are investigated. The respective reference products replaced are described below. Table 4 summarises the use options represented in the analysed scenarios and the types of xylan used.

Alkyl polyglucoside

Water-insoluble xylan can be used in cosmetic formulations as a potential replacement for alkyl polyglucoside (APG), a conventional palm oil- and sugar-based product. Alkyl polyglucoside is produced by a linkage of D-glucose and cetearyl alcohol. The latter is derived from palm kernel oil [Guilbot et al. 2013; Martinez et al. 2017].

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Additive for pig feed

The unmodified and modified low molecular weight xylans produced can be added to pig feed formulations (0.05-0.1% dry mas) to achieve improved gut health that can result in improved feed to weight conversion (2%) and reduced mortality (0.5%). Per kg (dry matter) of xylan added, this can result in saving 39 kg (dry matter) feed if expert expectations can be met in practise. Saved feed of a typical simple composition is considered as the reference system:

Adult pigs:

- 38% corn
- 18.6% soy
- 40% wheat
- 3% mineral feed
- 0.4% lysin

Piglets:

- each 1/3 soy, wheat and corn

Table 4: Types of xylans and their use cases.

Xylan used	Application	Product category	Replaced conventional product
Water-insoluble (WIS) xylan	Moisture cream / lotion	Cosmetics	Alkyl polyglucoside (APG)
Unmodified xylan	Additive to improve feed use efficiency	Pig feed additive	Part of pig feed
Low molecular weight (LMW) xylan	Additive to improve feed use efficiency	Pig feed additive	Part of pig feed

4.3.2 Co-product reference systems

The reference products replaced by the co-products 2nd generation glucose and lignin-based products are described below. The share of the replaced reference products by mass is provided in Table 5.

2nd generation glucose from cellulose

Glucose from cellulose hydrolysis serves as the carbon source for the fermentation to produce all enzymes used in the process. The rest is sold as 2nd generation glucose syrup. In both cases, it replaces 1st generation glucose that would otherwise be used.

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Lignin-based products

The pooled lignin streams are utilised via a lignin fractionation process. The METNIN™ process by the project partner MetGen was set as promising exemplary technology.

METNIN™ products include intermediate lignin fractions as well as ready-to-use formulations for industrial materials and chemicals. In the investigated scenario, the following products are produced which replace different conventional reference products:

- METNIN™ Resin which is a renewable component in phenol-formaldehyde resins and replaces the hazardous phenol.
- METNIN™ NANOPolyol which replaces fossil-based polyols in polyurethane foams.
- METNIN™ SHIELD which is designed to be applied in fibre packages as a moisture barrier. In this function, it replaces a conventional sizing agent consisting of both alkyl ketene dimer and starch.

Table 5: Share of the mass of reference products replaced by co-products.

Reference product	Phenol	Polyol	Alkyl ketene dimer	Starch	Glucose syrup
% of total reference products replaced by co-products	12 %	3%	5%	28%	52%

4.4 Description of scenarios

All variants described in sections 4.2.1 to 4.3 have to be combined to scenarios that each represent a consistent potential future implementation of the biorefinery concept. A total of six scenarios with three sub-scenarios each were investigated considering the expected suitability of the xylan products for the respective applications (Table 6).

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Table 6: EnXylaScope biorefinery scenarios for LCA evaluations.

FEEDSTOCK	APPLICATION	XYLAN MODIFICATION	SUB-SCENARIO
POPLAR	FEED ADDITIVE	UNMODIFIED	Conservative
			Typical
			Optimistic
		LOW MOLECULAR WEIGHT (LMW)	Conservative
			Typical
			Optimistic
	COSMETICS	WATER INSOLUBLE (WIS)	Conservative
			Typical
			Optimistic
WHEAT STRAW	FEED ADDITIVE	UNMODIFIED	Conservative
			Typical
			Optimistic
		LOW MOLECULAR WEIGHT (LMW)	Conservative
			Typical
			Optimistic
	COSMETICS	WATER INSOLUBLE (WIS)	Conservative
			Typical
			Optimistic

Sub-scenarios on process efficiencies

The efficiencies achievable after upscaling the current processes from lab to industrial scale are connected to considerable uncertainty. For that reason, sub-scenarios reflecting a range of plausible outcomes were introduced. The combination of unit operation and separation efficiencies that produced xylan recoveries of 65, 75 and 85 % as key characteristics were set as the conservative, typical and optimistic sub-scenarios respectively.

5 Results and conclusions on life cycle assessment

To evaluate environmental impacts related to an implementation of the EnXylaScope concept, a screening life cycle assessment was performed (see section 3.2). Several possible future implementations are analysed depicted in scenarios provided in section 4.4. Results and conclusions on climate change impacts as well as optimisation potentials are presented in section 5.1 and 5.2, respectively. Section 5.3 discusses further environmental impacts. Recommendations derived from results of the life cycle assessment as well as the life cycle environmental impact assessment (see chapter 6) can be found in chapter 7.

5.1 Climate change impacts

5.1.1 Overview of impacts

The following section gives an overview of the greenhouse gas balance connected with one possible implementation of EnXylaScope concept. In this scenario, water-insoluble modified xylan used as in cosmetics as main product and glucose as well as lignin as co-products are produced from wheat straw as biomass feedstock. In cosmetics, xylan can replace the conventional palm oil-derived alkyl polyglucoside. While glucose is set to replace 1st generation glucose (i.e. derived from dedicated crops) in the analysed scenarios, lignin is subjected to a fractionation process as an example of possible downstream processing which results in different products set to replace starch and alkyl ketene dimer as paper sizing agents, phenol, and polyols in varying proportions. For details on the scenarios see section 4.4. Figure 9 shows the resulting greenhouse gas balance.

Main contributions to climate impacts

Greenhouse gas emissions are dominated by the provision of heat, which is required both in the feedstock conversion and the downstream processing of lignin. Biomass provision and enzyme production are other considerable emission sources, which, however, are subordinate to heat provision. They are followed by emissions from the provision of various chemicals. This distribution of contributions is the same across other scenarios on xylan modification and biomass feedstock discussed in section 5.1.3 and 5.2.4, respectively.

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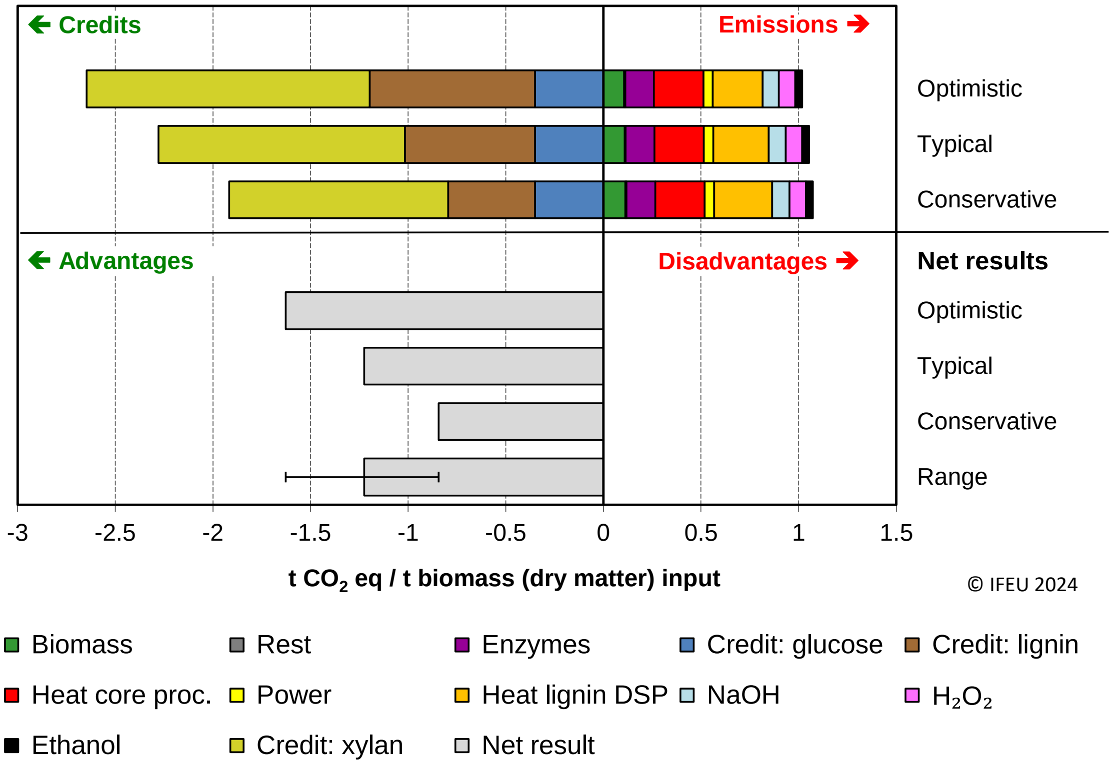

*Figure 9: **Overview of climate impacts.** Greenhouse gas balance of the biorefinery scenario using wheat straw as biomass feedstock and utilising modified xylan in cosmetic formulations compared to conventional reference products replaced by xylan and the co-products, respectively, for three process efficiencies. Upper panel: climate impacts aggregated by inputs. Lower panel: net results. DSP: downstream processing, H_2O_2: hydrogen peroxide, NaOH: sodium hydroxide.*

How to read Figure 9: The figure shows the cradle-to-grave climate impacts aggregated by different inputs. Greenhouse gas emissions amount to about 1 tonne of CO_2 equivalents per tonne of dry biomass input (positive values). They are contrasted with emissions, which are avoided, if the xylan-based product as well as glucose and the lignin-based co-products replace conventional products (see Table 4 and Table 5 in section 4.3), so that less of those are produced. These avoided emissions, which add up to about 1.8 - 2.6 tonnes of CO_2 equivalents, are displayed as credits (negative values) and exceed the total emissions in all three assessed process efficiency sub-scenarios (optimistic, typical, conservative). This results in net greenhouse gas savings (bottom rows) implying that this EnXylaScope scenario is beneficial from a climate change point of view. The last row shows the range of net savings, indicated by a thin black line stretching from the net result for typical process efficiency towards those for optimistic and conservative efficiency.

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Greenhouse gas savings and relevance of co-products

Using water-insoluble xylan to replace the palm oil-derived alkyl polyglucoside (APG) in cosmetic products can, even without considering co-product use, avoid emissions which are in the same range as the combined emissions of the whole biorefinery and its supply chain. Together with the credits for products replaced by the co-products lignin and glucose, this can result in considerable greenhouse gas net savings of about 1.2 tonnes of CO_2 equivalents. This is remarkable, considering that co-product use was not a focus of the EnXylaScope project and hence not investigated or optimised in detail.

Although all EnXylaScope processes were modelled on industrial scale, included lignin fractionation and use options for the lignin-based co-products represent early examples with considerable uncertainties in extrapolation regarding both emissions not yet accounted for and not yet optimised processes and applications. Calculated credits of lignin co-products are based on available preliminary datasets, in which lignin products replace more starch in certain applications than high-value fossil-based products. Bio-based products like starch have lower climate impacts than fossil-based alternatives. In terms of greenhouse gas net savings, other lignin use options could therefore benefit the biorefinery concept. The same applies to the produced 2nd generation glucose, which replaces 1st generation glucose. If converted to other products it could be the basis for replacing further fossil-based products. Such new applications provide considerable optimisation potentials that are particularly important if xylan replaces other bio-based products with moderate environmental impacts.

Key findings and conclusions:

- Key contributions to the carbon footprint of the investigated biorefinery concept originate from heat provision followed by biomass and enzyme production and to a lesser extent from required chemicals including hydrogen peroxide and sodium hydroxide. Therefore, sources of greenhouse gas emissions should be reduced in this order.
- Avoided emissions by utilisation of the main product xylan in cosmetics as potential alternative to the existing ingredient alkyl polyglucoside and the co-products lignin and glucose outweigh the total emissions and lead to considerable net greenhouse gas savings. Therefore, this biorefinery scenario is superior compared to conventional, mostly bio-based products from a climate change perspective.
- Optimisation of co-product uses is an important lever to improve the climate change mitigation potential of this biorefinery concept.

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5.1.2 Different use options of xylan products

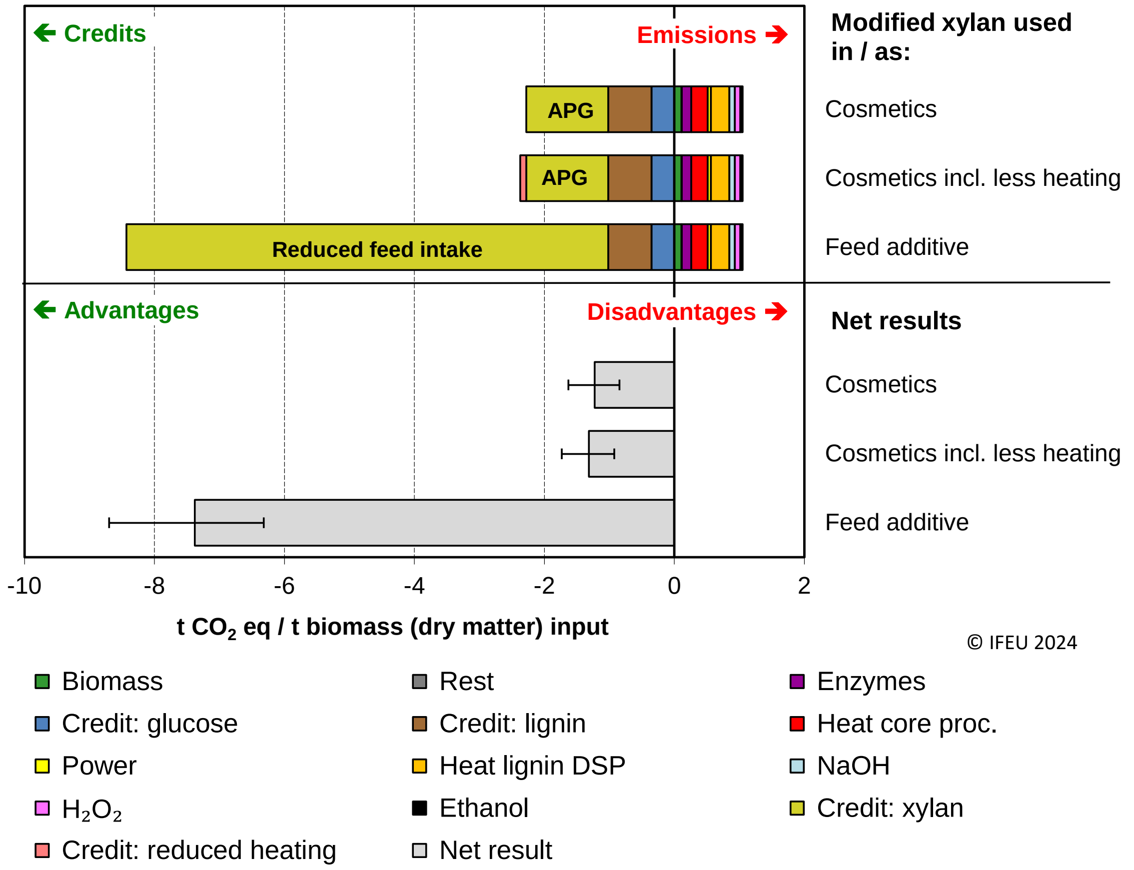

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*Figure 10: **Comparison of different use options of xylan products.** Greenhouse gas balance of the biorefinery scenario using wheat straw as biomass feedstock, comparing the application of water-insoluble xylan as a cosmetics ingredient with and without additionally saved heat during cosmetics formulation, and the application of low molecular weight xylan as a feed additive. Upper panel: climate impacts aggregated by inputs. Lower panel: net results. APG: alkyl polyglucoside, DSP: downstream processing, H_2O_2: hydrogen peroxide, LMW: low molecular weight xylan, NaOH: sodium hydroxide, WIS: water-insoluble xylan.*

The first scenario in Figure 10 in which xylan replaces alkyl polyglucoside in combination with the valorisation of the co-products is discussed in detail in section 5.1.1. This section compares this use option to two other ones.

In addition to replacing alkyl polyglucoside, the use of xylan might further lower processing temperatures during the formulation of cosmetics. As a variant of the scenario, the second row in Figure 10 estimates potential heat savings that could result from such lower processing temperatures, which were not investigated in detail in this project. While slightly improved greenhouse gas savings are possible, this effect does not change the general magnitude of achievable savings.

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In a second analysed application scenario, xylan, modified to have low molecular weight (LMW xylan), is used as an additive in pig feed which leads to improved animal health and feed use efficiency. If this works on large scale as expected from lab scale tests, about forty times as much pig feed could be replaced per tonne of xylan which would provide large credits of about 7 tonnes of CO_2 equivalents per tonne of dry biomass input. The production and modification of unmodified xylan to low molecular weight and water-insoluble xylan, respectively, are modelled based on identical data since both processes were so similar on lab scale that no substantial differences could be inferred for future industrial scale. Therefore, ranges of emissions are identical in this calculation, although they may differ in reality. In this scenario, the credits achievable by feed savings therefore directly translate to high greenhouse gas net savings. If this scenario can be met in practice, enormous greenhouse gas savings of more than 80 % compared to the provision of current amounts of pig feed could be achieved.

Key findings and conclusions:

> The application of xylan as a feed additive could yield enormous greenhouse gas savings of more than 80 % if the expected increases in feed use efficiencies can be met in practice. Therefore, substantial climate change mitigation could be achieved by realizing the scenario even without further optimisations of co-product use.

> From a climate change perspective, water-insoluble xylan and low molecular weight xylan are equivalent alternatives based on the current modelling. Decisions on the modified xylan type used can therefore be made solely according to technical considerations.

5.1.3 Xylan modification

In a simple configuration of the assessed biorefinery, xylan is extracted in an unmodified form. Subsequent modification in order to achieve a desired modification of functionality requires enzyme treatment and following washing and purification steps to remove all enzymes again. Enzymes for modification are produced on site using part of the produced co-product second generation glucose and various other inputs in a process very similar to producing the other enzymes used in the processes for delignification and cellulose depolymerisation, respectively.

Comparing the biorefinery scenarios with modified and unmodified xylan, additional emissions arise for the provision of more enzymes (Figure 11). The different properties of the two assessed variants of modified xylan, water-insoluble and low molecular weight xylan, however, support precipitation and thus support the subsequent washing and purification. This leads to a substantially reduced ethanol demand and less heat demand for its recycling. At least as long as heat is provided from natural gas, as modelled in these scenarios, resulting savings of greenhouse gas emissions overcompensate additional emissions from more enzyme production by far.

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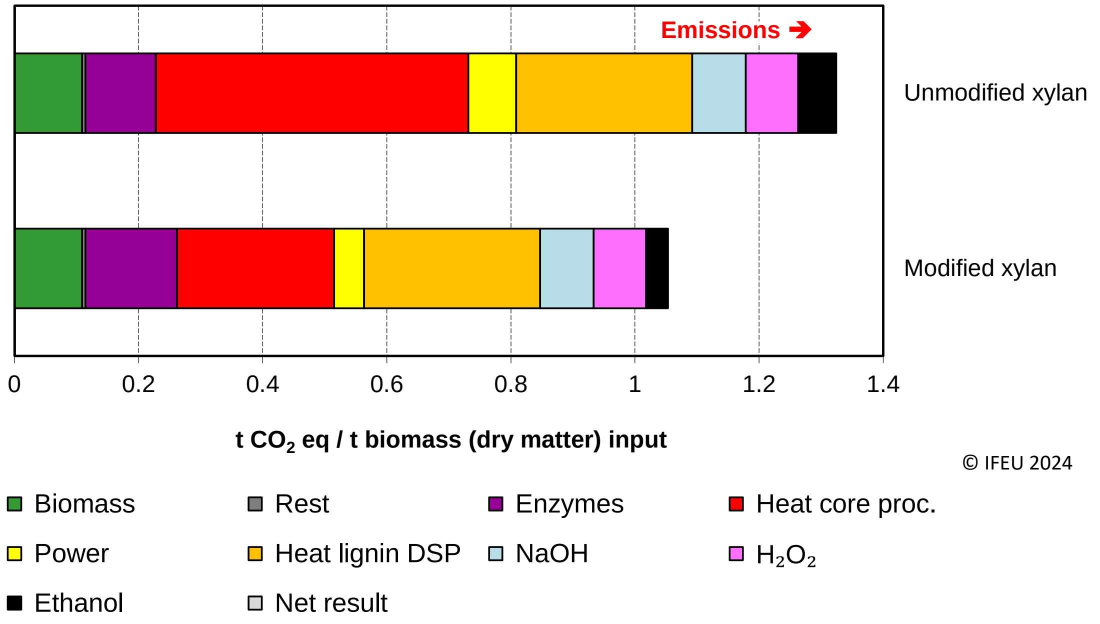

Figure 11: ***Impact of xylan modification on greenhouse gas emissions.*** *Greenhouse gas emissions of the biorefinery scenario using wheat straw as biomass feedstock and aggregated by inputs, comparing the production of unmodified and modified xylan. DSP: downstream processing,* H_2O_2*: hydrogen peroxide, NaOH: sodium hydroxide.*

Key findings and conclusions:

- Main contributions to the greenhouse gas emissions are identical for unmodified and modified xylan (heat, enzyme production, biomass production). Thus, optimisation potentials outlined in section 5.2 apply to both scenarios with and without xylan modification.
- Although an additional process step is needed to modify the extracted xylan, overall greenhouse gas emissions are lower compared to the production of unmodified xylan. If the intended xylan application allows both the unmodified and the modified form, the modified xylan should be used from a climate change perspective.

5.1.4 Excursus on climate impacts of land use and land use change

Greenhouse gas emissions from land use change (LUC, primarily from deforestation) and from land use (LU, primarily from use of drained peatlands) can represent substantial contributions to the greenhouse gas balance of bio-based products. As opposed to process-based emissions it is, however, not straightforward to allocate these LULUC emissions to products. The reason is that not a single product alone causes these emissions, but the overall amount of land use. Certain regions cause farmers to resort to, for example, cleared forest land or drained peatlands instead of standard agricultural

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land. Various views exist on the extent to which the responsibility should be distributed over all agricultural products produced in a region, to which extent those products from exactly these areas should receive more responsibility, and for how long a deforested area should count as deforested area. This results in several possible ways of quantifying these emissions in LCA.

In this study, we primarily follow the approach to distribute LULUC emissions equally to all land use in a certain region referred to as aLULUC [Fehrenbach et al. 2020]. In this excursus, it is firstly compared to not considering LULUC at all (compare first row in Figure 10 to first row in Figure 12). This shows that LULUC emissions contribute to both the biorefinery inputs and the reference products. About half of the net greenhouse gas emissions savings in this scenario arise from saved LULUC emissions. The main reason is that the replaced conventional cosmetics ingredient is derived from palm oil and thus its replacement can reduce emissions from deforestation and use of drained peatlands. Also, in the case of the use of xylan as a feed additive about half of the net savings result from avoided LULUC emissions. This arises from avoided LULUC due to less corn, soy, and wheat used as pig feed.

The aLULUC approach is additionally compared to potential maximum impacts resulting from direct deforestation and simultaneously direct use of drained peatlands. Since this risk is highest for palm oil as input, this was exemplarily calculated for the reference product alkyl polyglucoside (second row in Figure 12)[2]. In contrast, deforestation risks in the supply chain of biorefinery inputs are very low. Thus, achievable greenhouse gas emissions savings increase massively if deforestation for replaced conventional products can be reduced. With regard to pig feed, assessment of deforestation risk is more complex. While there is also a certain direct LUC risk in particular connected to soy from Brazil, the overall risk is expected to be lower compared to palm oil-based products since most required feed components can be obtained from European countries that can primarily cause indirect LUC effects that are even harder to allocate to products. This is, however, not addressed in detail here because also for this use option of xylan the result is a reduced LUC/deforestation risk for the biorefinery products compared to the reference products, which leads to the same qualitative outcome.

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[2] The cosmetics ingredient APG is also produced by project partner Seppic. Seppic makes high efforts to ensure that its value chains are deforestation-free. This exemplary calculation based on generic world market relations should by no means question the effectivity of Seppic’s efforts in this direction.

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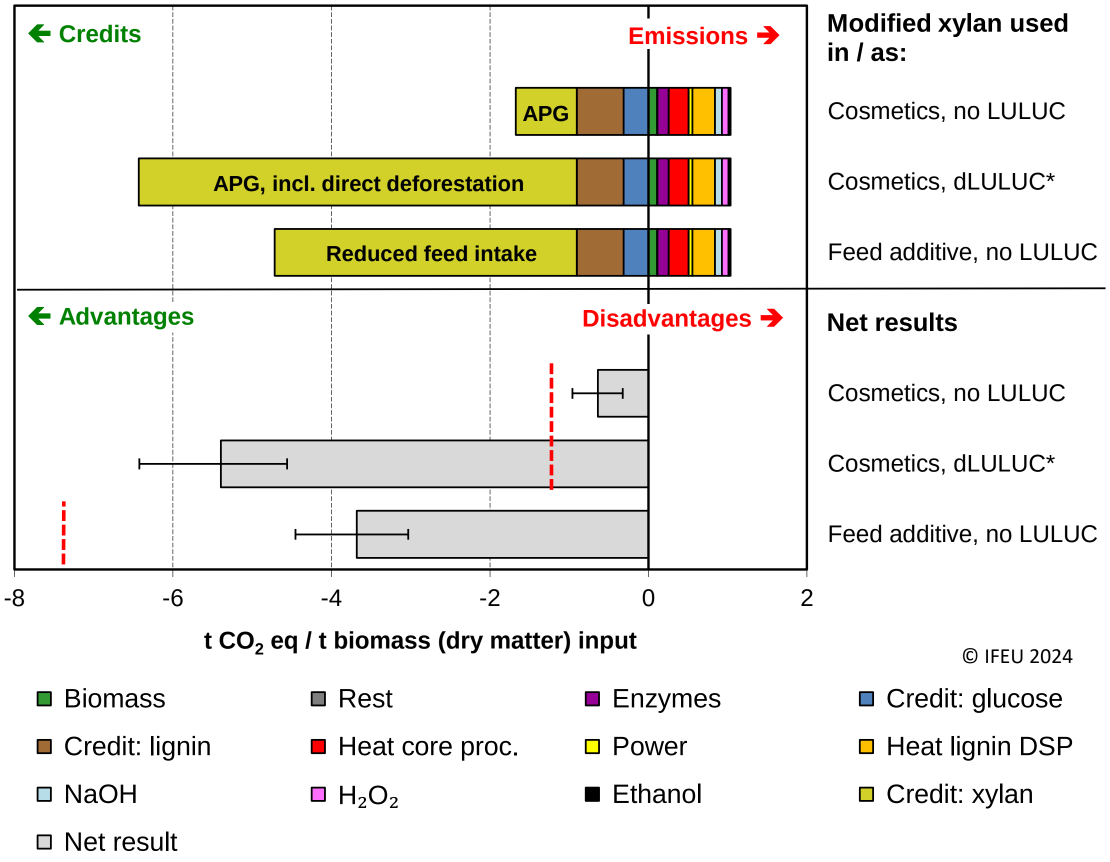

*Figure 12: **Comparison of different methodologies to assess the climate impact of land use and land use change.** Greenhouse gas balance of the biorefinery scenario using wheat straw as biomass feedstock, comparing the application of water-insoluble xylan as a cosmetics ingredient and the application of low molecular weight xylan as a feed additive for different methodologies to determine greenhouse gas emissions from land use and land use change, respectively. Upper panel: climate impacts aggregated by inputs. Lower panel: net results. Dashed red lines indicate the net result of the respective greenhouse gas savings according to the attributional land use and land use change (aLULUC) method as primarily applied in this study. APG: alkyl polyglucoside, DSP: downstream processing, H_2O_2: hydrogen peroxide, LMW: low molecular weight xylan, LULUC: land use and land use change, dLULUC: direct LULUC, aLULUC: attributional LULUC, NaOH: sodium hydroxide, WIS: water-insoluble xylan. *dLULUC exemplarily shown only for palm oil because of low direct deforestation risk for other used biomasses.*

If dedicated crops such as poplar from short rotation coppice (SRC) are used as biomass feedstock instead of wheat straw, this share of savings is determined by the efficiency of biomass production and use and the LULUC emissions connected to the land that is used to grow the biomass feedstocks for products and reference products, respectively. Following the aLULUC method, LU emissions from poplar cultivation can, depending on the country, be similarly high as avoided LULUC emissions from palm oil in the reference system (see also section 5.2.4). This can reduce net savings to almost zero but not lead to net additional emissions under the conditions of the assessed scenarios.

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Key findings and conclusions:

- About half of the greenhouse gas savings in the main scenarios originate from avoided land use and land use change (LULUC) following the aLULUC method. This generates additional advantages in particular for residue-based biorefinery scenarios over the replaced bio-based products. In scenarios using poplar, resulting potential emissions from drained peatlands can, however, reduce net savings to zero depending on its origin.
- The greenhouse gas savings associated with the avoided LULUC depend on the applied assessment methodology. There is no single “correct” methodology because the attribution of measurable LULUC emissions to products can follow different concepts of responsibility or accountability. Although this part of the avoided emissions can therefore be assessed differently depending on the applied rules, the biorefinery scenarios using wheat straw reduce climate change and land use change risks independently of the used methodology and those using poplar from short rotation coppice at least do not generate additional emissions.
- If the production of palm oil required for replaced cosmetics ingredients involves deforestation[2], greenhouse gas emissions increase massively. Replacement of such products, for which deforestation cannot be excluded with certainty, by xylan could represent an important measure for climate change mitigation.

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5.2 Optimisation potentials of climate change impacts

A main goal of the study is to provide optimisation measures to reduce greenhouse gas emissions and to highlight pathways towards later climate neutrality. This is analysed in the following for all inputs in the order of their contribution to greenhouse gas emissions.

5.2.1 Energy

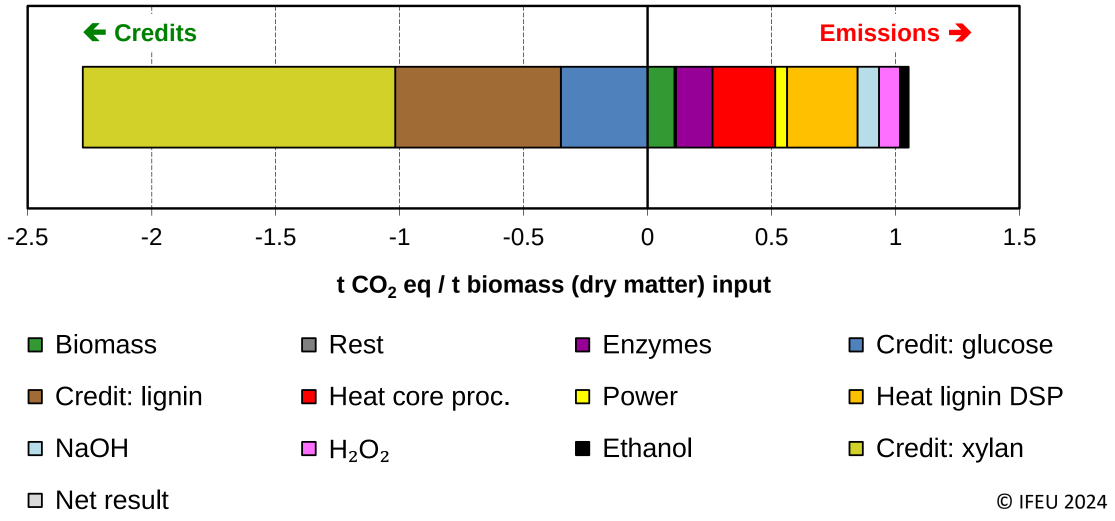

*Figure 13: **Contributions to the climate impacts of the biorefinery.** Greenhouse gas balance of the biorefinery scenario using wheat straw as biomass feedstock and modified xylan as a cosmetics ingredient with typical process efficiencies. Emissions and credits are aggregated by inputs. DSP: downstream processing, H_2O_2: hydrogen peroxide, NaOH: sodium hydroxide.*

Heat required for the biorefinery core process as well as the lignin downstream processing represents the largest contributor to the greenhouse gas emissions, while the impact of consumed electricity is comparably low from a climate change perspective (Figure 13). The assessed scenarios already adopt heat integration within individual processes and thus are already rather energy efficient.

Process heat for biorefinery is modelled to originate from a natural gas-fired boiler as it is standard in many chemical plants. The biggest lever to reduce resulting emissions is to plan for a fully electrified biorefinery. Most of the heat is consumed by ethanol distillation. Since this is a widely employed process, it is promising that vapour recompression, an innovative electrification technology to replace steam-driven distillation, becomes available in time for the construction of a first biorefinery according to the EnXylaScope concept. Combined with increasing availability of renewable electricity, which will also reduce impacts of further electricity use this is the most important route towards climate neutrality. In the transition phase to fully

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renewable grid electricity, it may be beneficial for environment and most likely also costs if the biorefinery could be planned to contribute to demand side flexibility. For example, buffer tanks and higher capacities could be introduced in the ethanol recycling loop so that energy-intensive recovery is paused at times of low renewable electricity shares in the grid.

Another potential alternative is to use biomass-fired boilers. Considering overall limited availability in particular around biorefineries and unavoidable residual greenhouse gas emissions, this is, however, less suitable to reach climate neutrality. Moreover, forests in many countries around the world including Europe are currently turning from net carbon sinks to net carbon sources. Thus, harvesting additional wood or forest residues for energy provision cannot be considered a climate-friendly alternative any more. Heat based on renewable hydrogen could be an option but availability will be limited, at least in the medium term, and efficiency will be considerably lower and cost accordingly higher than for direct use of electricity. Therefore, electrification should be explored before further optimisations of the heat use concept, such as further heat integration, is applied.

Key findings and conclusions:

- While climate impacts of electricity generation are continuously decreasing towards climate neutrality, heat provision from combustion is very hard to decarbonise.
- Therefore, measures to reduce the emissions connected with the heat demand, primarily electrification of processes, are the most important lever for reducing the greenhouse gas emissions associated with xylan production and for a pathway towards climate neutrality.
- Flexibility in electricity demand could be introduced by e.g. suitable buffers in the process to reduce consumption of remaining non-renewable electricity while the grid is being decarbonised.

5.2.2 Input chemicals

In a first step, the consumption of the input chemicals sodium hydroxide, hydrogen peroxide, and ethanol causing significant greenhouse gas emissions (Figure 13) should be reduced by efficiency measures. Reduction in hydrogen peroxide may for example be possible if less stringent bleaching of the products is sufficient. Consistent implementation and further optimisation of the developed recycling processes for sodium hydroxide and ethanol can further contribute to a reduction.

Climate neutrality does, however, also require a climate neutral provision of the remaining amounts of these chemicals. This seems feasible in the future for sodium hydroxide and hydrogen peroxide because these chemicals are or can be produced using green electricity or green hydrogen, respectively.

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Key findings and conclusions:

- Consistent implementation and further optimisation of the developed recycling processes for sodium hydroxide and ethanol are of great importance, as even the remaining small amounts cause considerable greenhouse gas emissions.
- Reduction of hydrogen peroxide represents a further, albeit smaller, potential for optimisation.
- In the future, using sodium hydroxide and hydrogen peroxide produced with renewable electricity can be important steps towards climate neutrality.

5.2.3 Enzymes

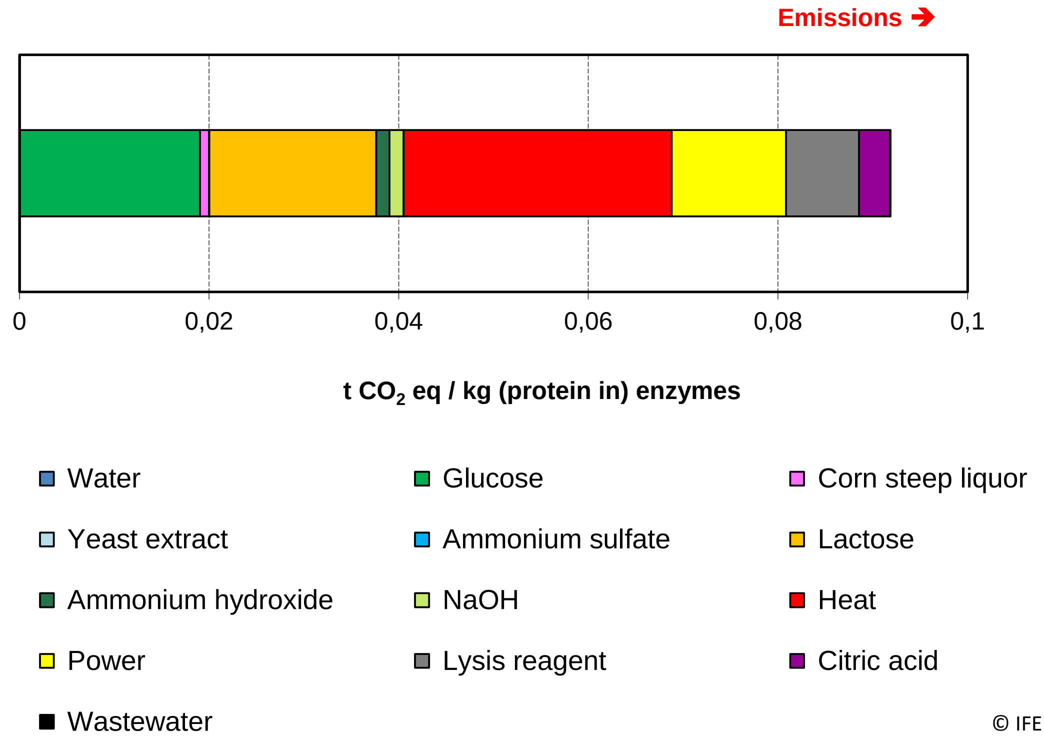

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*Figure 14: **Climate impacts of enzyme production.** Greenhouse gas emissions associated to the production of enzymes used for xylan modification, delignification, and cellulose depolymerisation, aggregated by inputs.*

The largest share of greenhouse gas emissions associated with the production of enzymes for xylan modification, delignification, and cellulose depolymerisation results from process heat, which is modelled to originate from natural gas combustion (Figure 14). Similar to the overall processes of the biorefinery (see section 5.2.1), reduction of the heat demand and climate-friendly provision of the heat e.g. using renewable electricity represent the most important optimisation measures. Electrification could be implemented by using a heat pump instead of natural gas-fired boilers. While the

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electricity mix is expected to be more and more dominated by renewable energy sources in the future, current enzyme production units could be combined with photovoltaic systems on site to provide the required electricity. This could also minimize the impact of further electrical power consumed during enzyme production, which is, however, subordinate to heat from a climate change perspective.

Other considerable greenhouse gas emissions are caused by glucose and lactose, which are used as carbon source and inducer, respectively. Although required amounts of lactose are much lower, climate impacts of lactose and glucose are similar (Figure 14). While glucose can be obtained from a variety of crops, lactose depends on dairy. Therefore, greenhouse gas emissions involve livestock breeding, which is one of the main drivers of climate change. Using alternative inducers as well as generally reducing the amount of lactose and glucose consumed could be promising optimisation levers.

Among the required chemicals, the lysis reagent used to disrupt the enzyme producing cells contributes the largest greenhouse gas emissions, while others such as ammonium sulfate or sodium hydroxide are small. If technically feasible, replacing the chemical-based lysis approach by a mechanical one driven by electricity could further reduce the climate change impact of the enzyme production.

Key findings and conclusions:

- The carbon footprint of the enzyme production is dominated by heat. As with the feedstock conversion, electrification of processes or other measures that reduce the heat demand are the most important optimisation lever.
- Although much more glucose than lactose is used for enzyme production, greenhouse gas emissions associated with the two sugar types are similar because lactose is, at least currently, an animal-based product. Both amounts should be reduced as far as possible and an animal-free alternative to lactose should be considered.
- Other relevant greenhouse gas emissions are associated with the chemical lysis agent used to obtain the enzymes from the producing cells. Replacing these agents by mechanical disruption techniques, ideally using renewable electricity, could reduce the carbon footprint of this step.

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5.2.4 Biomass feedstock

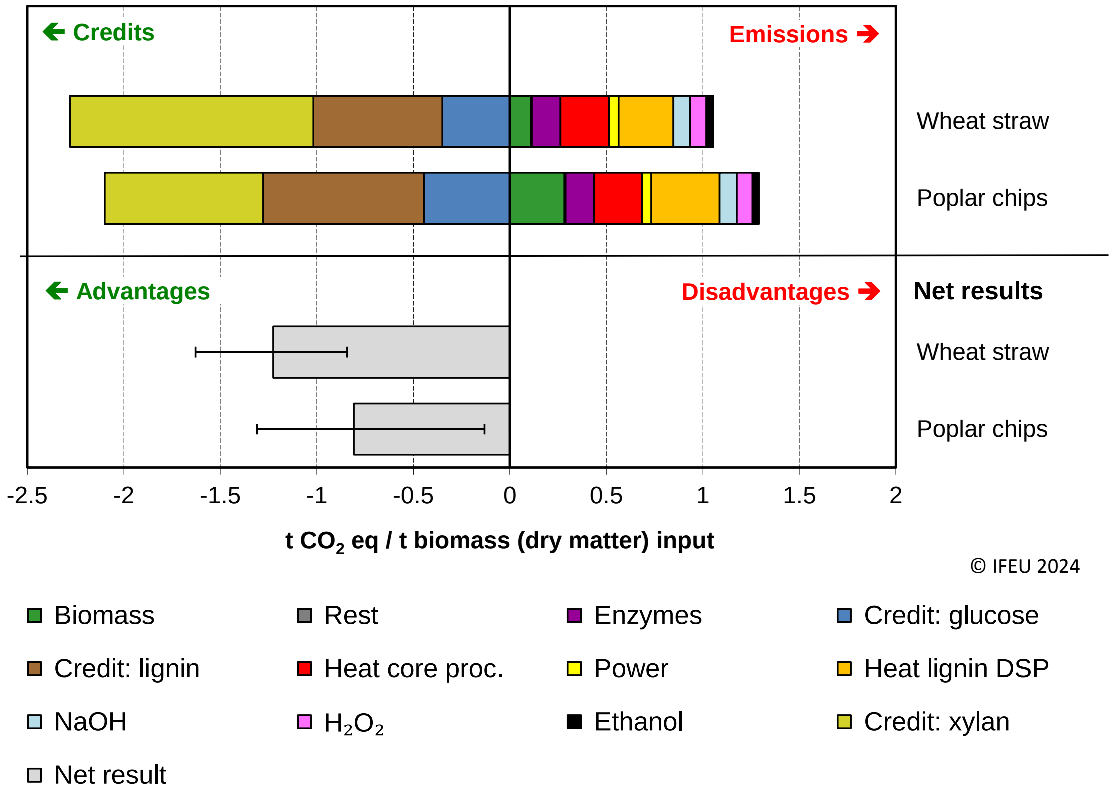

*Figure 15: **Impact of biomass feedstock type on greenhouse gas emissions and credits.** Greenhouse gas balance of the biorefinery scenario utilizing modified xylan as a cosmetics ingredient, comparing wheat straw and poplar chips as biomass feedstock. Upper panel: climate impacts aggregated by inputs. Lower panel: net results. DSP: downstream processing, H_2O_2: hydrogen peroxide, NaOH: sodium hydroxide.*

In previous sections 5.1.1 to 5.2.1, wheat straw is modelled as the biomass feedstock of the biorefinery. To assess the impact of feedstock type on the greenhouse gas balance, this section compares emissions and credits of the biorefinery concept between the use of wheat straw and the use of poplar chips from short rotation coppice (Figure 15).

While wheat straw represents an agricultural residue that is otherwise left on the field, poplar is a dedicated crop that requires land and higher efforts. Compared to residues, additional climate impacts arise from land use, planting, chipping, and the use of fertiliser. Therefore, greenhouse gas emissions related to biomass production are higher for poplar than for wheat straw. Decisive for the difference is also the type of land that poplar is grown on which in turn can depend on the respective country. For instance, growing poplar on drained peatlands (former bogs and mires), which exists in particular across northern Europe in different shares of total agricultural land of each country, can largely increase greenhouse gas emissions from land use change (see section 5.1.4) compared to obtaining it from countries with low such risks. The countries exemplarily

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used in this assessment are the Netherlands, Ireland and Spain in case of the conservative, typical, and optimistic sub-scenarios, respectively. This is the main cause of the large range of net results for poplar chips. Land use emissions can thus almost compensate for all greenhouse gas emission savings in the assessed scenario. Drained peatlands should therefore be excluded from a climate change perspective.

Wheat straw and poplar chips do not only differ with regard to their provision but also in their biological composition. Compared to wheat straw, poplar yields higher amounts of lignin and cellulose but lower amounts of xylan. This translates not only to an increase of the heat demand for lignin downstream processing but most importantly to altered credits as more (lignin, glucose) or less (xylan) reference products can be replaced. Based on the modelled product and co-product use cases included in Figure 15, the combined credits could be lower than those achievable with the wheat straw composition. This is, however, determined by all three credits, which could significantly differ in future implementations of the biorefinery concept. As the potential of replacing high-value products using this xylan-first biorefinery concept is expected to be higher for the xylan compared to lignin and glucose, larger amounts of xylan as obtained from wheat straw could imply a slight advantage over poplar. Considering the lower emissions for biomass production, wheat straw should in general be preferred from a climate change perspective if both wheat straw and poplar chips are technically suitable to produce the xylan type required in the respective consumer product. If a certain xylan type is needed that can only be derived from poplar, replacement of high-value products by xylan as well as the co-products is even more crucial to achieve substantial net greenhouse gas savings.

This assessment is based on the precondition, that enough straw is available that would otherwise be ploughed in or land for poplar cultivation that would otherwise be unused. Otherwise, substantial effects on climate change and other environmental impacts are possible if either soil organic carbon levels are reduced by excessive straw extraction, natural vegetation is cleared somewhere in the world to provide more arable land or current productive uses of biomass are replaced. Currently, sufficient unused straw is still available in many European countries but this has to be verified for the concrete planned location of a future biorefinery. Furthermore, land is released if products and co-products replace bio-based products as set in the assessed scenarios. This land can even be sufficient for cultivating poplar as feedstock depending on the scenario (see section 5.3.1). Otherwise, also if more fossil-based products should be targeted for substitution in the future, e.g. changes to a more plant-based diet in bigger parts of the population could release substantial amounts of arable land, which could be used for a sustainable bioeconomy.

Considering potential pathways towards climate neutrality, biomass provision is a weak point of any biorefinery concept because it is hard or impossible to make fully climate neutral. A decarbonisation of nitrogen fertiliser production using ammonia from green hydrogen and the replacement of Diesel in agriculture by battery-powered machinery

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seems feasible in the future but may still require quite some time to become available on a large scale. The same applies to emissions from drained peatlands and deforestation because resistance to taking that land out of use for rewetting or refraining from the extension of agricultural land at the expense of forest, respectively, remains high. While emissions of the long-lived climate gas dinitrogen monoxide from industrial fertiliser production are being more and more reduced using appropriate technologies, its emissions from fertiliser application to soils cannot be reduced much from a current perspective. Therefore, biomass should be used as efficiently as possible.

Key findings and conclusions:

- Greenhouse gas emissions related to feedstock provision are lower for wheat straw compared to poplar chips, as additional land and efforts are required to grow the latter.
- A substantial part of the emissions from poplar cultivation can originate from the use of drained peatlands. This has a relevant share of agricultural land in most European countries suitable for poplar cultivation and should be rigorously excluded from the supply chain.
- The results of this assessment are only valid if sufficient amounts of straw and/or unused arable land are available.
- Due to differences in biomass composition, the output of xylan, lignin, and glucose varies between wheat straw and poplar chips. While the amounts of glucose and lignin are higher, less xylan is extracted. In combination, this leads to overall lower credits for replaced products. If poplar chips are used a more environmentally beneficial use of main product and co-products by replacement of high-impact products is even more critical compared to the use of wheat straw.
- In direct comparison, using the residue wheat straw is more favourable from an environmental perspective. If suitable for an application, straw should therefore be used as long as sufficient amounts are left on the fields to conserve soil carbon levels. Otherwise, poplar from short rotation coppice is acceptable if high-impact products are replaced. However, biomass provision, even if from residues like straw, will remain an emission source as emissions such as nitrous oxide from soil cannot be avoided.

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5.3 Further environmental impacts

While climate change impacts assessed in sections 5.1 and 5.2 rightfully receive a lot of attention, human activities affect many other important environmental aspects, too. The impacts of the analysed biorefinery concept on these further aspects are assessed in this section. A particular focus is placed on analysing if these results are in conflict with those on climate change mitigation and whether further optimisation potentials can be identified.

5.3.1 Comparison of environmental impacts

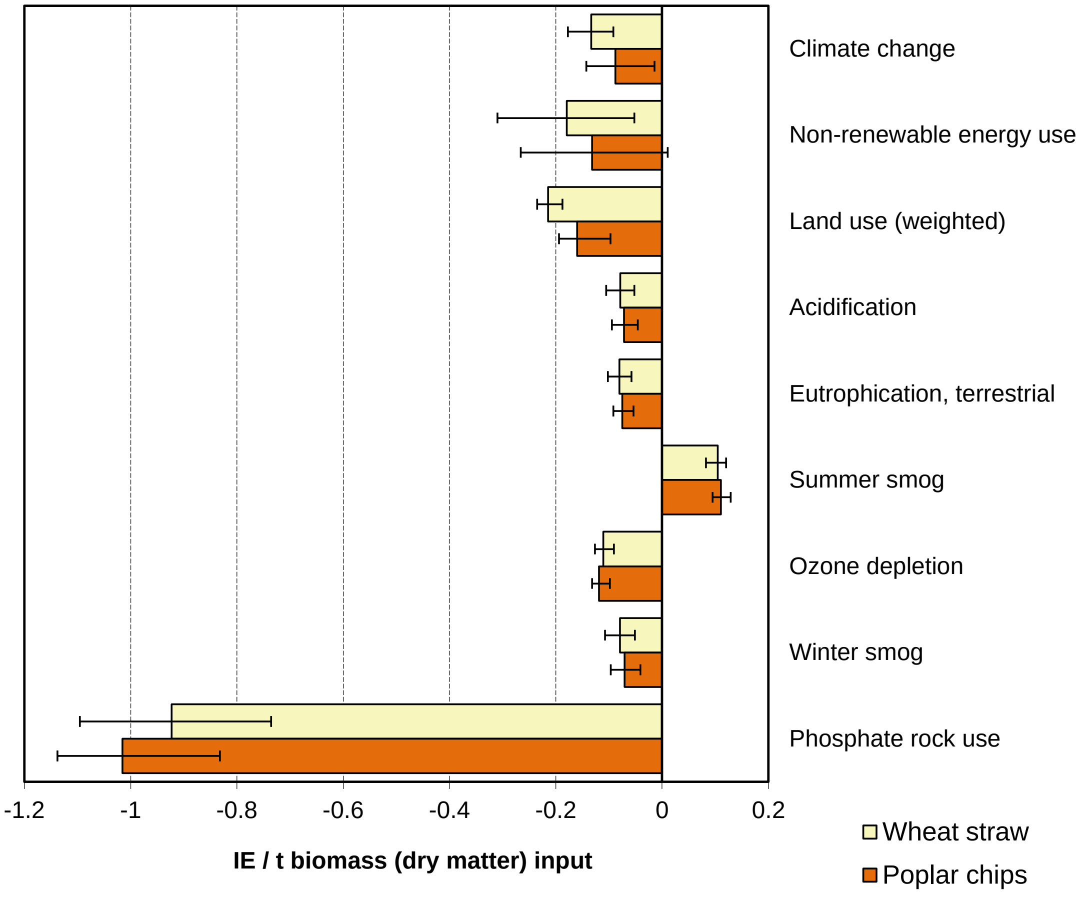

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Figure 16: ***Net results in different environmental impact categories.*** *Overview of net results in different environmental impact categories for the biorefinery scenario using modified xylan as a cosmetics ingredient, comparing wheat straw and poplar as biomass feedstock. Results are expressed in inhabitant equivalents (IE), i.e. as fractions of average emissions per capita and year in the European Union.*

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Most environmental impact categories show advantages for the investigated biorefinery process if modified xylan is used to replace alkyl polyglucoside that is used in cosmetics (Figure 16). Credits for avoided reference product emissions overcompensate the emissions associated with xylan and co-product production (Figure 17). At least in the typical sub-scenario, the only exception is the formation of additional summer smog caused by emission of ethanol vapours that can arise from drying after xylan precipitation. For the use of modified xylan as feed additive, however, all assessed environmental impacts show advantages of the investigated biorefinery (not shown).

In general, if wheat straw is used, savings can be achieved even in the lowest efficiency sub-scenario (see section 4.4) for all investigated impacts. If poplar chips are used, however, the use of non-renewable energy resources, i.e. crude oil, natural gas, coal, or uranium, as well as the climate change impacts (as discussed in section 5.2.4) can be

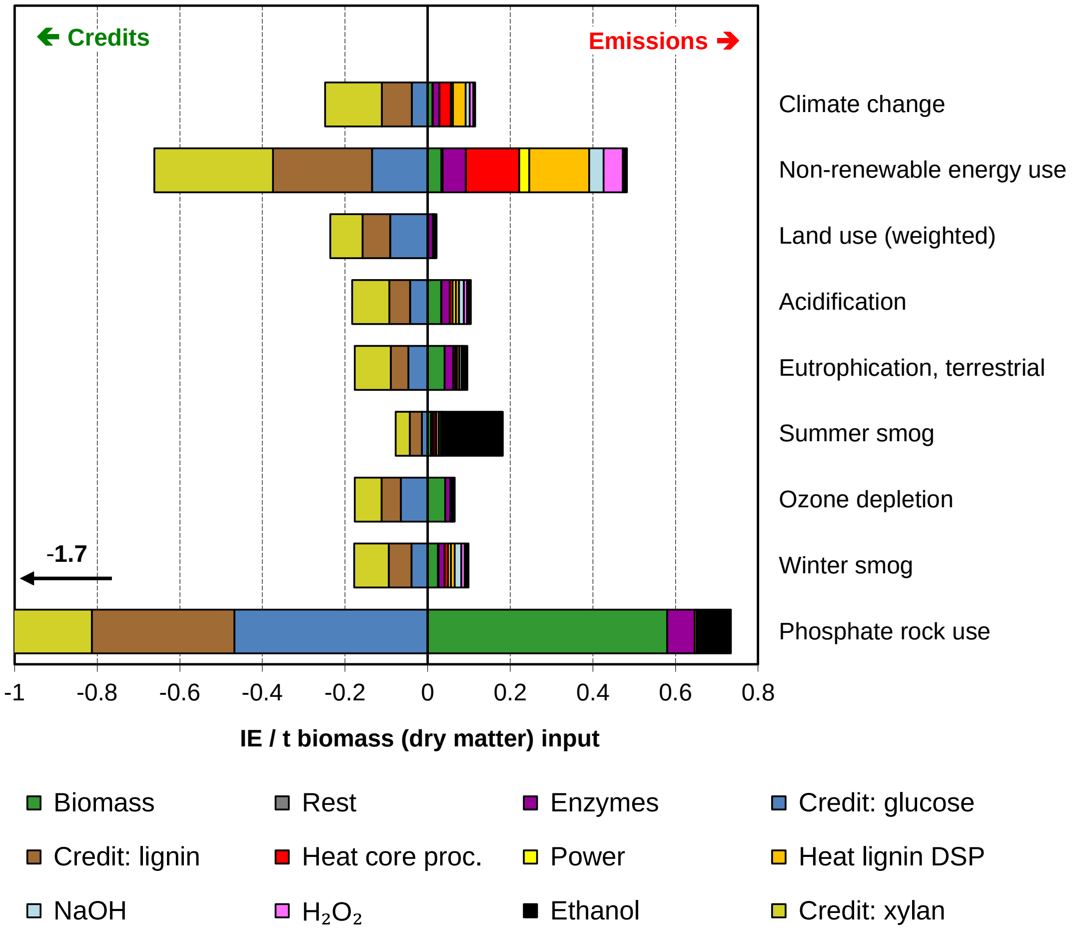

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Figure 17: ***Emissions and credits in different environmental impact categories.*** *Comparison of emissions and credits for the biorefinery scenario using wheat straw as biomass feedstock and the modified xylan as a cosmetics ingredient in different environmental impact categories. Results are aggregated by inputs. DSP: downstream processing,* H_2O_2*: hydrogen peroxide, NaOH: sodium hydroxide.*

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similar for the biorefinery and the combined reference products if only conservative process efficiencies are achieved and poplar is grown in countries with substantial shares of cultivated drained peatlands. Technical optimisation measures should therefore aim at highest possible process efficiency.

Thus, there would be no conflicting results on environmental impacts that argue against the implementation of the assessed scenarios if the emission of ethanol vapours could be sufficiently reduced and at least typical process efficiencies can be achieved in implementation. A main reason for this is that a mixture of products based on annual European crops and tropical crops and moderate shares of fossil resources is replaced by efficiently using biomass residues and the perennial European crop poplar.

The biggest environmental advantages of an implementation of the biorefinery scenarios can be related to reduced land use weighted by its distance to a natural state, ozone depletion, and phosphate rock use. They show the highest reductions of more than 50% or even 90% for land use relative to the conventional products (i.e. emissions vs. credits in Figure 17). Especially phosphate rock use stands out, as about 1 inhabitant equivalent, i.e. the average phosphate use caused by one person per year, could be saved per tonne of biomass input. Such a high relative contribution to European consumption of finite phosphate reserves is typical for bio-based systems because phosphate use is dominated by agricultural application of fertiliser. Highest savings are however related to land use if the residue wheat straw is used. This is of particular importance because land use is a main driver for the decline of biodiversity and current extinction rates are far beyond the safe operating space of planetary boundaries [Richardson et al. 2023]. Moreover, an analysis of the used hectares of arable land (unweighted) shows that, most of European arable land needed for the cultivation of poplar can be released by substituting the bio-based reference products. If xylan is used as feed additive, about 10 times more European arable land is released than is needed.

Comparing the use of wheat straw and poplar (Figure 16), results are comparable in most impact categories considering the range of results. Advantages for climate change mitigation and land use can however be achieved when using wheat straw, which results in a clear preference for wheat straw from an environmental perspective if both wheat straw and poplar can deliver xylan suitable for the respective application.

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Key findings and conclusions:

- Most environmental impact categories show a moderate improvement compared to the conventional, mostly equally bio-based alternatives.
- For land use, ozone depletion, and phosphate rock use advantages are substantial, both for wheat straw and poplar chips as biomass feedstock. Negligible to considerable climate benefits can be achieved mainly depending on the origin of the biomass feedstock as discussed in section 5.1 and 5.2.
- For the biorefinery scenarios using xylan as an ingredient in cosmetics, the only disadvantage relates to summer smog which is caused by the emission of ethanol vapours from the biorefinery, which should be reduced in the future. For the scenarios using xylan as feed additive, all environmental impacts show advantages.
- Depending on the shares of bio-based reference products of a future biorefinery, more European arable land could be released than is needed for poplar cultivation.
- Taken together, the analysed biorefinery concept has the potential to achieve considerable overall environmental benefits.
- While similar for most impact categories, the use of wheat straw has advantages from both a climate change and land use perspective compared to poplar. If the intended xylan application allows it, using wheat straw is therefore beneficial from an environmental perspective.

5.3.2 Further optimisation potentials

Comparing the relative contributions of inputs to different environmental impact categories, the main contributors to environmental impacts caused by the analysed biorefinery concept (i.e. heat, biomass, enzymes, and to a lesser extent chemicals) remain identical although relative contributions differ largely. This is true for both using wheat straw (Figure 18) and poplar chips (Figure 19) as biomass input. The efficiency measures derived in section 5.2 can and should therefore be applied to minimise all impacts. Process heat, biomass provision, and enzyme production represent the most relevant inputs in the majority of impact categories, which means that no major conflicts in the prioritisation of optimisation measures can be identified. As an exception, summer smog as the only disadvantageous impact of the biorefinery scenario using xylan as as an ingredient in cosmetics is largely caused by ethanol vapours, the reduction of which is an important optimisation measure in addition to the ones identified in section 5.2. Prevention of these emissions by suitable technical measures, e.g. by installation of condensation units, should be considered to resolve this issue.

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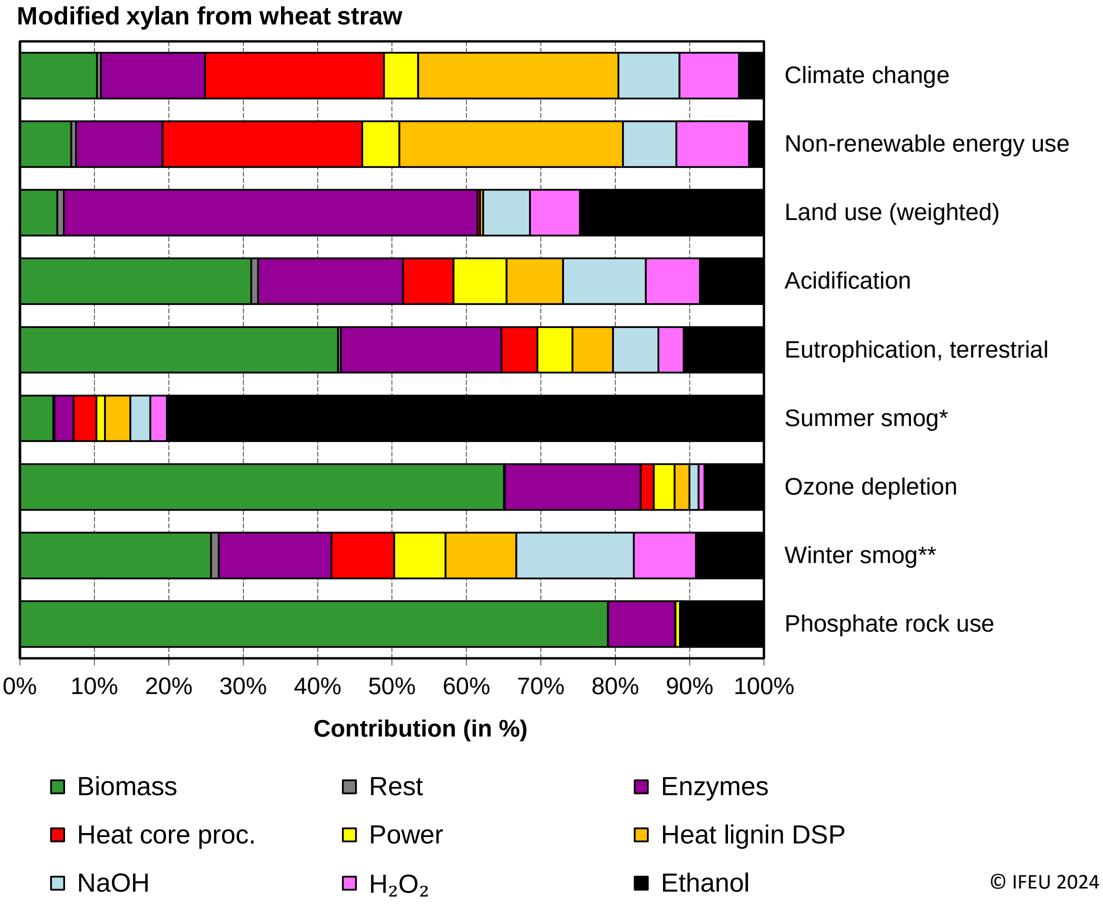

Figure 18: ***Breakdown of different environmental impacts by inputs for the biorefinery scenario using wheat straw.*** *Relative contribution of inputs to different environmental impacts for the biorefinery scenario using wheat straw as biomass feedstock and the production of modified xylan. DSP: downstream processing, H_2O_2: hydrogen peroxide, NaOH: sodium hydroxide, * photochemical ozone formation, ** particulate matter formation*

Comparing wheat straw and poplar as biomass feedstock, input contributions differ significantly only for land use since poplar as a dedicated crop requires additional land which is not the case for the collection of agricultural residues. Irrespective of the feedstock type, biomass dominates about half of the environmental impacts. Reducing the impacts related to biomass production is therefore an important optimisation lever from an environmental perspective. This implies that wheat straw and poplar should be used as efficiently as possible.

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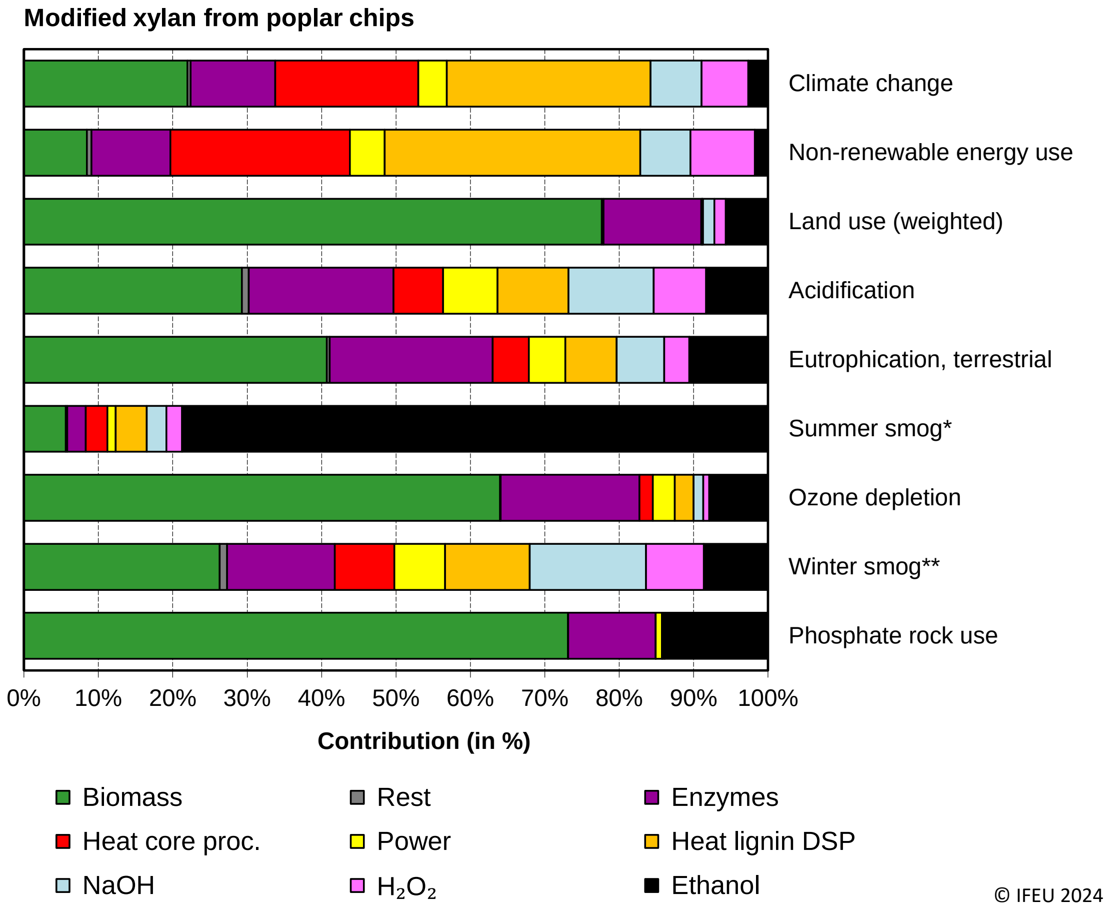

Figure 19: ***Breakdown of different environmental impacts by inputs for the biorefinery scenario using poplar chips.*** *Relative contribution of inputs in different environmental impact categories for the biorefinery scenario using poplar chips as biomass feedstock and the production of modified xylan. DSP: downstream processing,* H_2O_2*: hydrogen peroxide, NaOH: sodium hydroxide, * photochemical ozone formation, ** particulate matter formation.*

Key findings and conclusions:

- Similar inputs contribute substantially to all impact categories, both for wheat straw and poplar chips. Efficiency measures to reduce the respective inputs can therefore be applied to reduce all impacts simultaneously.
- Technical measures to prevent the emission of ethanol vapours should be found as they contribute substantially to summer smog.
- Biomass production dominates about half of the impact categories. Wheat straw and poplar should be obtained from sustainable production with low inputs.

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6 Results on life cycle environmental impact assessment

Local environmental impacts associated with the EnXylaScope concept and conventional reference systems were studied following the life cycle environmental impact assessment (LC-EIA) methodology (see section 3.3). Section 6.1 focusses on the impacts of the EnXylaScope concept whereas section 6.2 presents the impacts associated with the reference systems. A comparison of all investigated systems is shown in section 6.3.

6.1 Local environmental impacts of the EnXylaScope concept

Following the descriptions of the systems in chapter 4, the EnXylaScope concept is divided into several life cycle stages. For the purpose of the LC-EIA, the following stages are evaluated:

- Biomass feedstock provision (wheat straw extraction or poplar cultivation)
- Transport and logistics
- Biomass feedstock conversion (biorefinery)

The land use indicator in LCA for the provision of poplar[3] can give a good indication on the relative importance of these life cycle stages (see Figure 19): Biomass feedstock provision to the biorefinery dominates the results while logistics and conversion are less relevant. Therefore, the main emphasis of the analysis of local environmental impacts (LC-EIA) is put on biomass feedstock provision. Furthermore, the analysis is focussed on the main feedstock of the biorefinery (i.e. wheat straw or poplar) because it is more relevant than other types of biomass feedstock used for the production of auxiliary and consumable inputs such as lactose for enzyme production or sugar for ethanol provision. This LC-EIA complements the LCA by a much more fine-grained analysis that can also provide optimisation strategies.

6.1.1 Biomass feedstock provision

The EnXylaScope biorefinery concept with its xylan-first approach can be based on lignocellulose biomass from either biomass residues or cultivated biomass (dedicated crops). In EnXylaScope, wheat straw as an agricultural residue has been studied as well as poplar (short-rotation coppice) as a dedicated crop.

The provision of biomass feedstock includes both risks as well as opportunities, dependent on the type of feedstock. The assessment of feedstock-specific risks primarily depends on the comparison with alternative uses, i.e. on the so-called agricultural

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[3] The corresponding value for wheat straw as a residue is zero by definition. Nevertheless, its removal can lead to local environmental impacts.

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reference system. The agricultural reference systems defined within the EnXylaScope project are a) not extracting the wheat straw (but ploughing it in) and b) not using (additional) land for the cultivation of SRC poplar. In the latter case, the land in question would remain either unused agricultural land or natural land (e.g. grassland or rainforest, depending on the crop and geographical origin).

The risks of providing each biomass feedstock are evaluated against the above-mentioned reference systems by means of a qualitative, site-independent benefit and risk assessment. This led to feedstock-specific conflict matrices. In the following, this is exemplified for wheat straw. The two conflict matrices for SRC poplar are displayed in section 11.1.1 in the annex.

Example: Provision of wheat straw

Wheat is grown on deep, heavy and nutrient-rich high-quality soils and needs good drainage. Intensive agricultural use primarily leads to impacts on soil. Weed and pest control is obligatory, increasing the risk of soil compaction which is usually linked to negative aspects on the diversity of arable flora and epigeous fauna. Especially the young plants require application(s) of nitrogen fertiliser (approx. 150 kg / ha) which increases the risk of nutrient leaching and eutrophication. Intensive cereal cultures are grown as monocultures and this generally leads to impacts on soil, water, plants / biotopes, animals and biodiversity.

Following the scenario of a potential use as biomass feedstock in a biorefinery it is assumed, that two thirds of the straw yield is left on the field as residues. This approach is sustainable as [Panoutsou et al. 2012] estimate that an export of 40 % of straw in case of wheat will maintain the carbon cycle.

In the conventional reference system (counterfactual scenario) it is assumed that 100 % of the straw is left on the field and ploughed in the soil to maintain the soil organic carbon stock. Since both systems are sustainable, differences in impacts on the environmental factors between a conventional system (100 % residues left on field) and the sustainable use of straw (⅓, i.e. once every three years) in context with a use as biomass feedstock in a biorefinery are low.

In case of intensified use of straw for the biorefinery based on sustainable production conditions, the use of long-stalked cereal varieties might be increased to be able to provide more straw. This would lead to slightly positive effects for arable plants, since long-stalked varieties reduce the amount of pesticides necessary for weed control due to higher competitiveness. This might result in an increased number of animals linked to arable land (arthropods) and an increased biodiversity. Table 7 summarises the risks associated with the use of wheat straw for the biorefinery compared to no use of straw.

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Table 7: Risks associated with the sustainable provision of straw from wheat compared to the reference system of "straw left on field" (ploughing in)

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Soil erosion	neutral		neutral						
Soil compaction	neutral	neutral		neutral	neutral				neutral
Loss of soil organic matter	neutral[1]/ negative[1]			neutral	neutral				neutral
Soil chemistry / fertiliser	neutral	neutral							
Eutrophication	neutral	neutral	neutral	neutral	neutral				neutral
Nutrient leaching		neutral							
Water demand		neutral		neutral	neutral				neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ positive[2]	neutral/ positive[2]				neutral/ positive[2]
Loss of species				neutral/ positive[2]	neutral/ positive[2]				neutral/ positive[2]

1: No loss of SOM in case of a neutral humus balance, but lost (additional) carbon sequestration
2: Positive in case of long-stalked varieties since less weed control is necessary

As stated above, the conflict matrices for SRC poplar are displayed in section 11.1.1 in the annex.

Overview of EnXylaScope feedstocks

Subsequently, these risks of the biomass feedstocks used in the investigated biorefinery scenarios were aggregated and categorised from A (low risk) to E (high risk). The results are depicted in Table 8.

Overall, the removal of surplus straw, i.e. those quantities of straw that are not required to maintain the soil organic carbon content, is mostly neutral from the perspective of local environmental impacts. There might be an increase in habitat diversity in case long-stalked varieties are used.

In contrast to straw removal, the cultivation of poplar as a dedicated crop requires land which leads to land-use related impacts: These impacts can be neutral or positive, if unused or abandoned land (non-rotational fallow land) is cultivated. Soil compaction, for example, is relatively low and due to leave fall, soil organic matter is expected to be high. However, if cultivated at the expense of grassland, poplar may lead to loss of soil

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organic matter and other negative impacts, including loss of species. The cultivation of poplar can be optimised in terms of local environmental effects by cultivating poplar in buffer zones towards water bodies that can act as a nutrient trap reducing eutrophication. In wind-prone areas, strip cultivation in particular on large fields used for annual crops can reduce wind erosion.

It must be noted that straw as a biomass residue cannot directly be compared to dedicated crops since the reference systems are fundamentally different. Therefore, no clear preference can be stated from a local environmental perspective while both feedstocks can be provided sustainably.

Table 8: Risks associated with the provision of wheat straw and the cultivation of poplar compared to the respective reference system

How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

Type of risk	**Feedstock**					
	Wheat straw Reference system: straw ploughed in		**Poplar Reference system: non-rotational fallow land**		**Poplar Reference system: grassland**	
Soil erosion	C		B	A[1]	C	
Soil compaction	C		B		C	
Loss of soil organic matter	C		A		D	
Soil chemistry / fertiliser	C		B		D	
Eutrophi-cation	C		C		C	
Nutrient leaching	C		C	B[2]	D	C[2]
Water demand	C		C		C	
Weed control / pesticides	C		C		C	
Loss of land-scape elements	C		B		B*	D*
Loss of habitat types	B[3]	C	B		B*	D*
Loss of species	B[3]	C	B		D	

[1] In case of strip cultivation

[2] In case of cultivation in buffer zones towards water bodies

[3] In case of long-stalked varieties since less weed control is necessary

* Depending on the structure of the surrounding landscape positive or negative impacts are expected

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Key findings and conclusions

- The use of surplus straw is rated largely neutral in terms of local environmental impacts, meaning that low risks are associated with this feedstock.
- Cultivation of poplar as a dedicated crop can be neutral to positive, if unused or abandoned land (non-rotational fallow land) is available. However, if cultivated at the expense of grassland, poplar may lead to several negative impacts, including loss of species.
- Optimisation options: Cultivating poplar in buffer zones towards water bodies can act as a nutrient trap and strip cultivation can reduce wind erosion. The use of long-stalked wheat varieties could lead to positive local environmental impacts. These options should be used to minimise the local environmental impacts.
- No clear preference for straw or poplar can be deduced from a local environmental perspective while both feedstocks can be provided sustainably.

6.1.2 Transport and logistics

Transportation and distribution of biomass are mainly based on trucks and railway / ships with need of roads and tracks / channels. Depending on the location of the biomass conversion facility, there might be impacts resulting from the implementation of additional **transportation infrastructure**. In order to minimise transportation, it makes sense from an economic point of view to build the facility close to biomass production. As far as it is necessary to build additional roads, environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species, disturbance by moving vehicles).

Storage facilities for biomass can either be constructed at the site of biomass provision (decentralised storage on the field margin) and / or at the site of biomass conversion. In any case, additional buildings cause sealing and compaction of soil, loss of habitats (plants, animals) and biodiversity as well as reduced groundwater infiltration.

Overall, the impacts associated with transportation and logistics are not expected to be significant.

6.1.3 Biomass feedstock conversion

Biomass feedstock conversion and provision of bio-based products is done in a biorefinery. The local environmental impacts associated with the implementation of such a biorefinery are evaluated by means of a qualitative benefit and risk assessment (based on the investigation of potential effects on the environmental factors) and compared to reference scenario.

Impacts from implementing an EnXylaScope biorefinery are expected from

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- the construction of the facility,
- the facility itself: buildings, infrastructure and installations and
- the operation of the facility.

Impacts related to the **construction of the facility** are temporary and not considered to be significant.

Biorefineries need **buildings, infrastructure and installations** (e.g. conversion facilities, administration buildings, waste water treatment etc.), which are usually associated with soil sealing. Differences are expected regarding the biorefinery's location, depending on whether the project is developed on a greenfield site or on a brownfield site:

- A greenfield site is land currently used for agriculture or (semi)natural ecosystems left to evolve naturally.
- A brownfield site is land that was previously used for industrial, commercial or military purposes (often with known or suspected contamination) and is not currently used. Most of the area is expected to be already sealed and traffic infrastructure might (at least partly) be available.

Impacts are of course much more pronounced if a greenfield site or a previously unsealed brownfield site are chosen for the construction of the biorefinery.

Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Significant impacts are expected on water, soil, plants, animals and landscape and are highly dependent on local conditions.

Impacts from the **operation of the facility** are expected from:

- emission of noise
- emissions of gases and particulate matter
- emission of light
- drain of water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- disposal of wastes/residues
- risk of accidents (explosion, fire in the facility or storage areas, release of genetically modified organisms (GMO))

Significance of impacts might vary with the type of technology and the location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU.

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Key finding

- Local environmental impacts of biomass feedstock conversion can be reduced substantially if new biorefineries are built on (disused) industrial areas (“brownfield site”) instead of on agricultural land (“greenfield site”).

6.2 Local environmental impacts of the reference systems

Following a life cycle-oriented approach, the objective of the environmental assessment is to compare potential impacts of the biorefinery concept with other (conventional) reference systems.

There are two major reference products, which are compared to the **main xylan-based products** from the EnXylaScope concept:

- Cosmetics ingredient alkyl polyglucoside derived from palm oil
- Feed mix based on the main components wheat, maize and soy bean

In both cases, co-products are obtained, replacing a mixture of the following products (see also section 4.3.2):

- Sugar from sugar beet,
- Starch from maize or wheat grain,
- Alkyl ketene dimer from palm oil
- Chemicals from crude oil.

Alike the EnXylaScope concept, also the reference systems are divided into several life cycle stages. For the purpose of the LC-EIA, mainly feedstock provision and feedstock conversion are distinguished. Transport and logistics are considered separately.

6.2.1 Feedstock provision (substitutes for main xylan-based products)

EnXylaScope’s main xylan-based products are set to substitute products containing or derived from:

- Palm oil (for alkyl polyglucoside, reference 1)
- Wheat grain, maize grain and soy beans (for feed mix, reference 2)

As can be seen from this, all reference products are mainly of biogenic origin. The conflict matrices of the individual feedstocks can be found in section 11.1.2 in the annex.

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Overview of biomass feedstock provision (substitutes for main products)

Subsequently, these risks associated with the provision of the biogenic feedstocks were aggregated and categorised from A (low risk) to E (high risk) to enable a comparison. The results are depicted in Table 9.

Table 9: Risks associated with the provision of the biogenic feedstocks which are substituted by EnXylaScope's main xylan-based products
How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

	Reference 1		**Reference 2**			
Crop **Type of risk**	**Oil palm Ref. system: non-rotational fallow land**	**Oil palm Ref. system: rain forest**	**Wheat grain Ref. system: rotational fallow land**	**Maize grain Ref. system: rotational fallow land**	**Soybean Ref. system: rotational fallow land**	**Soybean Ref. system: rain forest**
Soil erosion	C	E	C	D	D	E
Soil compaction	B	E	C	C	D	E
Loss of soil organic matter	B	E	D	D	C	E
Soil chemistry / Fertiliser	C	D	D	D	D	E
Eutrophication	C	D	D	D	D	E
Nutrient leaching	C	D	D	D	E	E
Water demand	C	C	C	D	D	D
Weed control / pesticides	D	E	E	E	D	E
Loss of landscape elements	C	E	C	C	D	E
Loss of habitat types	E	E	D	D	E	E
Loss of species	E	E	D	D	E	E

6.2.2 Feedstock provision (substitutes for co-products)

The substitutes for the EnXylaScope co-products are

- Sugar from sugar beet (about 53 % w/w),
- Starch from maize or wheat grain (about 28 % w/w),
- Alkyl ketene dimer from palm oil (about 5 % w/w) and
- Chemicals from crude oil (about 15 % w/w).

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As can be seen from this, these reference products are mainly of biogenic origin, apart from a small share of the fossil feedstock crude oil. The conflict matrices of the individual feedstocks can be found in section 11.1.3 in the annex.

Overview of biomass feedstock provision (substitutes for co-products)

Subsequently, these risks associated with the provision of the biogenic feedstocks were aggregated and categorised from A (low risk) to E (high risk) to enable a comparison. The results are depicted in Table 10.

Table 10: Risks associated with the provision of the biogenic feedstocks which are substituted by EnXylaScope's co-products

How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

Crop Type of risk	Sugar beet Ref. system: rotational fallow land	Wheat grain Ref. system: rotational fallow land	Maize grain Ref. system: rotational fallow land	Oil palm Ref. system: non-rotational fallow land	Oil palm Ref. system: rain forest
Soil erosion	E	C	D	C	E
Soil compaction	E	C	C	B	E
Loss of soil organic matter	E	D	D	B	E
Soil chemistry / fertiliser	E	D	D	C	D
Eutrophication	D	D	D	C	D
Nutrient leaching	D	D	D	C	D
Water demand	E	C	D	C	C
Weed control / pesticides'	E	E	E	D	E
Loss of landscape elements	C	C	C	C	E
Loss of habitat types	D	D	D	E	E
Loss of species	D	D	D	E	E

The types of risks associated with the provision of the fossil feedstock crude oil are completely different in quality and quantity to those of biogenic feedstocks, see Table 22 in the annex (p. 87). Thus, a direct comparison at the level of risks not possible. However, a comparison of impacts at the level of environmental factors (water, soil, flora/fauna etc.), could be a solution, as [Keller et al. 2014] have shown. Due to the small share of the fossil feedstock crude oil, this topic is not further elaborated.

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6.2.3 Transport and logistics

As far as transportation and distribution as well as storage of biogenic feedstocks are concerned, the same statements apply as for the biorefinery feedstocks (see section 6.1.2).

The only fossil feedstock, crude oil, is usually shipped to Europe. Long-distance transportation increases exhaust gases (cargo ships, lorries) with potential impacts on water (ocean), related organisms (plants, animals, biodiversity), air quality and landscape. Natural gas is supplied via pipelines with additional impacts on the environment. The distribution within Europe is basically done via pipelines and vessels.

Overall, the local environmental impacts associated with transportation and logistics are not expected to be substantial.

6.2.4 Feedstock conversion

As far as conversion of biogenic feedstock conversion is concerned, the same statements apply as for the biorefinery feedstocks (see section 6.1.3).

Significance of impacts might vary with the type of technology and the location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU.

Key finding

> Local environmental impacts from the conversion of biogenic feedstocks as well as crude oil into (bio-based) products are mostly expected from the operation phase of the respective facilities.

6.3 Comparison: EnXylaScope concept vs. reference systems

In this section, the local environmental impacts associated with the EnXylaScope concept are compared to those associated with the conventional reference systems.

6.3.1 Feedstock provision

The supply of feedstock is linked to local environmental impacts that vary depending on the type of feedstock and technology. There are fundamental differences between the provision technologies which in case of biomass feedstock are linked to different agricultural practices and/or reference systems. Table 11 and Table 12 summarise the crop-specific conflict matrices of the EnXylaScope feedstocks and the references 1 & 2.

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Table 11: Risks associated with the provision of the EnXylaScope feedstocks compared to the biogenic feedstocks of reference 1 (cosmetics)

How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

	EnXylaScope			**Reference 1: Cosmetics**				
Crop	**Wheat straw**	**Poplar**	**Poplar**	**Oil palm**	**Oil palm**	**Sugar beet**	**Wheat grain**	**Maize grain**
Type of risk / **RS**	Straw ploughed in	Non-rot. fallow land	Grass-land	Non-rot. fallow land	Rain forest	Rot. fallow land	Rot. fallow land	Rot. fallow land
Soil erosion	C	B A[1]	C	C	E	E	C	D
Soil compaction	C	B	C	B	E	E	C	C
Loss of soil organic matter	C	A	D	B	E	E	D	D
Soil chemistry / fertiliser	C	B	D	C	D	E	D	D
Eutrophi-cation	C	C	C	C	D	D	D	D
Nutrient leaching	C	C B[2]	D C[2]	C	D	D	D	D
Water demand	C	C	C	C	C	E	C	D
Weed control / pesticides	C	C	C	D	E	E	E	E
Loss of land-scape elements	C	B	B* D*	C	E	C	C	C
Loss of habitat types	B[3] C	B	B* D*	E	E	D	D	D
Loss of species	B[3] C	B	D	E	E	D	D	D

[1] In case of strip cultivation

[2] In case of cultivation in buffer zones towards water bodies

[3] In case of long-stalked varieties since less weed control is necessary

* Depending on the structure of the surrounding landscape positive or negative impacts are expected

Overall, potential local environmental impacts associated with the provision of biomass feedstock to the EnXylaScope biorefinery concept are mainly neutral to positive, unless grassland is converted to poplar plantations. In contrast to this, both reference systems can entail substantial negative impacts. A more detailed comparison between the EnXylaScope concept and the reference system is not possible since the yields associated with the conventional crops and required amounts differ from those of wheat straw and poplar, respectively. Furthermore, biomass residue use cannot be directly compared to dedicated crops since the respective reference systems are fundamentally different.

Table 12: Risks associated with the provision of the EnXylaScope feedstocks compared to the biogenic feedstocks of reference 2 (feed mix)

How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

	EnXylaScope			**Reference 2: Feed mix**						
Crop	**Wheat straw**	**Poplar**	**Poplar**	**Wheat grain**	**Maize grain**	**Soy bean**	**Soy bean**	**Sugar beet**	**Oil palm**	**Oil palm**
Type of risk / **RS**	Straw ploughed in	Non-rot. fallow land	Grass-land	Rot. fallow land	Rot. fallow land	Rot. fallow land	Rain forest	Rot. fallow land	Non-rot. fallow land	Rain forest
Soil erosion	C	B A[1]	C	C	D	D	E	E	C	E
Soil compaction	C	B	C	C	C	D	E	E	B	E
Loss of soil organic matter	C	A	D	D	D	C	E	E	B	E
Soil chemistry / fertiliser	C	B	D	D	D	D	E	E	C	D
Eutrophication	C	C	C	D	D	D	E	D	C	D
Nutrient leaching	C	C B[2]	D C[2]	D	D	E	E	D	C	D
Water demand	C	C	C	C	D	D	D	E	C	C
Weed control / pesticides	C	C	C	E	E	D	E	E	D	E
Loss of landscape elements	C	B	B* D*	C	C	D	E	C	C	E
Loss of habitat types	B[3] C	B	B* D*	D	D	E	E	D	E	E
Loss of species	B[3] C	B	D	D	D	E	E	D	E	E

[1] In case of strip cultivation

[2] In case of cultivation in buffer zones towards water bodies

[3] In case of long-stalked varieties since less weed control is necessary

* Depending on the structure of the surrounding landscape positive or negative impacts are expected

Key findings and conclusions

- Biomass feedstock provision from dedicated (annual) crops for the reference system tends to be associated with qualitatively higher potential local environmental impacts than biomass feedstock provision for the biorefinery from lignocellulosic biomass and straw, unless the latter involves a land use change from grassland to cropland.
- Additionally, the reference system requires more land than biomass provision for a biorefinery according to the EnXylaScope biorefinery concept (see section 5.3.1). Taken together, local environmental impacts of the biorefinery are expected to be lower than those of the reference system.

6.3.2 Transport and logistics

Local environmental impacts of transport, distribution and storage are expected to be very similar for the lignocellulosic biogenic feedstocks and the conventional biogenic feedstocks.

6.3.3 Feedstock conversion

The conversion of feedstock causes local environmental impacts and is expected to be very similar for the lignocellulosic biogenic feedstock and the conventional biogenic feedstock. However, the conversion of biogenic feedstock differs significantly from the conversion of fossil feedstock. Due to the negligible share of the fossil feedstock crude oil, however, this topic is not further elaborated.

No significant differences are expected regarding the impacts related to the **construction of the facilities**. In both cases, the impacts are temporary and not considered to be significant.

Regarding the impacts related to **buildings, infrastructure and installations**, slight differences are expected between EnXylaScope and all other types of feedstock conversion. In all cases, significant impacts are expected due to soil sealing, if the conversion facility is developed on a greenfield site. On a brownfield site, in contrast, impacts are not expected to be significant. Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible.

Some impacts from the **operation of the facilities** are expected to be comparable, e.g. regarding noise, light and electromagnetic emissions. The same holds for water demand and wastewater production.

Key finding

> Local environmental impacts of EnXylaScope biorefineries do not differ significantly from those of conventional biomass conversion facilities.

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7 Recommendations

To further develop the analysed lignocellulose biorefinery concept into an environmentally friendly technology option, we recommend the following concrete steps to the respective stakeholder groups:

To process developers and research funding agencies

Engage in or support, respectively, the further development of sustainable integrating concepts of future biorefineries using underutilised lignocellulosic residues. The long-term process of establishing overall sustainable concepts should be initiated by funding demonstration plants. For the specific biorefinery concept analysed in this study, consider the following optimisation options for a sustainable implementation:

- Implement electrification of as many processes within the EnXylaScope concept as possible to reduce natural gas-based heat provision. Mechanical vapour recompression instead of distillation and heat pumps could be promising technologies to reach this goal. The design of new plants for the use of natural gas is increasingly incompatible with decarbonisation goals. If only renewable electricity is used in the future, electrification is the biggest step towards climate neutrality of the biorefinery concept as a whole.
- Use modified instead of unmodified xylan if both are suitable for the final consumer product. Although modification represents an additional process step, energy savings that result from favourable precipitation properties make the modified xylan advantageous from an environmental point of view. This is valid unless, at industrial scale, enzyme production turns out to consume more resources than expected and ethanol recovery can be achieved much more efficiently using renewable electricity.
- Seek for further xylan modifications that allow reduction of heat demand during the biorefinery processes.
- Use wheat straw as biomass feedstock instead of poplar because of reduced environmental impacts.
- If the intended xylan properties require the use of poplar as feedstock, make sure to obtain it from cultivation systems that are based on unused or abandoned land instead of grassland.
- Integrate enzyme production into the biorefinery facilities as it is modelled in the analysed scenarios. This could save emissions both from transport and from additional chemicals that might be needed to stabilise the enzyme cocktail.
- Try to replace chemical lysis agents in enzyme production by mechanical cell-disruption processes to use electricity instead of chemicals.

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- Reduce the amounts of lactose and, of secondary importance, glucose for enzyme production as far as technically possible for each intended product application.
- Optimise internal recycling processes for sodium hydroxide and ethanol rigorously, and reduce the amounts of hydrogen peroxide as far as possible.
- Take appropriate measures to minimize ethanol vapours released to the atmosphere as they can lead to substantial contributions to summer smog.
- Substantiate the beneficial effects of xylan on the health of pigs and other livestock in feeding trials as soon as sufficient amounts of xylan can be produced. If the analysed scenario of reduced feed demand due to improved health can be met in practice, large environmental benefits are possible.
- Develop applications for modified xylan that go beyond matching as closely as possible the functionalities of existing (preferably fossil-based) products. Additional functions and therefore value could not only provide a unique selling point but also replace further less sustainable products such as additives in formulations.
- Develop environmentally more advantageous applications of lignin, especially with the goal to replace larger amounts of more energy-intensive fossil-based products.
- Find alternative use options for the C6/cellulose stream to increase environmental advantages. For example, it could be investigated if cellulose can be used in form of fibres or if the glucose syrup after hydrolysis has functional advantages for certain applications compared to other glucose syrups.

To potential industrial operators of a future biorefinery

- Strategic decisions concerning the selection of the product portfolio in particular determine early on whether a biorefinery has the potential to produce environmentally friendly products over the entire product life cycle. A multitude of factors and influences has to be considered for the selection of the product portfolio. Therefore, a rigorous analysis of the associated environmental impacts at the planning stages of a concrete biorefinery is strongly recommended, which needs to be more specific than this necessarily generic study that is designed to support further technology development.
- For an implementation of an industrial-scale plant, consider regions that are unlikely to attract larger biorefineries due to limited biomass availability. This could prevent future competition for biomass that might lead to excessive biomass harvesting. Analyse availability of the required biomass early on in the site identification process.

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- If wheat straw is used, make sure that sufficient amounts are left on the fields to conserve soil carbon levels. Furthermore, alternative supply chains or biomass feedstocks should be established for periods of unfavourable weather conditions and related limited straw availability. The cultivation of long-stalked cereal varieties could increase straw availability and have ecological co-benefits.
- Longer planning is particularly necessary if poplar is used as it needs to grow for several years before being harvested.
- Try to identify e.g. disused industrial sites to build the biorefinery (“brownfield”) instead of using e.g. productive agricultural land (“greenfield”). This should however not lead to substantially increased transportation needs.

To political decision makers

- Establish clear sustainability criteria for biomass residues that are consistent across sectors with regard to how much of which residue can be extracted. This is needed to limit negative environmental impacts from excessive aggregate use. This requires clear aims and targets for conservation of nature and agricultural soils and their active management.
- In the mid- to long-term, biomass allocation plans should be developed at national and / or European level. Due to the fact that environmental burdens and social impacts of resource scarcity do not possess an adequate price, market mechanisms cannot replace these plans.
- Support the establishment of short rotation coppice of poplar and similar lignocellulosic crops for material use applications such as analysed in this study taking competition for arable land into account. However, exclude support for cultivation on drained organic soils and conversion of grassland for poplar cultivation. Particular attention should be given to cultivation practices with further ecological benefits such as strip cultivation to prevent erosion and cultivation next to water bodies to prevent nutrient leaching.
- Support prebiotics in animal husbandry. Scenarios like the ones studied here can have great environmental benefits including reduced pressure on deforestation. Searching for other options to reach this goal seems worthwhile although environmental impacts of producing the prebiotics have to be taken into account.

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8 Abbreviations

aLULUC	Attributional land use and land use change
APG	Alkyl polyglucoside (palm oil- and sugar-based cosmetics ingredient)
C5	Sugars components with 5 carbon atoms (hemicellulosic sugars)
C6	Sugar components with 6 carbon atoms (cellulosic sugars)
dLULUC	Direct land use and land use change
EIA	Environmental impact assessment
EU	European Union
GAX	Glucurono(arabino)xylan
GMO	Genetically modified organism
GX	O-acetyl-(4-O methyl-glucurono)xylan
IE	Inhabitant equivalents (fractions of average emissions per capita and year in the European Union)
ISO	International Organisation for Standardisation
ILCD	International Reference Life Cycle Data System
ILCSA	Integrated life cycle sustainability assessment
LCA	Life cycle assessment
LC-EIA	Life cycle environmental impact assessment
LCI	Life cycle inventory
LCIA	Life Cycle Impact Assessment
LCT	Life cycle thinking
LMW	Low molecular weight
LU	Land use
LUC	Land use change
RO	Reverse osmosis
SOM	Soil organic matter
SRC	Short rotation coppice
WIS	Water-insoluble
WP	Work Package

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9 Acknowledgements

The authors would like to thank all EnXylaScope project partners sincerely for the provision of information and data, which forms the basis of the environmental life cycle assessment, notably the mass and energy flow data provided to task 7.1.

Furthermore, we are also grateful to Dr. Oscar Bedzo and Dr. Lalitha Gottumukkala for providing the system description chapter to all sustainability assessment reports and for the close interaction and continuous valuable discussions in WP 7 in particular on input data and project context. Moreover, we would like to thank our IFEU colleagues Dr. Sonja Haertlé, Dr. Hanna Karg and Dr. Guido Reinhardt for valuable discussions, comments and support in preparing the report. We would also like to extend our gratitude to Dr. Carolina Peñalva and Javier Pérez from AITIIP for the professional coordination and management of the project.

This deliverable is part of the EnXylaScope project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000831.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101000831

11 Annex

11.1 Supplements to LC-EIA

In the following, supplementary material to the Life Cycle Environmental Impact Assessment (LC-EIA) is presented. In section 11.1.1, the conflict matrices for the EnXylaScope feedstock SRC poplar are shown. Section 11.1.2 and 11.1.3 present conflict matrices for crops that are providing the substitutes for the EnXylaScope main products and co-products, respectively, constituting the reference system. All conflict matrices are taken from ifeu's internal database [IFEU 2024] with slight adaptations and were originally elaborated in previous projects, among others [Keller et al. 2014, 2017; Reinhardt, Rettenmaier, & Wagner 2019].

11.1.1 EnXylaScope: Local impacts of biomass feedstock provision

In the following, two conflict matrices for SRC poplar are shown for two different reference systems: non-rotational fallow land (Table 13) and grassland (Table 14).

Provision of SRC poplar

Table 13: Risks associated with the cultivation of SRC poplar compared to the reference system of non-rotational fallow land

Type of risk	Affected environmental factors								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Land-scape**	**Human health & recreation**	**Bio-diversity**
Soil erosion	neutral[1] positive[4]		neutral[1]						
Soil compaction	positive[1]	neutral[1]		neutral/ positive[1]	neutral/ positive[1]				neutral/ positive[1]
Loss of soil organic matter	positive[1]			neutral/ positive[1]	neutral/ positive[1]				neutral/ positive[1]
Soil chemistry / fertiliser	positive[1]	neutral[1]	neutral[1]						
Nutrient leaching	neutral[1]	neutral[1]	(positive[3])						
Eutrophi-cation	neutral	neutral	neutral	neutral[1]	neutral				neutral
Water demand		neutral	negative	neutral					neutral
Weed control / pesticides		neutral[1]	neutral[1]	neutral[1]	neutral[1]				neutral[1]
Loss of land-scape elements				neutral/ positive[1]	neutral/ positive[1]	positive[1]	neutral/ positive[1]	positive[1]	neutral/ positive[1]
Loss of habitat types				positive[2]	positive[2]				
Loss of species				positive[2]	positive[2]				positive[2]

[1]: Regarding the total cultivation period of the crop; slightly negative in the first year

[2]: No threatened/protected habitats considered in the reference system.

[3]: In case of cultivation in buffer zones towards water bodies, leaching from fertilisation of other cultures

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on adjacent fields can be reduced. Otherwise not applicable.

[4]: In case of strip cultivation.

Table 14: Risks associated with the provision of SRC poplar at the expense of grassland

Type of risk	**Affected environmental factors**								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Land-scape**	**Human health & recreation**	**Bio-diversity**
Soil erosion	neutral[1]		neutral[1]						
Soil compaction	neutral	neutral		neutral	neutral				neutral
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative							
Eutrophi-cation	neutral[1]	neutral[1]	neutral[1]	neutral[1]	neutral[1]				neutral[1]
Nutrient leaching		negative	(positive[3])						
Water demand		neutral		neutral	neutral				neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of land-scape elements				negative/ positive[2]	negative/ positive[2]	negative/ positive[2]	negative/ positive[2]	negative/ positive[2]	negative/ positive[2]
Loss of habitat types				negative/ positive[2]	negative/ positive[2]				negative/ positive[2]
Loss of species				negative	negative				negative

[1]: Slightly negative in the first year, neutral over the total cultivation period

[2]: Depending on the structure of the surrounding landscape positive or negative impacts are expected

[3]: In case of cultivation in buffer zones towards water bodies, leaching from fertilisation of other cultures on adjacent fields can be reduced. Otherwise not applicable.

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11.1.2 Reference systems: Local impacts of substitutes for main products

In the following, conflict matrices for crops that are providing the substitutes for the EnXylaScope main products are presented. For reference system 1, it is oil palm, while for reference system 2, the feed mix consists of wheat, maize and soybean. For oil palm and soybean, two conflict matrices each are presented which differ in terms of reference system (non-rotational fallow land and rainforest, respectively).

Provision of palm oil

Table 15: Risks associated with the cultivation of oil palms compared to the reference system of non-rotational fallow land

Type of risk	**Affected environmental factors**								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Land-scape**	**Human health & recreation**	**Bio-diversity**
Soil erosion	neutral/ positive[1,2]		negative[2]						
Soil compaction	neutral/ positive[1,2]	neutral/ positive[1]		negative	negative				negative
Loss of soil organic matter	neutral/ negative[2]			neutral/ negative[2]	neutral/ negative[2]				neutral/ negative[2]
Soil chemistry / fertiliser	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		neutral	neutral				neutral
Weed control / pesticides		negative	negative	negative	negative				negative
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				negative	negative				negative
Loss of species				negative	negative				negative

[1]: reduced number of maintenance cycles (perennial crop), manual harvesting
[2]: huge space between seedlings; negative in the first two years;

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Table 16: Risks associated with the cultivation of oil palms compared to the reference system of rain forest

Type of risk	**Affected environmental factors**								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Land-scape**	**Human health & recreation**	**Bio-diversity**
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative	negative						
Nutrient leaching	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Water demand		negative	negative	negative					negative
Weed control / pesticides		negative	negative	negative	negative				negative
Loss of landscape elements				negative	negative	negative	negative	negative	negative
Loss of habitat types				negative	negative				
Loss of species				negative	negative				negative

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Provision of wheat

Table 17: Risks associated with the cultivation of wheat (straw left on the field and ploughed in) compared to the reference system of "non-cropping" (rotational fallow land)

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Soil erosion	neutral/ negative[2]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral/ negative[2]			neutral/ negative[2]	neutral/ negative[2]				negative
Soil chemistry / fertiliser	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative							
Water demand		negative		negative	negative				neutral
Weed control / pesticides		neutral/ negative[1,2]	neutral/ negative[1,2]	neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1,2]
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1,2]
Loss of species				neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1,2]

[1]: Negative in case of short stemmed varieties; long-stalked varieties afford less weed control

[2]: Negative impact can be minimised by crop rotation; e.g. winter wheat and / or double cropping

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Provision of maize

Table 18: Risks associated with the cultivation of maize (straw ploughed in) compared to the reference system rotational fallow land

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral/ negative[1,2]			neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1]
Soil chemistry / fertiliser	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control / pesticides		negative	negative	negative	negative				negative
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative[1]	neutral/ negative[1]				neutral/ negative[1]
Loss of species				neutral/ negative[1]	neutral/ negative[1]				neutral/ negative[1]

[1]: Negative impact can be minimised in case of crop rotation (succeeding crop), e.g. winter wheat;
[2]: Ploughing of straw is usually not enough for a total compensation of nutrient loss

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Provision of soybean

Table 19: Risks associated with the cultivation of soy beans compared to the reference system rotational fallow land

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative	negative	negative	negative				neutral
Nutrient leaching	negative	negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Water demand		negative	negative	neutral	neutral				neutral
Weed control / pesticides		negative	negative	negative	negative			negative	negative
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral	neutral				neutral
Loss of species				neutral	neutral				neutral

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Table 20: Risks associated with the cultivation of soy beans compared to the reference system of rain forest

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Soil erosion	negative		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative			negative	negative				negative
Soil chemistry / fertiliser	negative	negative	negative						
Nutrient leaching	negative	negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Water demand		negative	negative	negative					negative
Weed control / pesticides		negative	negative	negative	negative				negative
Loss of land-scape elements				negative	negative		negative	negative	negative
Loss of habitat types				negative	negative				
Loss of species				negative	negative				negative

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11.1.3 Reference systems: Local impacts of substitutes for co-products

In the following, conflict matrices for crops that are providing the substitutes for the EnXylaScope co-products are presented.

Provision of sugar beet

Table 21: Risks associated with the cultivation of sugar beet (ploughing of leaves) compared to the reference system of non-cropping (rotational fallow land)

Type of risk	**Affected environmental factors**								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Land-scape**	**Human health & recreation**	**Bio-diversity**
Soil erosion	negative[1]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral/ negative[1,2]			neutral/ negative[1,2]	neutral/ negative[1,2]				neutral/ negative[1,2]
Soil chemistry / fertiliser	negative	negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control / pesticides'		negative	negative	negative	negative				negative
Loss of land-scape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative[1]	neutral/ negative[1]				neutral/ negative[1]
Loss of species				neutral/ negative[1]	neutral/ negative[1]				neutral/ negative[1]

[1]: Negative impact can be minimised in case of crop rotation (succeeding crop), e.g. winter wheat;
[2]: Ploughing of leaves is usually not enough to compensate loss of nutrients

Provision of wheat

See Table 17 in section 11.1.2.

Provision of maize

See Table 18 in section 11.1.2.

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Provision of palm oil

See Table 15 and Table 16 in section 11.1.2.

Provision of crude oil / gas

Table 22: Impacts on environmental factors related with the value chains of crude oil / gas provision; potentially significant impacts are marked with thick frames; reference scenario: no use

Technological factor	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Prospection	negative			negative	negative				negative
Drilling / mining	negative	negative	negative	negative	negative		negative		negative
Waste (oil- and water-based mud)	negative	negative	negative	negative	negative				negative
Demand of water (process water)		negative	negative	negative	negative		negative		negative
Emissions (exhaust fumes, water, metal)		negative	negative	negative	negative	negative		negative	
Land requirements	negative	negative	negative	negative	negative	negative	negative		negative
Demands of steel (tubes, equipment)	negative			negative	negative		negative		
Transportation (carriers, pipelines)	negative	negative	negative	negative	negative	negative	negative	negative	negative
Refining / processing	negative	negative	negative	negative	negative		negative	negative	negative
Accidents (traffic, pipeline leakage)	negative	negative	negative	negative	negative		negative	negative	negative

☐ **Likely significant impacts**

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Table 23: Potential impacts on the environment related to crude oil / gas provision compared to the reference system "no use"

How to read the table: ***Impacts are ranked in five comparative categories (A, B, C, D, E); "A" and "B" are assigned to the best options concerning the factor, but are not used in this case; "E" is assigned to unfavourable options concerning the factor; reference scenario: "no action"-alternative***

Technological factor	Crude oil / gas provision
Prospection	C
Drilling / mining	E
Waste (oil- and water-based mud)	D
Demand of water (process water)	C / D[2]
Emissions (exhaust fumes, dust, water, metal)	C / D[2]
Land requirements	C / D[1]
Demands of steel (tubes, equipment)	D
Transportation (carriers, pipelines)	D
Refining / processing / enrichment	D
Accidents (traffic, pipeline leakage)	E

[1]: Increased land requirements in on-shore production

[2]: Increased impact in crude oil provision

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