



# EnXylaScope

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

## Sustainability of an innovative enzyme-based process for the production of xylan products

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## 1 Executive 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 lignocellulose 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 applications. In addition, this novel 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 derived 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. A common set of scenarios based on mass and energy balances from detailed process models representing **potential future industrial-scale biorefinery variants** at a scale of 15 kt biomass input per year was evaluated. The scenarios comprise the use of several xylan variants as an ingredient in cosmetics and as a health-improving feed additive for pigs that has the potential to reduce the pig feed demand by up to forty times the mass of the additive. The co-products glucose and lignin are valorised, too.

This report by IFEU covers the integrated sustainability assessment. It integrates all results on previously determined environmental, economic and social impacts that can be associated with the future implementation of the novel biorefinery concept. It joins and complements recommendations how to improve the concept, taking potential conflicts and synergies of individual sustainability aspects into account.

The analysed scenarios (variants of potential future industrial-scale implementations of the novel lignocellulose biorefinery concept) are expected to have mostly advantageous environmental, economic and social sustainability impacts compared to alternative, mostly bio-based products of equivalent use. **All analysed scenarios are profitable and substantial environmental benefits are possible** depending on the use of the xylan. Only few potential negative environmental impacts or high social risks in the supply chain were found. These potential disadvantages are particularly relevant for the most mature scenario that could serve as a blueprint for a first implementation. However, all disadvantages can and should be mitigated by identified measures.

The main drawbacks of the analysed scenarios and the respective mitigation options are: **Ethanol emissions** lead to increased summer smog/ozone formation compared to alternative products. This should be prevented by appropriate treatment of the vapours resulting from xylan drying after ethanol precipitation. Negative local environmental impacts can arise from **excessive extraction of straw** from the fields and from cultivating





**poplar short rotation coppice on land previously used as permanent grassland.** Furthermore, poplar cultivation in regions with high shares of **arable land on drained peatlands** should be avoided because associated emissions can be as high as all greenhouse gas emission savings otherwise associated with the biorefinery. These disadvantages can and should be excluded by diligent biomass sourcing. Besides environmental aspects, supplies particularly from medium- and low-income countries can be associated with high **social risks**. In such cases, negative social impacts should be avoided by buying certified goods or by engaging directly with the suppliers. Mitigations may lead to certain costs but seem realistic without affecting the profitability too much.

These **findings support a fast upscaling** of the analysed biorefinery concept to verify the process and product performance underlying the analysed scenarios. Several **critical parameters should be verified with priority on a larger scale** (e.g. demo): **Product performance** is particularly important because the specialty xylans are high-value products that require corresponding production efforts. Based on current knowledge, these efforts seem to be justified by the performance, i.e. by the replacement of existing products with higher sustainability impacts. This however still needs to be verified on a larger scale. The **technical suitability of the assessed feedstocks** needs to be verified under real-world conditions because the removal of impurities such as bark or dirt could alter assessment results significantly if additional processing is required. Finally, **regulatory compliance** should be verified to remove a possible road block or avoid a re-design of parts of the process.

Beyond the analysed scenarios, the following technical optimisation options seem worthwhile to explore for an improved environmental and economic performance: Research and development efforts should be invested into improving the **wheat straw xylan qualities** to support further applications. Generally, **further use options for xylans and lignin** should be explored aiming at the replacement of more energy-intensive, high-value fossil-based products. In particular enzymatically modified xylan promises to enable unconventional applications that are out of reach with unmodified xylan. To make investments future-proof, any future biorefinery needs to become largely **climate neutral** during its expected lifetime. The most important step towards this goal is not to rely on steam supply from fuel combustion but instead on **electrification**.

Further to technical optimisation, a future industrial-scale plant will require a critical analysis of the **sustainable availability of biomass feedstocks** at its location to avoid an excessive use of resources. The relatively small economically required scale of this high-value product bio-refinery compared to e.g. 2<sup>nd</sup> generation biofuel plants will be an advantage to this end. An extension of the feedstock base can mitigate respective risks. If xylan from poplar short rotation coppice is used as feed additive to lower feed demand as effectively as modelled in the scenarios, this **can release considerably more arable land than needed** for its cultivation. An optimised combination of feedstocks and applications thus has the potential to overcome resource constraints. Overall, the results highlight a plausible pathway for upscaling and market entry and towards promising long-term perspectives.





## 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 integrated sustainability assessment that joins and integrates all results from the previous environmental, techno-economic and social assessments.

## 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 work package 7 that implements this integrated life cycle sustainability assessment is depicted in Figure 1.



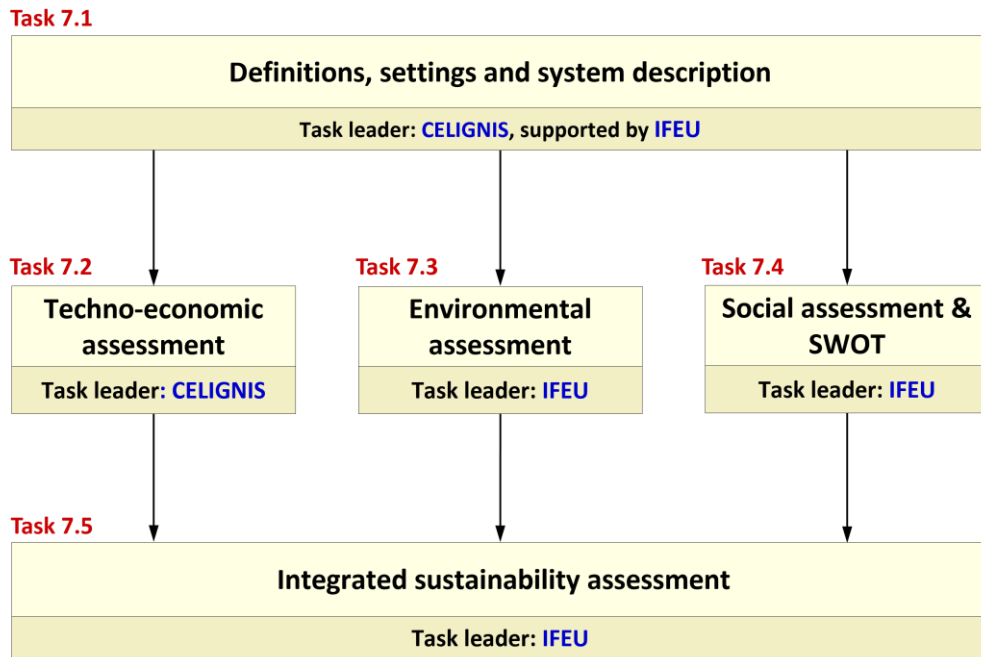


Figure 1: Structure of the work package on sustainability assessment in EnXylaScope.

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 integrated sustainability assessment are described in section 3.2.

### 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 are based. General definitions and settings 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 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?<sup>1</sup>

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<sup>1</sup> 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.



- > 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

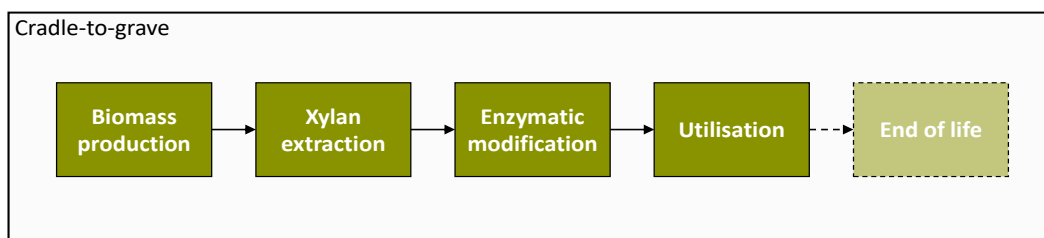
With the scope definition, the object of the sustainability assessment (i.e. the exact product or other system(s) to be analysed) is identified and described. The scope should be sufficiently well defined to ensure that the comprehensiveness, depth and detail of the study are compatible and sufficient 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. End of life is identical to utilisation in the analysed scenarios with consumptive use of the product.*

### Geographical coverage

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



- > 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 ('n<sup>th</sup> plant') is considered in the sustainability assessment. The technologies developed by the various partners are 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 2<sup>nd</sup> 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, and 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 integrated life cycle sustainability assessment (ILCSA)

The integrated sustainability assessment in EnXylaScope is based on the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015]. In the following sub-sections, specific settings and methodological choices are detailed.

### 3.2.1 General approach

ILCSA extends the concept of environmental life cycle assessment (LCA). It consists of the same general phases as an LCA study and provides a framework for integrated LCA, LCC or TEA, S-LCA and further analyses (Figure 3). To ensure that results of integrated analysis are compatible, ILCSA studies provide common goal and scope definitions (see section 3.1) and common scenarios resulting from common system modelling (see chapter 4).

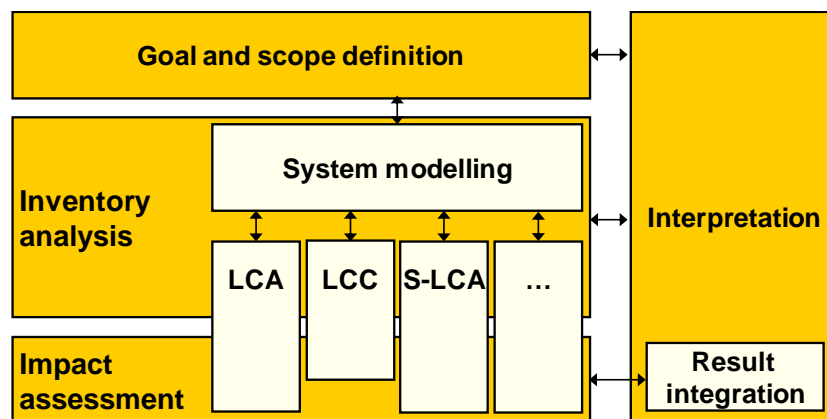


Figure 3: Phases of integrated life cycle sustainability assessment (ILCSA) studies. LCA: (environmental) life cycle assessment, LCC: lifecycle costing, S-LCA: social life cycle assessment. Adapted from [Keller et al. 2015].

Results are then joined to deliver common conclusions and recommendations. There are two general ways of integrating a diverse set of indicator results of a set of scenarios:

### Weighting and mathematical integration

All indicators could be mathematically combined into one score using weighting factors or ranked otherwise according to a weighting algorithm. These approaches, in particular the required weighting factors or schemes, cannot be entirely based on scientific facts but depend on personal value-based choices defined beforehand. Furthermore, conflict





situations do not become apparent and decisions regarding these conflicts depend on weighting factors, which are hard to understand for decision-makers not involved in the study. Therefore, this approach is not applied.

## Structured discussion

All strengths, weaknesses and conflicts of the options can be discussed verbally argumentatively. This can make conflicts transparent and enable their active management. Considering the number of options and indicators, this requires a structured approach. This approach is followed in this study. This section describes the methodology used for the structured comparison and presentation of decision options based on a multi-criteria analysis.

### 3.2.2 Collection of indicators and results

Indicators and results for all scenarios are provided by the parallel assessments addressing one single sustainability perspective each [Bedzo et al. 2025; Breyer et al. 2025; Karg et al. 2025]. They are collected in overview tables. In some cases, indicators are selected or aggregated by the authors of the respective contributing studies to focus on the most relevant aspects for decision support.

The integrated sustainability assessment of this project is based on:

- > 9 quantitative environmental indicators from the life cycle assessment (LCA)
- > 3 qualitative environmental indicators from the life cycle environmental impact assessment (LC-EIA)
- > 2 quantitative economic indicators and 1 qualitative technological indicator from the techno-economic assessment (TEA)
- > 4 quantitative social indicators from the social life cycle assessment (S-LCA)

No further adjustments are made except for rescaling quantitative data to a common basis if necessary. Thus, all specific settings, methodological choices including underlying estimates, and data sources apply unchanged as documented in the respective reports.

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly (see also Figure 12). Dark and light green boxes represent overall advantageous results. Orange and red boxes represent overall disadvantages (if applicable). Yellow boxes represent a minor sustainability impact. This way of categorising results supports the identification of options that perform best among all studied options but also maintains the quantitative information on the sustainability performance of a scenario. Results are collected for all assessed main scenarios. Additional results, such as from sensitivity analyses based on dedicated scenarios, are used to contextualise the results and taken into account for the overall conclusions (chapter 6) and recommendations (chapter 7).





### 3.2.3 Additional indicators

Climate protection under the condition of limited financial resources has to use the available financial resources as efficiently as possible. Efficiency means here to achieve the highest possible greenhouse gas (GHG) emission savings with the lowest monetary expenditures necessary for that. GHG abatement costs are frequently used as indicator for this purpose. GHG abatement costs are defined as quotient of the differential costs for a GHG reduction measure and the avoided GHG emissions by this measure.

GHG abatement costs represent an efficiency indicator to prioritise expenses such as subsidies. Because all analysed EnXylaScope scenarios are expected to be economically profitable, there are no losses, required subsidies or the like to calculate such an indicator. Moreover, abatement costs have to be interpreted carefully because in many situations their robustness and comparability are poor. For further details and a critical review of the method see [Pehnt et al. 2010]. Consequently, this additional indicator is not determined for the EnXylaScope concepts.

### 3.2.4 Benchmarking

The benchmarking step compares all scenarios to one benchmark scenario. This serves the purpose to answer questions such as 'What are the trade-offs if the economically most favourable scenario would be implemented?'. Benchmarking tables focus the attention on one decision option and deliver additional information on the robustness of differences.

The benchmark is chosen according to the questions to be answered and the respective perspectives of various stakeholders. Depending on the question to be answered, overview tables may contain all or a part of the indicators and scenarios. The unit of reference underlying the comparison of quantitative indicators is chosen according to the question.

A subsequent categorisation of the benchmarking results reflects the robustness of advantages or disadvantages over the benchmark taking into account the ranges of the results under conservative, typical and optimistic boundary conditions. For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question of whether a scenario performs better than the benchmark regarding a certain indicator. Therefore, these quantitative differences are categorised into very advantageous [++], advantageous [+], neutral [0], disadvantageous [-], or very disadvantageous [--].

Two scenarios are considered very different ([++] or [--]) if their ranges of results do not intersect. They are considered different ([+] or [-]) if only minor intersections occur. If the typical values of both scenarios are within the range of the respective other scenario, then they are not considered different [0]. For all qualitative indicators, rating of differences is done analogously. In this case, a typical value is also counted as being





within the range of the respective other scenario if its qualitative rating is identical to that of the end of the range of the other scenario.

### 3.2.5 Overall comparison

For an overall comparison, a verbal-argumentative discussion of decision options is supported by structured tables containing overviews of original indicator results or benchmarking results. Benchmarking tables can be used to deduce further concrete recommendations that could not be based on the underlying individual indicators but at the same time cannot contain all information from the underlying assessments. The deduction of recommendations from overview and benchmarking tables therefore also requires further in-depth analyses of the contributions e.g., of life cycle stages or unit processes that lead to these results. Obviously, all available information on individual contributions to all results cannot be displayed in one table. Necessary additional information is provided as background information to the reader in the discussion (e.g., differences A, B and C, which become apparent in benchmarking Table Z, are caused by the input of substance X in process Y; therefore, the input of substance X should be reduced as far as possible.). This way, overview and benchmarking tables provide additional insight, support the discussion, help not to miss any relevant aspect and make recommendations comprehensible.

## 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 4 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 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.

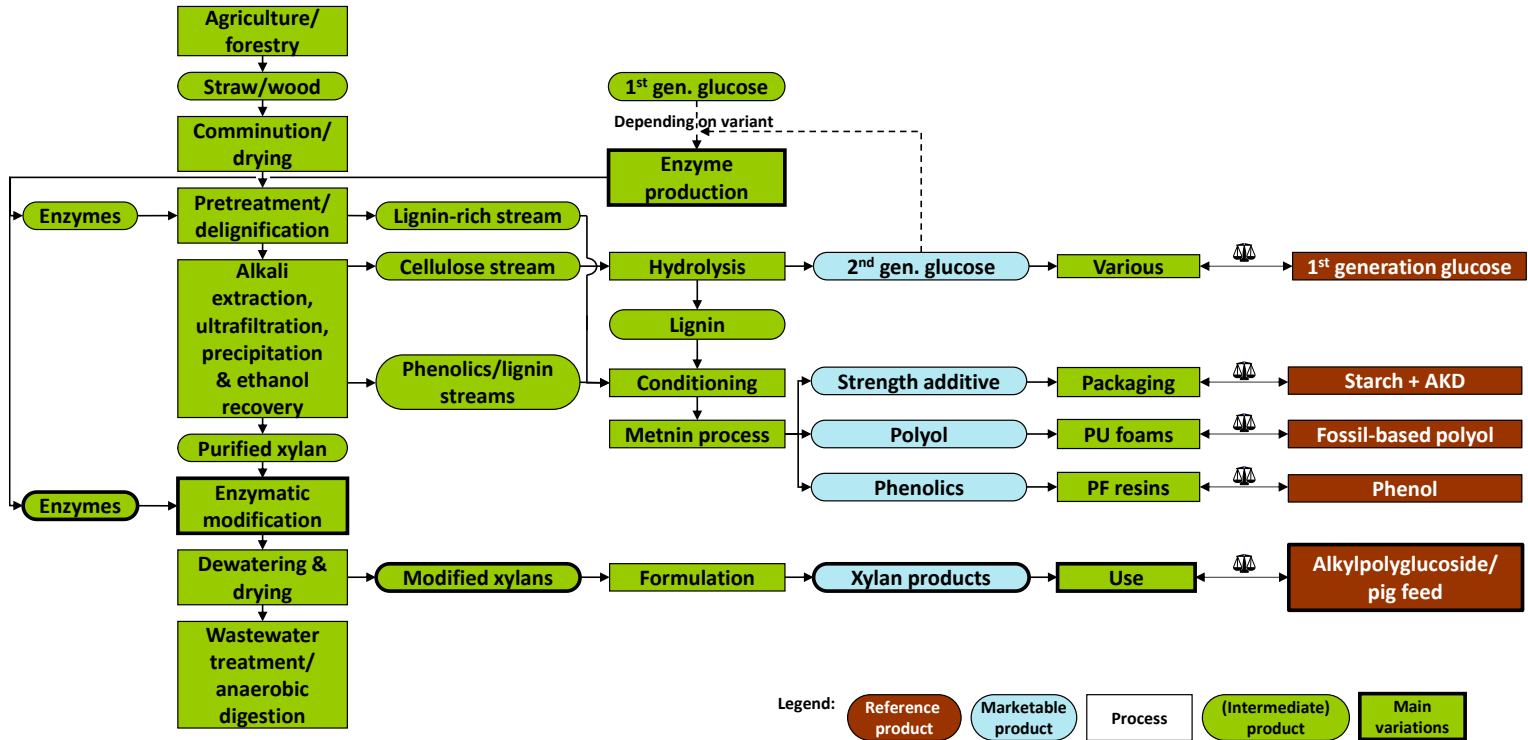


Figure 4: Simplified diagram showing the xylan extraction process in a biorefinery concept.

## 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 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 5) 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. 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.

## 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 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.

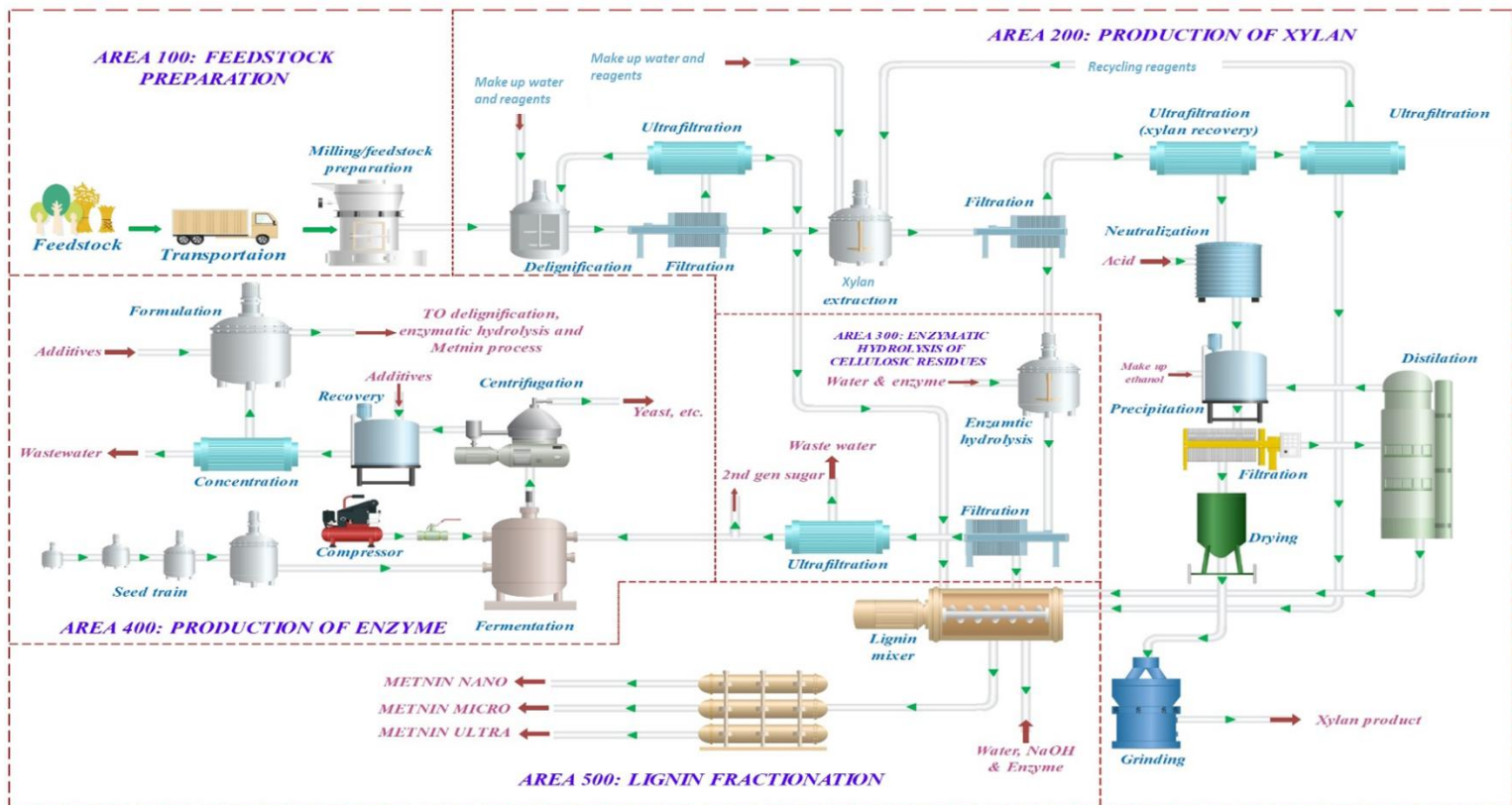


Figure 5: Simplified process flow of unmodified xylan production in a biorefinery concept. From [Bedzo et al. 2025], © by Celignis Limited.





## 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 °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 °C. After the reaction is completed, the reaction is briefly heated to 90 °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 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 6). 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.

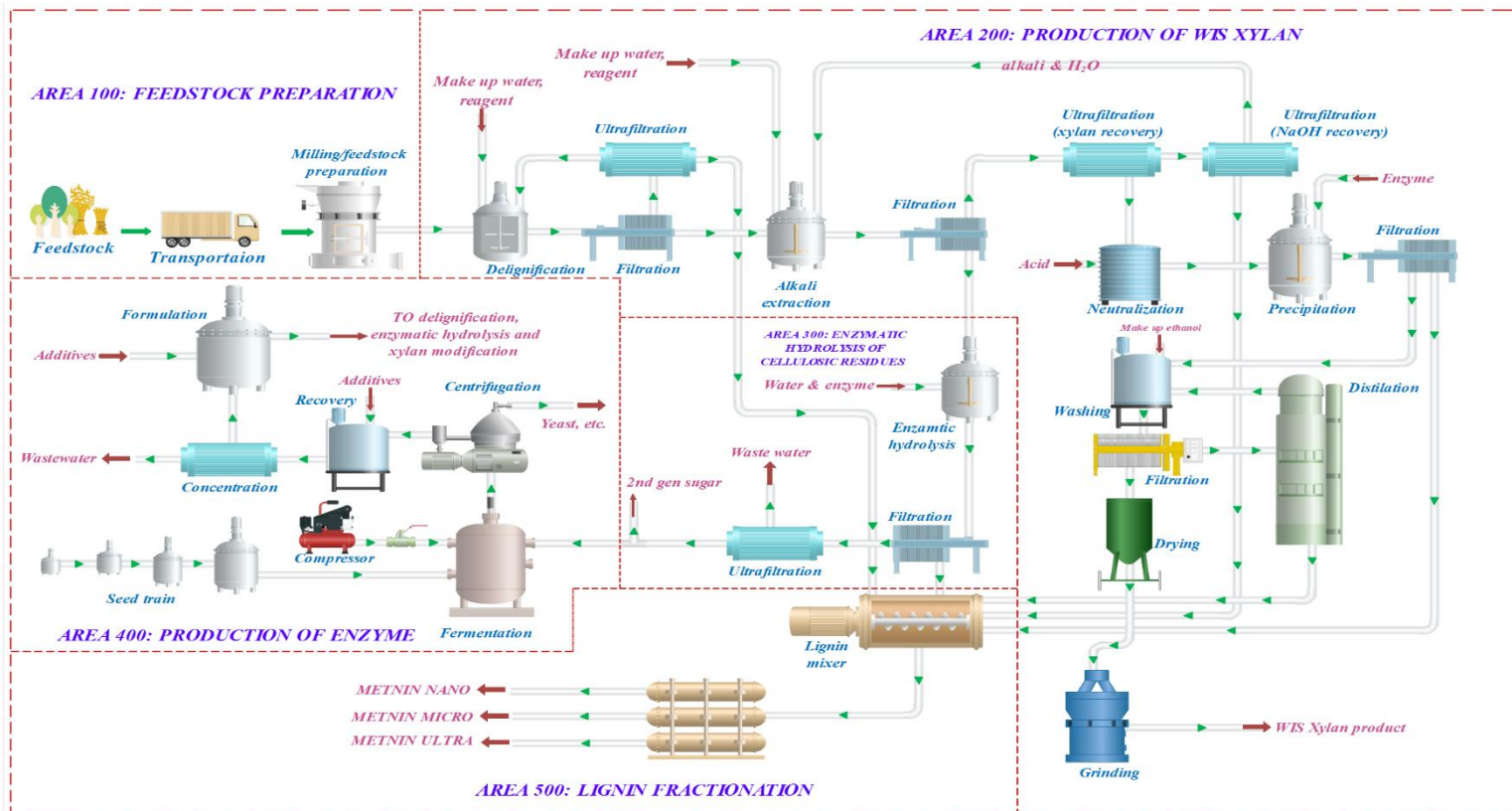


Figure 6: Simplified process flow of modified xylan production in a biorefinery concept. From [Bedzo et al. 2025], © by Celignis Limited.





## 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 2<sup>nd</sup> 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 1 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].

#### 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 1: 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 2<sup>nd</sup> generation glucose and lignin-based products are described below. The share of the replaced reference products by mass is provided in Table 2.

#### 2<sup>nd</sup> 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 2<sup>nd</sup> generation glucose syrup. In both cases, it replaces 1<sup>st</sup> generation glucose that would otherwise be used.

#### 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 2: 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 3).

Table 3: EnXylaScope biorefinery scenarios.

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

### Sub-scenarios and sensitivity analyses

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.

Additionally, several parameters were varied only in the environmental, techno-economic or social assessment, respectively, because of their different relevance. They were included in the range of sub-scenarios as described in section 6.1.1.





## 5 Summaries of contributing studies

This integrated sustainability assessment builds on several contributing studies, analysing economic, environmental and social aspects of the EnXylaScope scenarios. These are summarised in this chapter and integrated in chapter 6.

### 5.1 Summary of techno-economic assessment

*This summary of the report on techno-economic assessment [Bedzo et al. 2025] was contributed by Oscar K. Bedzo, Celignis. For details, please refer to the report.*

Enzyme-assisted alkali treatment is employed under specified conditions to facilitate the liberation and dissolution of the hemicellulosic content of selected lignocellulosic biomasses (wheat straw and poplar woodchips), followed by a series of separation and purification processes to ultimately generate unmodified and modified xylans. The tests and demonstrations carried out indicate that the ingredients are suitable for high value applications in cosmetics and as a health-improving feed additive for pigs.

The cellulose and lignin-rich residue streams of the xylan extraction process are also valorised to maximize resource use and efficiency in alignment with the biorefinery concept. The cellulose stream was found to be suitable for glucose production via enzymatic hydrolysis whereas a fractionation for high-value applications is foreseen for the lignin.

The various combinations of feedstock type, xylan modification, xylan consumer product application, xylan recovery efficiency and lignin valorisation methods resulted in 36 possible implementations of EnXylaScope biorefinery scenarios (Table 4), including additional scenarios, in which lignin is sold for external use ("NO METNIN"). These scenarios were evaluated for economic feasibility using indicators such as internal rate of return (IRR) and payback period (PBP).

#### Conclusions

The techno-economic evaluation has provided important insight into the economics of the EnXylaScope biorefinery concept for the production of modified and unmodified xylans from wheat straw or poplar woodchips while valorising the lignin and cellulosic side streams. The decision points that resulted in the various biorefinery scenarios were

- > Feedstock type (wheat straw or poplar woodchips)
- > Xylan modification (modified or unmodified)
- > Xylan use (feed or cosmetic)
- > Optimization sub-scenario (conservative or typical or optimistic)
- > Lignin valorisation (METNIN or NO METNIN)





Table 4: Summary of profitability indicators of the EnXylaScope biorefinery scenarios. IRR: internal rate of return, PBP: payback period

FEED-STOCK	APPLI-CATION	XYLAN MODIFICATION	METNIN	SUB-SCENARIO	ID	Xylan production, tpa	IRR, %	PBP, yr	Ranking of IRR
POPLAR	FEED	UNMODIFIED	NO METNIN	Conservative	1	2590	28.5%	2.1	36
				Typical	2	2812	30.7%	1.9	35
				Optimistic	3	3002	32.5%	1.8	34
			METNIN	Conservative	4	2590	33.6%	1.7	33
				Typical	5	2812	36.3%	1.5	30
				Optimistic	6	3002	38.8%	1.4	28
		LMW	NO METNIN	Conservative	7	2511	47.6%	1.0	23
				Typical	8	2709	50.2%	0.9	21
				Optimistic	9	2899	52.7%	0.9	18
			METNIN	Conservative	10	2511	50.7%	0.9	19
				Typical	11	2709	52.9%	0.9	16
				Optimistic	12	2899	55.0%	0.8	11
	COSMETIC	WIS	NO METNIN	Conservative	13	2511	47.6%	1.0	24
				Typical	14	2709	50.2%	0.9	22
				Optimistic	15	2899	52.7%	0.9	17
			METNIN	Conservative	16	2511	50.7%	0.9	20
				Typical	17	2709	53.9%	0.8	15
				Optimistic	18	2899	55.0%	0.8	11
WHEAT STRAW	FEED	UNMODIFIED	NO METNIN	Conservative	19	3136	33.6%	1.7	32
				Typical	20	3453	36.4%	1.5	29
				Optimistic	21	3868	39.9%	1.3	26
			METNIN	Conservative	22	3136	36.2%	1.5	31
				Typical	23	3453	39.4%	1.4	27
				Optimistic	24	3868	43.1%	1.2	25
		LMW	NO METNIN	Conservative	25	3040	54.3%	0.8	14
				Typical	26	3318	57.6%	0.8	7
				Optimistic	27	3718	62.1%	0.7	1
			METNIN	Conservative	28	3040	55.1%	0.8	10
				Typical	29	3318	58.0%	0.8	5
				Optimistic	30	3718	62.0%	0.7	3
	COSMETIC	WIS	NO METNIN	Conservative	31	3040	54.3%	0.8	13
				Typical	32	3318	57.6%	0.8	7
				Optimistic	33	3718	62.1%	0.7	1
			METNIN	Conservative	34	3040	55.1%	0.8	9
				Typical	35	3318	57.9%	0.8	6
				Optimistic	36	3718	62.0%	0.7	3





The outcomes of the techno-economic assessment under the given system definition and parameters allow us to make the following conclusions.

- > The introduction of the METININ process results in a slight margin of profitability as observed with the increase in IRRs.
- > The cost of feedstock has been identified as a significant driving factor for profitability of the biorefineries as it contributes at least 27% of the variable operating costs.
- > The reagents were found to be significant contributors to the variable operating costs as they jointly contributed at least 25%.
- > The heating requirement for the unmodified xylan production was higher than that required for the modified xylan production. This stems largely from the ripple effect of the lower ethanol requirement during the modified xylan production.
- > The modified xylan production biorefineries presented higher IRRs than the counterpart unmodified xylans making them to be of higher economic feasibilities.
- > Application of xylan in feed potentially generates savings of up to 2% on cost compared to feed without additive.
- > Application of xylan in cosmetic potentially does not have any significant negative economic impact on product formulation.
- > The combination of process and separation efficiencies resulted in various sub scenarios evaluated. The optimistic sub scenarios rendered the highest profitability but these are conditions that are still to be attained with extensive R & D investments. The typical and conservative sub scenarios are reflective of the state of the art and they still indicate a good margin of profitability. This is beneficial in the sense that the current state of the xylan production technology has a high degree of economic feasibility at the set product prices and the set production scale.

## 5.2 Summary of environmental assessment

*This summary of the report on environmental assessment [Breyer et al. 2025] was contributed by Maximilian Breyer, IFEU. For details, please refer to the report.*

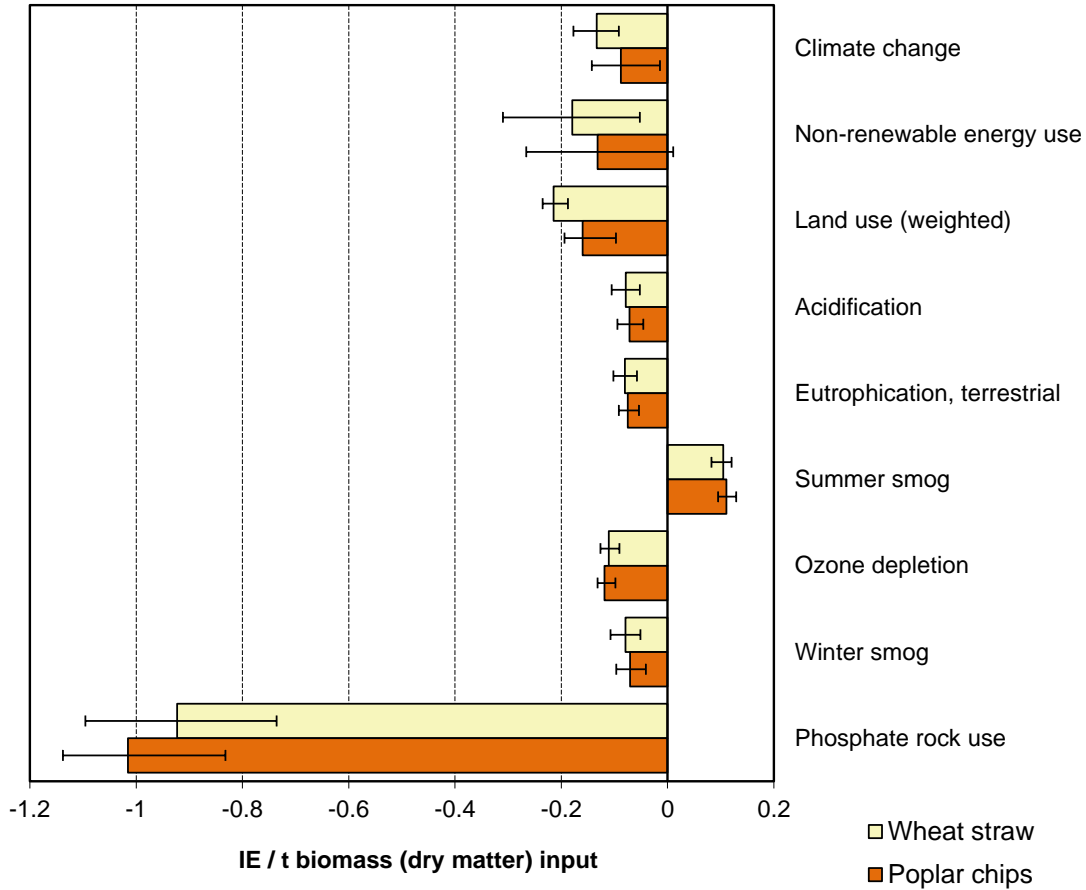
The environmental assessment assesses the potential environmental impacts that can be associated with the future implementation of the biorefinery concept and derives recommendations for their improvement.





## 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 (Figure 7).



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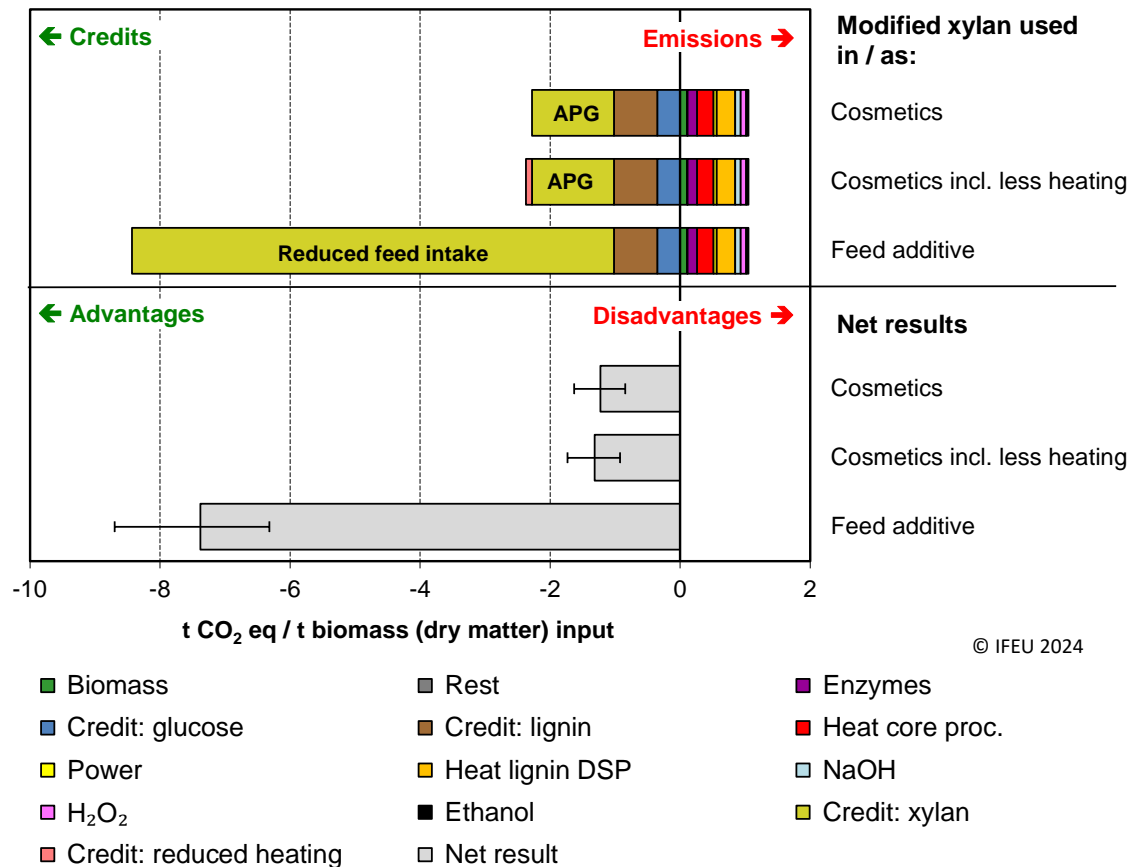
*Figure 7: Net results in different environmental impact categories. Overview of net results in different environmental impact categories for the biorefinery scenario using modified xylan as a cosmetics ingredient, comparing wheat straw and poplar as biomass feedstock. Results are expressed in inhabitant equivalents (IE), i.e. as fractions of average emissions per capita and year in the European Union.*

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. In addition to life cycle assessment, local environmental impacts were analysed in life cycle environmental impact assessment. The use of surplus straw and poplar cultivation (short rotation coppice) is possible at neutral to positive local environmental impacts unless too much straw is removed or poplar is cultivated at the expense of grassland.



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Figure 8: 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<sub>2</sub>O<sub>2</sub>: hydrogen peroxide, LMW: low molecular weight xylan, NaOH: sodium hydroxide, WIS: water-insoluble xylan.

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 (Figure 8) 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 (Figure 9). 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.
- > 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”).

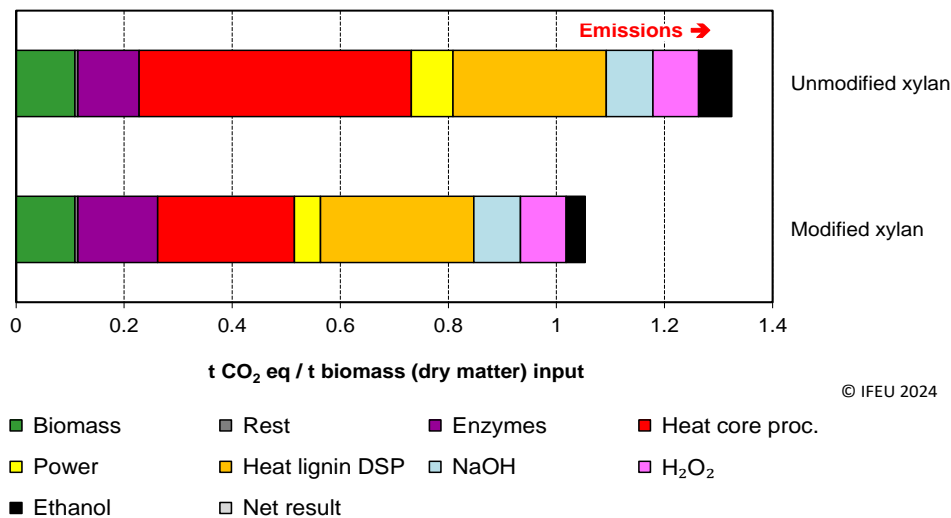


Figure 9: Impact of xylan modification on greenhouse gas emissions. Greenhouse gas emissions of the biorefinery scenario using wheat straw as biomass feedstock and aggregated by inputs, comparing the production of unmodified and modified xylan. DSP: downstream processing, H<sub>2</sub>O<sub>2</sub>: hydrogen peroxide, NaOH: sodium hydroxide.

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 2<sup>nd</sup> generation glucose provides certain environmental advantages over 1<sup>st</sup> 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 the co-products 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.

## 5.3 Summary of social assessment

*This summary of the report on social assessment [Karg et al. 2025] was contributed by Hanna Karg, IFEU. For details, please refer to the report.*

The social assessment analyses the potential social impacts that can be associated with the future implementation of the biorefinery concept and derives recommendations for their improvement.

### Supply chain risks

A major source of social risks is the supply chain of inputs required for the biorefinery process. We used social life cycle assessment (S-LCA) to assess the social risks in the supply chain and the social risks associated with work at the plant. The results show that external inputs are the social risk hotspots of xylan production; social risks arising from the production at the plant itself, located in the EU, are negligible. The main parameters that influence the level of social risks in the supply chain as determined by the S-LCA are the input quantities, which are determined by the biorefinery process, the unit price, which is mainly determined by the world market, and the country of origin of the inputs, which can be influenced by the plant operator. Reducing the quantity of inputs reduces the social risks, but also reduces social benefits such as the job creation and contribution to local economies. Therefore, reducing social risks is not the primary goal, but social risks should be used as an indicator of where in the supply chain more attention needs to be given to social impacts.

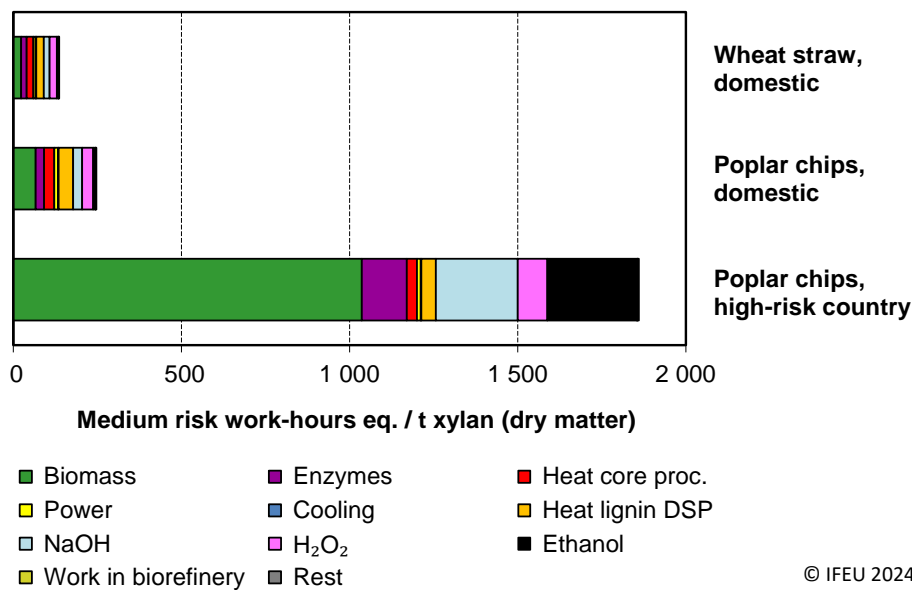
The main social risks do not originate from EU countries but arise from the supply chains of external inputs, which mainly originate from countries with poorly regulated and/or enforced social and labour standards. Thus, the social risks associated with the biorefinery products are strongly influenced by the country of origin of the purchased





inputs, although high-risk supplier countries may also be hidden in the supply chain of products from otherwise low-risk countries.

For the production of xylan according to the assessed biorefinery concept, the country of origin has a particularly large impact on the provision of biomass, sodium hydroxide, and ethanol, i.e., inputs that are generally available from low-risk countries. If these inputs are sourced from high-risk countries such as Belarus or Pakistan, which can have a substantial share of the global market for these products, the social risks can multiply (Figure 10).



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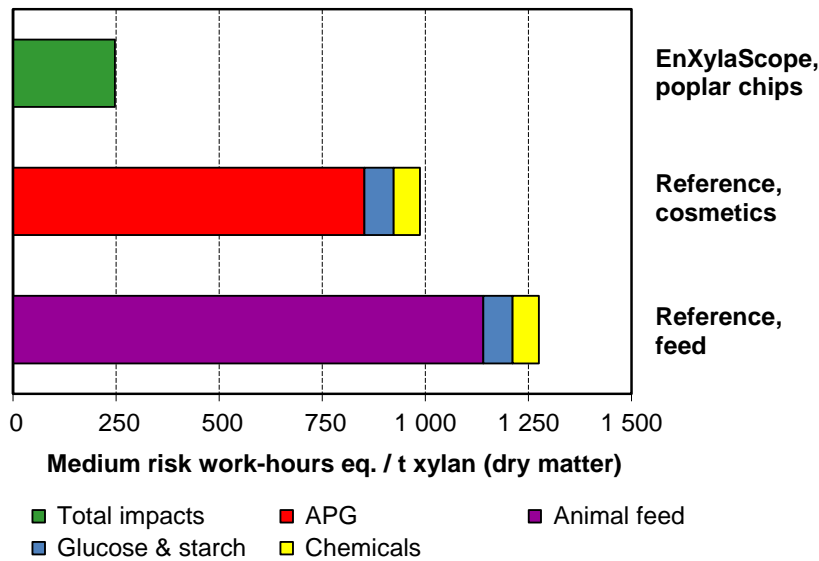
Figure 10: Difference in social risks between wheat straw and poplar from different supplier countries. Social risks associated with the production of modified xylan and co-products glucose and lignin-based products from wheat straw and poplar chips, by country of origin (mrwh eq). Feedstock: wheat straw or poplar; country: domestic (Ireland) or high-risk country with substantial world market share; sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H<sub>2</sub>O<sub>2</sub>: hydrogen peroxide.

### Avoiding adverse social impacts in the supply chain

At this stage of process development, there is no need to optimise the biorefinery processes in order to reduce the social impacts for three reasons:

1. Compared to conventional products, the social supply chain risks associated with xylan produced in the biorefinery are substantially lower (Figure 11).
2. The process does not require inputs that are only available from high-risk countries.
3. The identified risk differences between the assessed process variants are small.





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*Figure 11: Social risks associated with biorefinery and reference products for domestic sourcing (mrwh eq). Biorefinery products include the production of modified xylan and co-products glucose and lignin-based products from poplar chips. The reference products of xylan used in cosmetics or as feed additive reducing the demand for animal feed include APG and animal feed, as well as the reference products of the co-products. Country of origin: domestic (Ireland); sub-scenario: typical process efficiencies. APG: alkyl polyglucoside.*

In contrast, the differences in social risks between scenarios with different supplier countries are much larger. Preventing or minimising the potential negative social impacts in the supply chain only becomes relevant when an industrial plant is being built. Then, most of the social risks in the supply chain associated with xylan products can be mitigated through responsible sourcing of biomass and chemicals. There are three options for responsible sourcing:

- > Sourcing from low-risk countries if the majority of the supply chain is located in these countries
- > Sourcing from certified suppliers following trusted standards, where inputs are purchased from high-risk countries or where substantial parts of upstream processes take place in high-risk countries
- > Sourcing from high-risk countries where direct engagement with responsible suppliers to ensure social standards is possible.

Sourcing from high-risk countries can improve the living and working conditions of stakeholders in these countries, but this requires access to first-hand information, such as supplier audits, and the leverage to hold suppliers accountable for non-compliance.

Priority for supplier audits should be given to biomass suppliers, where most of the risks arise from the production itself and where the opportunities to make a difference in the upstream supply chain may be greater than for chemicals. This also applies to local





biomass suppliers where social risks may arise from the poor living and working conditions of seasonal migrant workers, who have been identified as a potential vulnerable group in the context of biomass production. This type of information will become increasingly important for the companies involved when the EU Corporate Sustainability Due Diligence Directive (CSDDD) requires large companies to identify and address potential and actual adverse impacts on human rights.

### *Managing local social impacts*

Social impacts, both positive and negative, may also occur locally when the biorefinery operates on an industrial scale. These potential social impacts were assessed in a participatory process with all project partners using a SWOT analysis.

The results show that the biorefinery can create jobs for highly skilled technical and non-technical workers and increase farmers' incomes if biomass is sourced from local suppliers. In order to minimise the risks to biomass producers and employees that arise from the emergence of a single powerful economic actor in a rural environment, fair negotiations on wages and biomass supply are needed. Poplar producers in particular, who have to make large and long-term investments to establish short rotation coppice, are at risk of becoming dependent on a single large customer. The use of wheat straw as a biomass residue with limited availability and transportability may affect existing straw users.

A new biorefinery and innovative enzyme production can provide opportunities for skills development locally and elsewhere, while the further development of enzymes in particular can also provide a positive stimulus to research and the scientific community. The local community can also benefit from the biorefinery through positive impacts on the local economy and services, particularly in less privileged rural areas. To fully realise the potential benefits, local procurement strategies should be sought, and risks to the local community and neighbours minimised, including increasing land and housing prices, traffic, and emissions. Early engagement with local stakeholders, including farmers, neighbours, and the local community, to take account of their needs and views is therefore essential. This can and should be actively supported and facilitated by the local municipality at a proposed new biorefinery site.

Other external risks may affect local stakeholders, such as unforeseen scientific progress and uncertain product uptake by industry, as well as uncertain political support and regulatory challenges related to novel enzymes and potentially also genetically modified organisms (GMOs) that need to be managed.

Taken together, this study highlights several potential social impacts that may arise in the supply chain of inputs or in the operation of the biorefinery. The findings should be considered early in the further process of commercialising this biorefinery concept, in order to actively improve social impacts at different stages of biorefinery development.





## 6 Results and conclusions

### 6.1 Overview of sustainability impacts

#### 6.1.1 Selection of scenarios and indicators

Six scenarios of possible future mature industrial scale implementations of the biorefinery concept developed in the EnXylaScope project (see chapter 4) were analysed for their impacts on environment, economy and society in the previous assessments [Bedzo et al. 2025; Breyer et al. 2025; Karg et al. 2025]. Each of these includes three sub-scenarios, representing conservative, typical and optimistic conditions for a future implementation. These were all selected for the integrated sustainability assessment.

Besides the parameters that vary between these scenarios, additional parameters that are particularly relevant for environmental, economic or social outcomes were varied in sensitivity analyses in the respective assessments. The following further parameters were found to have a considerable impact on the results range and were included in the following sub-scenarios:

- > The exact conditions of biomass provision have a particular influence on local environmental impacts but are less relevant for other studied sustainability indicators. Therefore, variations were included for local environmental indicators, but not for the others. For example, the cultivation of poplar short rotation coppice on whole fields of typical crop land is expected to have positive impacts on soil and biodiversity compared to annual crops. Strip cultivation could further increase the benefits for soils due to limiting erosion and cultivation in buffer zones towards water bodies can help to improve water quality (included in optimistic sub-scenarios). However, if poplar is cultivated on former permanent grassland, this would have negative environmental impacts (included in conservative sub-scenarios).
- > The techno-economic assessment additionally includes an option in which the lignin is not internally converted to high-value products using the METNIN process. Instead, it is sold at a lower price for external conversion and use. This externalisation of parts of the added value affects profitability, while it is irrelevant for the environmental and social assessments. Therefore, this parameter was not varied in the latter assessments. The economic results without internal lignin conversion were used in the conservative sub-scenarios in the integrated assessment.
- > Social supply chain risks are heavily affected by the geographic origin of several supplies. This is less important for and could not be studied at the current level of maturity in the techno-economic assessment that focuses on the profitability of the biorefinery based on world market prices because these rather affect the profitability of the suppliers in the various countries. Similarly, the differences





between the origins of the supplies were not studied in detail in the environmental assessment at this stage because of the lower importance for the overall results. Instead, European mixes or, if unavailable, world market mixes were used. The social risk assessment results from supplies from high-risk countries were used in the conservative sub-scenarios, from world market leaders in the typical sub-scenarios and from domestic origin in the optimistic sub-scenarios of the integrated assessment.

Various environmental, economic and social impacts or risks were studied in the respective assessments, which form the basis of this integrated sustainability assessment (for summaries see chapter 5). The performance of assessed scenarios and conventional reference systems regarding all these aspects were quantified or qualitatively rated using various indicators. The suitability and scientific validity of the indicators were verified in the individual assessments.

For the integrated sustainability assessment, the indicators of the life cycle assessment (LCA) and the economic indicators of the techno-economic assessment (TEA) were directly adopted. Indicators on local environmental impacts (LC-EIA) were combined into the three summarising indicators soil, water and biodiversity. Additionally, discussions in the TEA on technological maturity were condensed into the respective qualitative indicator by expert judgement to highlight this important aspect in the discussion. For social risks mainly arising from the supply chain, the 5 more aggregated category-level indicators ('labour rights and decent work', 'health and safety', 'society', 'governance' and 'community') provided by the social hotspot database (SHDB) [Bennema et al. 2022] were chosen instead of a larger set of sub-category indicators. The results of the SWOT analysis were not condensed into any indicators due to their heterogeneous nature and are therefore not represented in the results table. They are summarised in section 5.3 and are referred to individually mainly in chapter 7 to provide additional recommendations.

## 6.1.2 Additional indicators

The combination of economic and selected environmental indicators into abatement costs can yield additional information on the efficiency e.g. of potential policy measures. For example, greenhouse gas (GHG) abatement costs could indicate, how much reduction in emissions could be achieved per Euro of additional costs or incentives (see also section 3.2.2). Since all assessed scenarios are profitable without additional costs or incentives, GHG abatement costs were not calculated.

## 6.1.3 Categorisation

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly (Figure 12): Green boxes represent overall advantageous results, i.e. an improvement or a lower risk compared to a situation without EnXylaScope. Orange and red boxes represent overall disadvantages, i.e. a dete-





rioration compared to a situation without EnXylaScope. Yellow boxes represent minor sustainability impacts (see section 3.2.2 for further explanations). The economic indicators do not comprise a direct comparison to the reference system but indicate the profitability of the scenarios. They are categorised according to percentiles of the ranges from zero to the highest value for the internal rate of return (IRR) and the lowest value to 10 years for the pay-back period, respectively. This way of categorising results supports the identification of options that perform best among all studied options but also maintains the quantitative information on the sustainability of a scenario.

*Table 5: Overview of sustainability indicators selected for the integrated assessment.*

Impact category	Short description
<b>Environment: global/regional impacts</b>	
Climate change	Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases.
Acidification	Shift of the acid/base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword "acid rain").
Eutrophication, terrestrial	Input of excess nutrients into terrestrial ecosystems directly or indirect via gaseous emissions and erosion (e.g. nitrogen species such as ammonia and nitrogen oxides).
Summer smog	Formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword "ozone alert" or "Photochemical smog").
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as chlorofluorocarbons or nitrous oxide (keyword 'ozone hole').
Winter smog / particulate matter formation	Damage to human health due to air pollutants, such as fine, primary particles and secondary particles (mainly from NO <sub>x</sub> , NH <sub>3</sub> and SO <sub>2</sub> , keyword 'London smog').
Non-renewable energy use	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Land use	Occupation of land weighted by the degree of human influence compared to land in its natural state [Fehrenbach et al. 2015, 2019].
Phosphate rock use	Depletion of the limited phosphate resources and contribution to increasing scarcity [Reinhardt et al. 2019].
<b>Environment: local impacts</b>	
Soil	Soil quality is affected e.g. by erosion, compaction or organic matter content.
Water	Local water availability for ecosystems and its quality.
Biodiversity	Local biodiversity among animals and plants.





Impact category	Short description
<b>Techno-economic aspects</b>	
Internal rate of return (IRR)	Measure of profitability: Discount rate at which a net present value of zero is obtained for the investment.
Pay-back period	Alternative measure of profitability: Time in years after which investments have been paid back from revenues.
Maturity	Qualitative assessment of the gap between the current state of development and a first large-scale implementation.
<b>Society</b>	
Social risks: Labour rights & decent work	Risk of unfair conditions of work or labour accords violations in the value chain; such as child labour, low wages, forced labour, excessive working time or suppression of workers association.
Social risks: Health & safety	Risk along the value chain of high prevalence of occupational injuries and deaths, as well as high exposure to workplace hazards.
Social risks: Society	Risk of human right violations along the value chain; such as infringements of indigenous rights, weakness of gender equality, potential for high conflicts, prevalence of diseases, poverty and inequality, and threat to environmental sustainability.
Social risks: Governance	Risk of manufacturing processes located in countries or regions with weak legal systems, lack of democracy and freedom of speech, with high risk of corruption or poor law enforcement.
Social risks: Community	Risk of negative impacts along the value chain to the local community; such as school for children, drinking water, sanitation, hospital beds and land ownership of small land holdings.

## 6.1.4 General sustainability performance

The results for all selected scenarios and indicators under typical, optimistic and conservative boundary conditions are shown in Figure 12. The environmental indicators show differences in environmental impacts of the EnXylaScope system compared to reference systems providing equivalent products. The economic indicators show the profitability of the analysed potential future biorefineries. The social indicators highlight potential social risks when establishing these value chains.

Independent of scenario-specific relative advantages and disadvantages, several results apply to the EnXylaScope system in general:

- > All analysed scenarios are sufficiently to highly profitable.
- > Only few potential negative environmental impacts or high social risks in the supply chain were found for some scenarios, while substantial environmental benefits are possible in other scenarios, mainly depending on the use of the xylan and to some extent on biomass sourcing.





- > Conflicts between indicators and dimensions of sustainability are not inherent to the systems because all net environmental burdens and high social risks can be mitigated by identified measures, while maturity deficits can be overcome by additional research and development. Nevertheless, these mitigation measures have to be implemented, which may lead to certain costs but seems realistic without affecting the profitability too much. Potential sustainability-related disadvantages compared to existing products are particularly relevant for the most mature scenario that could serve as a blueprint for a first implementation. How these could be mitigated is discussed further in section 6.2.4.

These findings support a fast upscaling of the biorefinery concept to verify the process and product performance underlying the analysed scenarios. The ranges of possible results indicate high chances for a sustainable implementation unless unexpected changes in critical parameters occur. Such unexpected changes are not unusual between the current state of development in the lab and the modelled scenarios based on 15 000 t (dry matter) biomass input per year. Critical parameters to be verified on a larger (e.g. demo) scale include:

- > Product performance: This is particularly important because the specialty xylans are high-value products that require corresponding production efforts. Based on current knowledge, these efforts seem to be justified by the performance, i.e. by the replacement of existing products with higher sustainability impacts. This however still needs to be verified on a larger scale.
- > Technical suitability of the assessed feedstocks: In particular the use of poplar chips from short rotation coppice needs to be verified under real-world conditions. The removal of impurities such as soil particles (attached to straw) or inhibitors originating from bark or the bark itself could alter assessment results significantly if additional processing is required.
- > Sustainable availability of the assessed biomass feedstocks: If excessive amounts of straw are extracted from the fields, this can lead to substantial negative impacts including on climate change resulting from reduced soil organic carbon stocks or reduced soil quality. The use of other biomass feedstock could circumvent such situations of limited supply but would also lead to a different overall performance of the process and potentially also of the products. An extension of the feedstock base prior to industrial-scale implementation (including an adapted sustainability assessment) can mitigate respective risks. Poplar short rotation coppice in contrast can provide steady biomass supply but requires additional arable land in Europe in the first place. Even if the overall land use footprint (weighted by the intensity of land use) is negative because more land and more intensively used land is released by replacing other existing bio-based products including palm-oil based ones, this does not necessarily lead to sufficient arable land availability in Europe. This can be mitigated if the use as





feed additive can be verified and implemented for part of the xylan because lower feed demand can release about 10 times more arable land in temperate regions with high shares in Europe. This would be more than needed for poplar cultivation.

- > Regulatory compliance: It was not part of this assessment but could potentially prevent market access or require a re-design of certain process steps, which could substantially alter sustainability performance.

Taken together, a promising biorefinery concept focusing on xylan and designed for industrial scale has been developed in this project starting from an initial proof of concept that was far from suitable for upscaling.

Indicator	Unit	Typical performance					
		Scenarios		Modified xylan		Unmod. xyl.	
				Cosmetics	Feed additive	Cosmetics	Feed additive
				Wheat straw		Poplar	
<b>Environmental assessment</b>							
Climate change	t CO <sub>2</sub> eq / t biomass DM input	-1.2	-7.4	-7.2	-0.8	-4.8	-4.6
Acidification	kg SO <sub>2</sub> eq / t biomass DM input	-3	-40	-40	-3	-27	-27
Eutrophication, terrestrial	kg PO <sub>4</sub> eq / t biomass DM input	-0.4	-7.9	-7.9	-0.4	-5.3	-5.3
Summer smog	kg NMVOC eq / t biomass DM input	6	-11	-14	6	-5	-8
Ozone depletion	g CFC-11 eq / t biomass DM input	-6	-123	-124	-7	-82	-83
Winter smog	kg PM2,5 eq / t biomass DM input	-2	-27	-27	-2	-18	-18
Non-renewable energy use	GJ / t biomass DM input	-6	-34	-29	-5	-22	-18
Land use (weighted)	ha aL-eq · a / t biomass DM input	-0.05	-0.95	-0.96	-0.04	-0.62	-0.63
Phosphate rock use	kg phosphate rock eq / t biomass DM input	-21	-425	-429	-23	-287	-288
Soil	-	0	0	0	+	+	+
Water	-	0	0	0	0	0	0
Biodiversity	-	0	0	0	+	+	+
<b>Techno-economic assessment</b>							
Internal rate of return	%	58%	58%	39%	54%	53%	36%
Pay-back period	Years	0.8	0.8	1.4	0.8	0.9	1.5
Maturity	-	0	-	-	+	-	-
<b>Social assessment</b>							
Social risks: labor rights and decent work	Medium risk work-hours eq. / t biomass DM input	183	183	210	495	495	555
Social risks: health and Safety	Medium risk work-hours eq. / t biomass DM input	326	326	373	844	844	950
Social risks: society	Medium risk work-hours eq. / t biomass DM input	137	137	158	383	383	430
Social risks: governance	Medium risk work-hours eq. / t biomass DM input	221	221	250	573	573	640
Social risks: community	Medium risk work-hours eq. / t biomass DM input	130	130	151	370	370	416

Figure 12: Overview of selected sustainability indicator results for selected scenarios of possible future implementations of the EnXylaScope biorefinery concept. Values are taken from the original assessments. They are categorised from very disadvantageous (red, not occurring) via neutral (yellow) to very advantageous (dark green). For details see section 6.1.

Figure 12 continues on the next page with results based on data extrapolated under conservative and optimistic conditions for future implementations of the EnXylaScope biorefinery concept, respectively.





		Conservative performance					
		Modified xylan		Unmod. xyl.	Modified xylan		Unmod. xyl.
		Cosmetics	Feed additive		Cosmetics	Feed additive	
		Wheat straw			Poplar		
Indicator	Unit						
<b>Environmental assessment</b>							
Climate change	t CO <sub>2</sub> eq / t biomass DM input	-0.8	-6.3	-6.1	-0.1	-3.7	-3.5
Acidification	kg SO <sub>2</sub> eq / t biomass DM input	-2	-35	-35	-2	-23	-23
Eutrophication, terrestrial	kg PO <sub>4</sub> eq / t biomass DM input	-0.3	-7.0	-7.0	-0.3	-4.6	-4.6
Summer smog	kg NMVOC eq / t biomass DM input	7	-9	-11	7	-3	-5
Ozone depletion	g CFC-11 eq / t biomass DM input	-5	-109	-110	-6	-73	-73
Winter smog	kg PM <sub>2,5</sub> eq / t biomass DM input	-1	-23	-23	-1	-15	-15
Non-renewable energy use	GJ / t biomass DM input	-2	-26	-22	0	-16	-11
Land use (weighted)	ha aL-eq · a / t biomass DM input	-0.04	-0.84	-0.85	-0.02	-0.54	-0.55
Phosphate rock use	kg phosphate rock eq / t biomass DM input	-17	-377	-379	-19	-253	-255
Soil	-	-	-	-	-	-	-
Water	-	-	-	-	-	-	-
Biodiversity	-	-	-	-	-	-	-
<b>Techno-economic assessment</b>							
Internal rate of return	%	54%	54%	34%	48%	48%	29%
Pay-back period	Years	0.8	0.8	1.7	1	1	2.1
Maturity	-	0	-	-	+	-	-
<b>Social assessment</b>							
Social risks: labor rights and decent work	Medium risk work-hours eq. / t biomass DM input	918	918	1126	3199	3199	3649
Social risks: health and Safety	Medium risk work-hours eq. / t biomass DM input	464	464	507	3971	3971	4011
Social risks: society	Medium risk work-hours eq. / t biomass DM input	923	923	1133	2573	2573	3041
Social risks: governance	Medium risk work-hours eq. / t biomass DM input	886	886	1059	4167	4167	4518
Social risks: community	Medium risk work-hours eq. / t biomass DM input	809	809	1017	2065	2065	2533

		Optimistic performance					
		Modified xylan		Unmod. xyl.	Modified xylan		Unmod. xyl.
		Cosmetics	Feed additive		Cosmetics	Feed additive	
		Wheat straw			Poplar		
Indicator	Unit						
<b>Environmental assessment</b>							
Climate change	t CO <sub>2</sub> eq / t biomass DM input	-1.6	-8.7	-8.5	-1.3	-5.8	-5.6
Acidification	kg SO <sub>2</sub> eq / t biomass DM input	-4	-46	-46	-3	-30	-30
Eutrophication, terrestrial	kg PO <sub>4</sub> eq / t biomass DM input	-0.6	-9.1	-9.2	-0.5	-5.9	-5.9
Summer smog	kg NMVOC eq / t biomass DM input	5	-15	-18	5	-7	-10
Ozone depletion	g CFC-11 eq / t biomass DM input	-7	-141	-142	-7	-91	-92
Winter smog	kg PM <sub>2,5</sub> eq / t biomass DM input	-3	-31	-31	-3	-21	-20
Non-renewable energy use	GJ / t biomass DM input	-11	-42	-38	-9	-29	-25
Land use (weighted)	ha aL-eq · a / t biomass DM input	-0.06	-1.09	-1.10	-0.05	-0.70	-0.70
Phosphate rock use	kg phosphate rock eq / t biomass DM input	-25	-489	-493	-26	-318	-320
Soil	-	0	0	0	++	++	++
Water	-	0	0	0	0	0	0
Biodiversity	-	0	0	0	+	+	+
<b>Techno-economic assessment</b>							
Internal rate of return	%	62%	62%	43%	55%	55%	39%
Pay-back period	Years	0.7	0.7	1.2	0.8	0.8	1.4
Maturity	-	0	-	-	+	-	-
<b>Social assessment</b>							
Social risks: labor rights and decent work	Medium risk work-hours eq. / t biomass DM input	100	100	113	301	301	333
Social risks: health and Safety	Medium risk work-hours eq. / t biomass DM input	182	182	208	532	532	593
Social risks: society	Medium risk work-hours eq. / t biomass DM input	67	67	78	200	200	227
Social risks: governance	Medium risk work-hours eq. / t biomass DM input	133	133	152	400	400	445
Social risks: community	Medium risk work-hours eq. / t biomass DM input	64	64	75	190	190	215





## 6.2 Comparison of scenarios

This chapter discusses advantages and disadvantages that are expected to arise from the realisation of different scenarios. None of the scenarios scores best in all indicators. Therefore, no best solution can be identified on an entirely scientific basis without value-based choices. This is an almost unavoidable result if the sustainability assessment of a system with a certain degree of complexity is sufficiently comprehensive. Furthermore, at the current stage of development, it is not necessary to decide for one scenario to implement. In this case, it is not even required to exclude any of the analysed scenarios, because none of them is connected to unacceptable and unavoidable sustainability impacts (see section 6.1.4). Instead, this comparison of scenarios identifies optimisation potentials and trade-offs to support further development.

To this end, all scenarios are compared to one benchmark scenario at a time. Two scenarios are considered very different ([++] or [--]) if their ranges of results do not intersect. They are considered different ([+] or [-]) if only minor intersections occur. If the typical values of both scenarios are within the range of the respective other scenario, then they are not considered different [0].

### 6.2.1 Identification of benchmark scenarios

Several scenarios are identified as useful benchmarks, which perform best on certain sets of indicators or due to outstanding technical performance (not reflected in the indicators). For additional information on the scenarios, see section 4.2.

1. Modified xylan from straw used as feed additive:  
This scenario performs better than or similar to all other scenarios regarding almost all evaluated indicators.
2. Modified xylan from poplar used as feed additive:  
This scenario shows superior results compared to the first benchmark in impacts on soil and biodiversity under typical and optimistic conditions.
3. Modified xylan from poplar used in cosmetics:  
This is currently the technically most mature scenario.  
This is the case although unmodified xylan appears to be the more mature technology from a process perspective as it avoids the complexities of enzymatic modification that still is to be validated at scale. However, modified xylan production is feasible at a smaller scale due to the high-value nature of the ingredient for applications such as in cosmetics, which makes it easier to implement at least as a first step.





## 6.2.2 Benchmark I: Modified xylan from straw used as feed additive

All scenarios show a worse or similar performance compared to this benchmark regarding almost all analysed indicators. This is indicated by the negative or neutral ratings in Figure 13.

Indicator	Unit	Scenarios	Benchmarking				
			Modified xylan		Unmod. xyl.		
			Cosmetics	Feed additive	Cosmetics	Feed additive	
			Wheat straw		Poplar		
<b>Environmental assessment</b>							
Climate change	t CO <sub>2</sub> eq / t biomass DM input		--	o	--	--	--
Acidification	kg SO <sub>2</sub> eq / t biomass DM input		--	o	--	--	--
Eutrophication, terrestrial	kg PO <sub>4</sub> eq / t biomass DM input		--	o	--	--	--
Summer smog	kg NMVOC eq / t biomass DM input		--	o	--	--	--
Ozone depletion	g CFC-11 eq / t biomass DM input		--	o	--	--	--
Winter smog	kg PM <sub>2,5</sub> eq / t biomass DM input		--	o	--	--	--
Non-renewable energy use	GJ / t biomass DM input		--	o	--	--	--
Land use (weighted)	ha aL·eq·a / t biomass DM input		--	o	--	--	--
Phosphate rock use	kg phosphate rock eq / t biomass DM input		--	o	--	--	--
Soil	-		o		+	+	+
Water	-		o		o	o	o
Biodiversity	-		o		+	+	+
<b>Techno-economic assessment</b>							
Internal rate of return	%		o		--	-	--
Pay-back period	Years		o		--	--	--
Maturity	-		++		o	++	o
<b>Social assessment</b>							
Social risks: labor rights and decent work	Medium risk work-hours eq. / t biomass DM input		o		o	-	-
Social risks: health and Safety	Medium risk work-hours eq. / t biomass DM input		o		o	--	--
Social risks: society	Medium risk work-hours eq. / t biomass DM input		o		o	-	-
Social risks: governance	Medium risk work-hours eq. / t biomass DM input		o		o	-	-
Social risks: community	Medium risk work-hours eq. / t biomass DM input		o		o	-	-

Figure 13: Comparison of all other scenarios to the benchmark “modified xylan from wheat straw used as feed additive”. Advantages (++) or disadvantages (--) of the scenario compared to the benchmark are rated as detailed in section 3.2.4.

Compared to this benchmark, the **alternative use of the same xylan in cosmetics** scores clearly worse regarding all global and regional environmental indicators resulting from LCA. The main reason for this is that the use as feed additive for pigs has the potential to save enormous amounts of feed (about 40 times of the added xylan by dry mass) because of an improved gut health of the livestock. While the environmental impact of the xylan production is identical, the enormous advantages due to the avoided feed use result in an overall much better performance of xylan use as feed additive. The break-even point in terms of climate change mitigation would be reached between the use of xylan in cosmetics and as feed additive if the saved feed amount was only about 6 times of the added xylan dry mass. Most other indicator results are similar between these use options: Local environmental impacts are identical because the same feedstock is used and profitability is identical because of the same sales price and production conditions





of the xylan set in both scenarios. For the same reason, social risks in the supply chain are identical, too. As for the environmental impacts, however, the use in cosmetics does not have the potential to avoid as many social impacts in the supply chain as the use as a feed additive. Since this comparison to the reference products is not as simple as for environmental aspects because risks and not impacts are evaluated (see [Karg et al. 2025]), and because in both cases the EnXylaScope supply chain can have much lower risks than the reference, this is still scored equally. The advantage of the cosmetics application, however, is its higher maturity.

The **alternative use of unmodified xylan** results in a substantially lower but still high profitability due to a lower expected sales price of the product. Otherwise, it causes very similar impacts compared to the benchmark of using modified xylan. While a detailed analysis of the mass and energy balances and thus also of the environmental and social impacts clearly shows efficiency-related advantages of modified xylan, these advantages are smaller than the result ranges due to uncertainty (see Figure 9 and [Breyer et al. 2025; Karg et al. 2025]). This leads to the shown neutral rating. The lower the uncertainty will get during further development, the more prominent the advantages of modified xylan are expected to become because the further development of the process is likely to lead to rather similar changes in process efficiencies with and without modification. Moreover, modified xylan has superior technical properties and allows applications like in cosmetics that are not possible without modification. This is why the foreseen respective scenario was cancelled. Taken together, the scenarios using modified xylan are economically clearly advantageous and have a tendency to become more advantageous also regarding most other aspects in the course of the further process development.

The **alternative use of poplar as a feedstock instead of straw** as in the benchmark scenario leads to disadvantages in most indicators. Exceptions are local environmental impacts on soil, biodiversity and to a certain degree also impacts on water. While poplar short rotation coppice can bring more diversity into an agricultural landscape dominated by annual plants, an increased extraction of straw is either neutral or negative. The additional cultivation of poplar, however, requires additional land and therefore negatively effects in particular land use and climate change. Scenarios with both feedstocks are highly profitable, but poplar profitability is slightly lower given the identical feedstock prices defined in the scenarios. For higher poplar chip prices, its profitability would further decrease.





## 6.2.3 Benchmark II: Modified xylan from poplar used as feed additive

		Benchmarking							
		Modified xylan		Unmod. xyl.		Modified xylan		Unmod. xyl.	
Indicator	Unit	Cosmetics		Feed additive		Cosmetics		Feed additive	
		Wheat straw				Poplar			
<b>Environmental assessment</b>									
Climate change	t CO <sub>2</sub> eq / t biomass DM input	--	++	++	--				o
Acidification	kg SO <sub>2</sub> eq / t biomass DM input	--	++	++	--				o
Eutrophication, terrestrial	kg PO <sub>4</sub> eq / t biomass DM input	--	++	++	--				o
Summer smog	kg NMVOC eq / t biomass DM input	--	++	++	--				+
Ozone depletion	g CFC-11 eq / t biomass DM input	--	++	++	--				o
Winter smog	kg PM <sub>2,5</sub> eq / t biomass DM input	--	++	++	--				o
Non-renewable energy use	GJ / t biomass DM input	--	+	+	--				o
Land use (weighted)	ha aL-eq · a / t biomass DM input	--	++	++	--				o
Phosphate rock use	kg phosphate rock eq / t biomass DM input	--	++	++	--				o
Soil	-	-	-	-	o				o
Water	-	o	o	o	o				o
Biodiversity	-	-	-	-	o				o
<b>Techno-economic assessment</b>									
Internal rate of return	%	+	+	--	o				--
Pay-back period	Years	+	+	--	o				--
Maturity	-	++	o	o	++				o
<b>Social assessment</b>									
Social risks: labor rights and decent work	Medium risk work-hours eq. / t biomass DM input	+	+	+	o				o
Social risks: health and Safety	Medium risk work-hours eq. / t biomass DM input	++	++	++	o				o
Social risks: society	Medium risk work-hours eq. / t biomass DM input	+	+	+	o				o
Social risks: governance	Medium risk work-hours eq. / t biomass DM input	+	+	+	o				o
Social risks: community	Medium risk work-hours eq. / t biomass DM input	+	+	+	o				o

Benchmark

Figure 14: Comparison of all other scenarios to the benchmark “modified xylan from poplar used as feed additive”. Advantages (++) or disadvantages (--) of the scenario compared to the benchmark are rated as detailed in section 3.2.4.

There are only few sustainability aspects, in which other scenarios are superior compared to the use of modified xylan from wheat straw as feed additive (green cells Figure 13), which would lead to forgone benefits if that scenario was implemented. One of these aspects is that the second benchmark that uses poplar instead of straw is rated superior to the overall best performing first benchmark in impacts on soil and biodiversity. This results from better results under typical and optimistic boundary conditions. The detailed analysis of local environmental impacts concludes that both feedstocks can be provided sustainably and unsustainably depending on conditions, which are very different and independent of each other for both feedstocks [Breyer et al. 2025]. For that reason, no general preference for either feedstock can be deduced from a local environmental perspective while the introduction of short rotation coppice has the potential to introduce beneficial structures into typical agricultural landscapes.

Besides this aspect, comparing all other scenarios to this second benchmark as shown in Figure 14 leads to very similar insights as the first benchmarking. Also if poplar is used as a feedstock, the unmodified xylan and the use in cosmetics compare similarly to the





benchmark instead using modified xylan and with the application as a feed additive, respectively. Furthermore, straw as a feedstock compares favourably to poplar regarding most indicators in this application as well. Therefore, the insights gained from the first benchmarking with straw as a feedstock are transferrable.

## 6.2.4 Benchmark III: Modified xylan from poplar used in cosmetics

Indicator	Unit	Scenarios	Benchmarking					
			Modified xylan		Unmod. xyl.			
			Cosmetics	Feed additive	Cosmetics	Feed additive		
			Wheat straw		Poplar			
<b>Environmental assessment</b>								
Climate change	t CO <sub>2</sub> eq / t biomass DM input		+	++	++		++	++
Acidification	kg SO <sub>2</sub> eq / t biomass DM input		o	++	++		++	++
Eutrophication, terrestrial	kg PO <sub>4</sub> eq / t biomass DM input		o	++	++		++	++
Summer smog	kg NMVOC eq / t biomass DM input		o	++	++		++	++
Ozone depletion	g CFC-11 eq / t biomass DM input		o	++	++		++	++
Winter smog	kg PM <sub>2,5</sub> eq / t biomass DM input		o	++	++		++	++
Non-renewable energy use	GJ / t biomass DM input		o	++	++		++	++
Land use (weighted)	ha aL-eq · a / t biomass DM input		+	++	++		++	++
Phosphate rock use	kg phosphate rock eq / t biomass DM input		o	++	++		++	++
Soil	-		-	-	-		o	o
Water	-		o	o	o		o	o
Biodiversity	-		-	-	-		o	o
<b>Techno-economic assessment</b>								
Internal rate of return	%		+	+	--		o	--
Pay-back period	Years		+	+	--		o	--
Maturity	-		--	--	--		--	--
<b>Social assessment</b>								
Social risks: labor rights and decent work	Medium risk work-hours eq. / t biomass DM input		+	+	+		o	o
Social risks: health and Safety	Medium risk work-hours eq. / t biomass DM input		++	++	++		o	o
Social risks: society	Medium risk work-hours eq. / t biomass DM input		+	+	+		o	o
Social risks: governance	Medium risk work-hours eq. / t biomass DM input		+	+	+		o	o
Social risks: community	Medium risk work-hours eq. / t biomass DM input		+	+	+		o	o

Figure 15: Comparison of all other scenarios to the benchmark “modified xylan from poplar used in cosmetics”. Advantages (++) or disadvantages (--) of the scenario compared to the benchmark are rated as detailed in section 3.2.4.

Using modified xylan from poplar in cosmetics is currently the technically most mature scenario. The comparison of all other scenarios to this benchmark shows several advantages of the other scenarios over the benchmark indicated by green cells in Figure 15. Nevertheless, Figure 12 shows that the sustainability performance of this scenario is good enough in most aspects so that it can be pursued as an initial application. Whether this most mature scenario can be a sufficiently sustainable first implementation following the “Do No Significant Harm” principle depends on the boundary conditions of its implementation. Several negative impacts or high risks associated with this scenario, respectively, can be identified from the results under conservative conditions





in Figure 12 that are classified as disadvantageous (orange). The use of modified xylan from poplar in cosmetics can lead to:

- > More summer smog compared to the conventional products through the emission of volatile organic carbon compounds. This is mainly caused by the emission of ethanol from the drying of xylan. This can be avoided by appropriate treatment of the vapours.
- > Negative local environmental impacts if poplar is cultivated on land previously used as permanent grassland. This type of land use change is not allowed in many European countries. Furthermore, greenhouse gas emissions from drained peatlands can compensate or even overcompensate all climate change mitigation depending on the origin of the cultivated poplar. This can be avoided through diligent biomass sourcing. For details, see [Breyer et al. 2025].
- > High social risks if procurement from high-risk countries does not take local social conditions into account. This can be avoided by purchasing only certified goods where supply chains include such countries, or by direct engagement with suppliers. Compared to the use of wheat straw, poplar chips could lead to higher but likewise avoidable risks because they could also be imported, which is not economic for straw. For details, see [Karg et al. 2025].

If the above optimisations can be ensured, then the use of modified xylan from poplar in cosmetics could be a sustainable first application. If such a scenario can be realised, then further applications could follow to make use of the full potential of the developed technology. This would in particular include the use of (part of) the xylan as feed additive (Figure 15) if the feed use efficiency can be increased as modelled in the scenario. Once a reliable production of polymeric xylan with several modification options is established, it is very plausible that many other sustainable applications are found.





## 7 Recommendations

Several scenarios representing potential variants of future mature technology, industrial-scale implementations of the EnXylaScope biorefinery concept were analysed for their potential sustainability impacts. Taken together, all scenarios can be implemented in a sufficiently sustainable way if certain mitigation measures are taken and certain boundary conditions are ensured (chapter 6). Beyond that, several sustainability aspects, including profitability, can be further improved by optimisation. For a sustainable implementation and the realisation of the identified further potentials, we recommend the following concrete steps to the respective stakeholder groups with the indicated priorities:

### 7.1 To process developers

Engage in the further development of sustainable integrated concepts of future biorefineries using underutilised lignocellulosic residues. The specific biorefinery concept analysed in this study shows high potentials of being sustainable and profitable. Therefore, it **should be upscaled with priority** and the following **technical process optimisations** should be addressed in this next step:

- > **Verify the technical suitability of the feedstocks** on a larger scale. The removal of impurities such as soil particles (attached to straw) or inhibitors originating from bark or the bark itself could alter sustainability impacts significantly if additional processing is required. For poplar, the use of industrial residues like saw dust could be an alternative depending on availability at scale.
- > **Electrify** as many processes within the EnXylaScope concept as possible to reduce natural gas-based heat provision. Explore in particular the possibility of implementing mechanical vapour recompression instead of distillation and/or heat pumps 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.
- > Take appropriate measures to **minimize ethanol vapours** released to the atmosphere as they can lead to substantial contributions to summer smog.

Additionally, the following process optimisations should be considered as far as possible:

- > 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.

- > **Integrate enzyme production with the biorefinery** 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.
- > Optimise processes targeted at **reducing the reagent consumption** in the biorefinery. From an environmental perspective, optimise in particular internal recycling processes for sodium hydroxide and ethanol rigorously, and reduce the amounts of hydrogen peroxide as far as possible. Furthermore, limit the amounts of lactose and, of secondary importance, glucose for enzyme production as far as technically possible for each intended product application.

**Verify product performance** on a larger scale and **explore further product use options:**

- > Invest research and development efforts into **improving the wheat straw xylan qualities** to improve its suitability for the various product applications. This can lead to higher sustainability benefits compared to using poplar chips in particular regarding profitability, climate change mitigation, land use and social risks.
- > **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 further **applications for modified xylan** that go beyond drop-in, i.e. 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 improve sustainability by replacing further products such as additives in formulations. To this end, **further xylan modifications** may also be explored.
- > Further develop the **applications of lignin** via the METNIN process or alternative use options, 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.

While results of this sustainability assessment are only applicable to the assessed scenarios, these are expected to still change during further process development. Therefore, the following should be considered in future decision-making during the development process:





- > When considering **major process changes**, such as changes in biomass feedstock and product portfolio, update LCA and TEA and at least screen for potential additional social risks and local environmental impacts.
- > **Decisions on possible process variants** for further development should be primarily based on sustainability indicators other than social risks, as the differences between the assessed technical scenarios in terms of social risks are not substantial and because no inherently high-risk inputs have been identified. Unless, for example, biomass feedstock from outside of the EU is used or xylan modification is switched from enzymatic catalysis to catalysts using conflict minerals this is not expected to change.

## 7.2 To research funding agencies

- > Support **the further development of this xylan-first biorefinery concept** to help realize its potential to deliver sustainability benefits. This should include the technical developments described in section 7.1. The medium-term process of the commercialisation should be initiated by co-funding a demonstration plant.
- > Dedicated funding programmes should be established for **transdisciplinary research on poplar production for biorefineries** to identify and address constraints faced by farmers (in living labs or other participatory, co-creative formats). This could help farmers to switch to short rotation coppice, which has also been identified as an important element of a sustainable agricultural transition [Agora Agriculture 2024].

## 7.3 To potential industrial operators of a future biorefinery

### Planning and operation of the biorefinery

- > Strategic decisions concerning the selection of the **product portfolio** in particular determine early on whether a biorefinery has the potential to be overall sustainable. A multitude of factors and influences has to be considered for the selection of the product portfolio. Therefore, a rigorous analysis of the associated sustainability 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 the **location** of an industrial-scale plant, take the following boundary conditions into account:
  - > Ensure **sufficient sustainable biomass availability** also in years with unfavourable weather conditions in the site selection process. Take more frequent droughts due to climate change into account. This will require biomass potential analyses for all candidate locations. Otherwise, the biorefinery's demand might lead to excessive biomass harvesting and



negative impacts on existing users of the same biomass. This is particularly relevant for residues with limited availability and transportability such as wheat straw.

- > If residues such as wheat straw are targeted as main feedstock, **use the advantages of the relatively small minimum scale** that is economically required for this type of biorefinery: Regions that are unlikely to attract larger biorefineries due to limited but nevertheless stable biomass availability could prevent future competition for biomass.
- > As far as possible, additionally consider the following:
  - > If poplar is targeted as feedstock, try to locate the biorefinery in **regions with existing poplar plantations** and potential to increase plantation sizes. Connecting to existing markets with more than one customer on the one hand reduces supply risks and on the other hand also reduces risks for poplar farmers investing in short rotation coppice if the biorefinery should stop operating.
  - > Building the biorefinery in **less privileged rural areas** can create social benefits in the local community and beyond. These benefits are further enhanced by sourcing as many inputs and services as possible locally.
  - > 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.
- > **Engage with local stakeholders**, including farmers, neighbours, and the local community, **early on, communicate realistic expectations and take their needs and views into account**. Otherwise, real or presumed negative impacts such as on neighbours and the local community, including increasing or decreasing land and housing prices, emissions, and traffic – even if minimised as far as possible – can lead to local opposition. This can jeopardise an entire project, for example by objections against construction or by boycotting the later feedstock sales.
- > Invest in the **qualification of the local workforce** for the biorefinery itself, provide equal employment opportunities for all societal groups and provide incentives in particular for the biomass suppliers to follow this example.

## Supply chain

- > If **wheat straw** is used, make sure that **sufficient amounts are left on the fields** to conserve soil organic 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.





- > If the intended xylan properties require the use of **poplar as feedstock**, ensure to exclude the cultivation on drained peatlands or the conversion of permanent grassland for poplar cultivation. Preferably obtain it from cultivation on unused or abandoned land. Otherwise, explore the possibilities of strip cultivation on existing crop land to achieve benefits for soils due to limiting erosion. Additionally, cultivation in buffer zones towards water bodies can improve water quality by reduced nutrient leaching. **Longer planning** is particularly necessary if poplar is used as it needs to grow for several years before being harvested.
- > Most of the social supply chain risks associated with xylan products can be mitigated through responsible sourcing of biomass and chemicals. There are **three options of responsible sourcing**:
  1. Sourcing from low-risk countries if the majority of production takes place in these countries
  2. Sourcing from certified suppliers following trusted standards, when purchasing inputs from high-risk countries or when substantial parts of upstream processes take place in high-risk countries
  3. Sourcing from high-risk countries if direct engagement with responsible suppliers is possible
- > Priority for supplier audits should be given to **biomass suppliers, where most of the risks arise from the production itself** and where the opportunities to make a difference in the upstream supply chain may be greater than for chemicals. Note that domestic biomass production can also create social risks, for example by employing seasonal migrant workers in poor working conditions.

## 7.4 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 peatlands as well as 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. Risk reduction measures for farmers investing in short rotation coppice such as subsidies for initial investments in the plantation could be a suitable approach.
- > **Support probiotics in animal husbandry.** Scenarios such as the addition of certain forms of xylan to feed as studied here can have great sustainability benefits including reduced pressure on deforestation. Such a support should ensure that sustainability impacts of producing the probiotics are taken into account.
  - > Thoughtful and well-balanced supply chain laws at national level to meet the requirements of EU's corporate sustainability due diligence directive (CSDDD) can induce social improvements on a large scale. To increase acceptance and adoption, **companies need support in meeting their due diligence requirements**, e.g.,
    - > by supporting easy-to-use risk assessment tools to help identify social risk hotspots in the supply chain
    - > by supporting certification schemes and facilitating access to certified suppliers
  - > Create **planning security for start-up companies** in the biotechnology sector by providing advice on the regulatory landscape and by harmonising rules.

## 7.5 To local communities

- > The local municipality at a proposed site of a new biorefinery can and should, as a neutral actor, **actively create a supportive environment for a dialogue** with the biorefinery operators, to ensure that benefits of such a new economic actor can be realised but potential disadvantages are avoided as far as possible, e.g.,
  - > by facilitating citizens' dialogue meetings to ensure that people can participate in the process
  - > by appointing a responsible person in the municipality to act as a general point of contact and to balance conflicting interests.





## 8 Abbreviations

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)
CSDDD	EU Corporate Sustainability Due Diligence Directive
DSP	Downstream processing
GAX	Glucurono(arabino)xylan
GHG	Greenhouse gas
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)
ILCSA	Integrated life cycle sustainability assessment
IRR	internal rate of return
LCA	Life cycle assessment
LCC	Life cycle costing
LC-EIA	Life cycle environmental impact assessment
LCT	Life cycle thinking
LMW	Low molecular weight
PBP	Payback period
RO	Reverse osmosis
S-LCA	Social life cycle assessment
SHDB	Social hotspot database
SWOT	Strenghts, weaknesses, opportunities, threats
TEA	Techno-economic assessment
WIS	Water-insoluble





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