EnXylaScope

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

D7.4

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

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1 Summary

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

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

This report by IFEU covers the social assessment. It assesses 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

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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, which can have a substantial share of the global market for these products, the social risks can multiply.

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, 2) the process does not require inputs that are only available from high-risk countries, and 3) the identified risk differences between the assessed process variants are small.

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:

1. Sourcing from low-risk countries if the majority of the supply chain is located in these countries
2. 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
3. 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.

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More details on the social risk hotspots identified by the S-LCA in the supply chain of xylan production, and further recommendations to mitigate these risks, can be found in chapters 5 and 7 of this report. 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 a 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 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.

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2 Introduction

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

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

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

The social assessment includes the identification of social risk hotspots in the supply chain of the EnXylaScope process using social life cycle assessment (S-LCA) (results in chapter 5) and the evaluation of potential negative and positive impacts that occur at the local level once the biorefinery operates on an industrial scale. This was done using SWOT analysis (results in chapter 6).

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3 Methodology

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

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

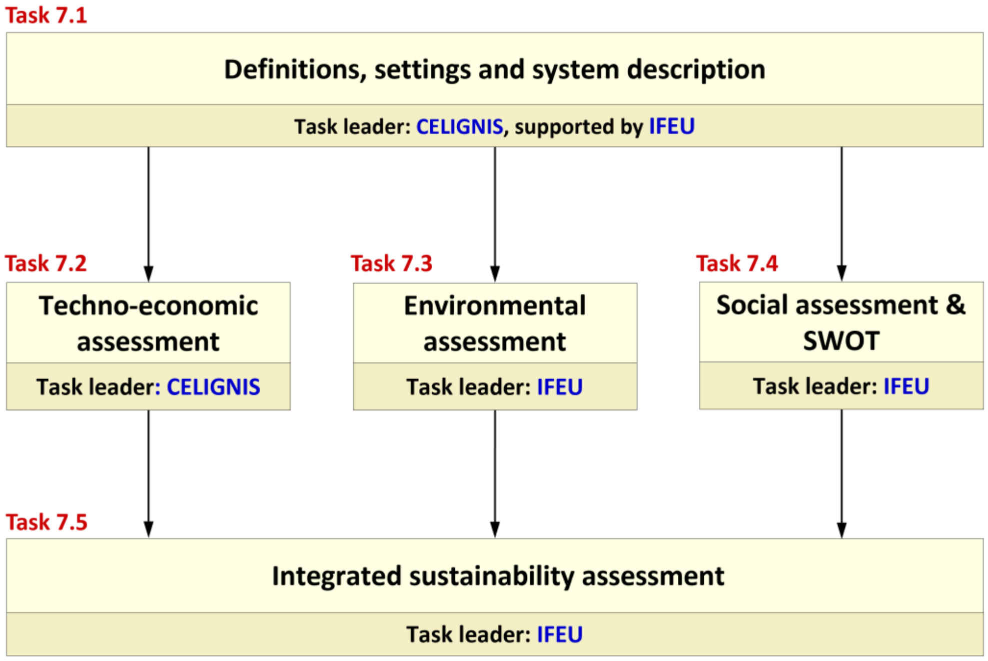

Figure 1: Structure of the work package on sustainability assessment in EnXylaScope.

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 social assessment are described in section 3.2 for social life cycle assessment and section 3.3 for the SWOT analysis.

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3.1 Common definitions and settings

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

3.1.1 Goal definition

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

Intended applications

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

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

Target audience

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

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

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Guiding questions

The following key research questions guide the sustainability assessment.

Main question:

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

This main question leads to the following **sub-questions**:

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

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

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

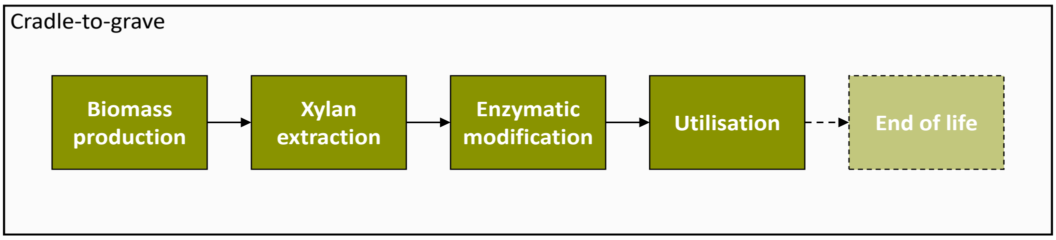

Figure 2: System boundary (cradle-to-grave) applied within the EnXylaScope project.

Geographical coverage

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

Decision:

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

Technical reference

The technical reference describes development status, maturity and scale.

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

Plant scale

A large-scale plant for hemicellulose extraction processes that is currently reported to be operational by a Swedish company is about 15 000 tonnes of biomass dry matter input per year which corresponds to approximately 45 tonnes per day which is relatively small scale compared to large 2nd generation ethanol biorefineries

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(150 000 – 250 000 tonnes of biomass per year). The scale of 15 000 tonnes/year processing was adopted as a sufficient baseline scale for the xylan production facility.

Timeframe

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

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

Settings for system modelling

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

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

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

Social life cycle assessment (S-LCA) is based on the life cycle thinking approach similar to environmental LCA. Therefore, many requirements from international environmental LCA standards [ISO 2006a; b][2] and the common definitions and settings described in section 3.1 can be and are applied to this S-LCA study, too. The methodology of this S-LCA study follows the guidelines for social life cycle assessment of products and organisations [Benoît Norris et al. 2020] and uses generic country and sector-specific data on social issues to identify social risk hotspots in the supply chain [Bennema et al. 2022]. Several specific settings and methodological choices nevertheless have to be made for each individual study based on this methodology. In the following, these choices are detailed.

3.2.1 Choice of assessment approach

We used the Reference Scale Assessment (RS) as impact assessment method. It allows estimating the magnitude and significance of potential social risks associated with a product system. It classifies the observed social risks of activities related to a product system compared to a reference scale. This classification can be based on international standards, local legislation or industry best practice – but also on other documented criteria [Benoît Norris et al. 2020].

The methodology for assessing potential social risks is shown schematically in Figure 3. Information on the mass and energy balance, prices of inputs, utilities and activities, the country from where these inputs and utilities are purchased or where these activities take place, and information on labour in the biorefinery (foreground system) are combined with data provided by the Social Hotspots Database (SHDB)[Bennema et al. 2022]. For each country-specific sector (defined by the input and its country of origin), the work performed in that sector and purchases from other country-specific sectors are taken into account. The SHDB uses the multiregional input/output (MRIO) model GTAP (Global Trade Analysis Project) to trace back the purchases from other country-specific sectors [Aguiar et al. 2016]. The social risks associated with work in these sectors are assessed using a reference scale. In the SHDB, the social risks observed in a country-specific sector for each indicator are classified into the social risk levels ‘low’, ‘medium’, ‘high’ and ‘very high’, using the criteria described in [Bennema et al. 2022]. Risks are expressed in medium risk work-hours equivalent for each input or activity at the level of 5 categories or 30 subcategories.

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[2] At the time of this analysis, the ISO standard on S-LCA [ISO 2024] was not yet available.

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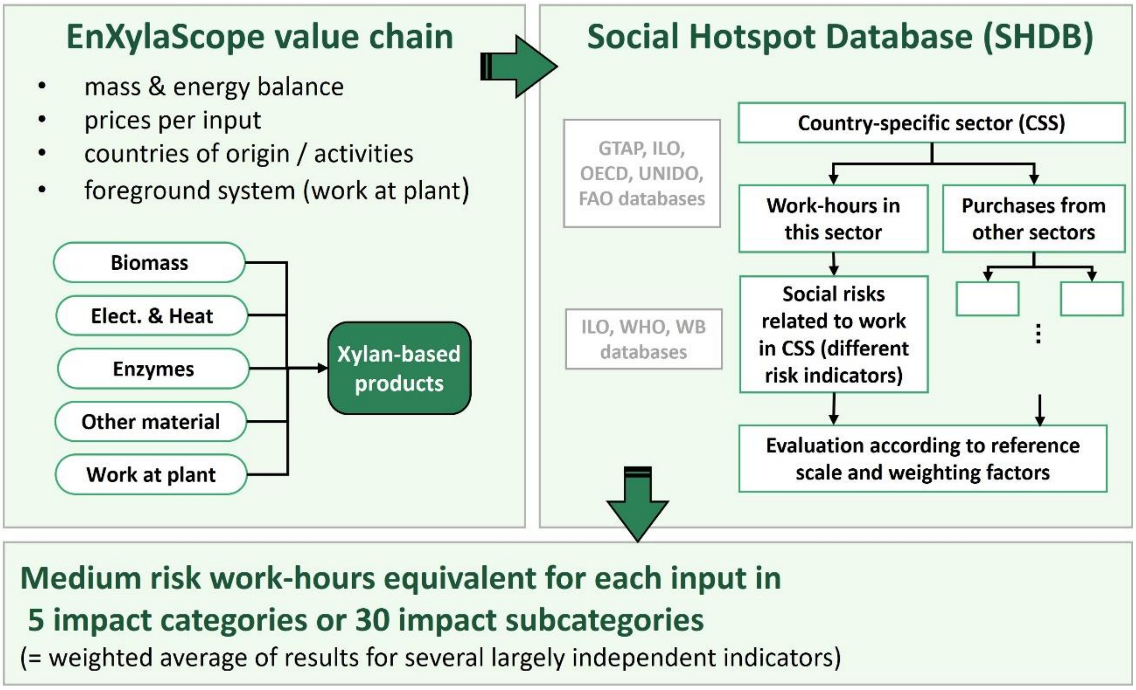

Figure 3: Methodology for evaluating the social risks of the EnXylaScope value chain with the Social Hotspots Database (SHDB).

3.2.2 Background database

Background data on social risks are taken from the Social Hotspots Database (SHDB, version 2022 (V5) [Bennema et al. 2022]), which is based on the multiregional input/output (MRIO) model GTAP version V9 (reference year 2011)[Aguiar et al. 2016].

3.2.3 Activity variable

Observed social risks classified according to the reference scale approach are related to an activity variable to allow a link to a product system. Following the approach of the SHDB, the activity variable chosen is the number of hours worked in the individual country-specific sector. This reflects the labour intensity of a production activity. The activity variable is multiplied by a factor associated with the social risk level of an indicator in a country-specific sector in order to calculate the medium risk work-hours equivalent. In this project, the factors proposed by [Bennema et al. 2022] are used.

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3.2.4 Indicators, impact categories, and aggregation

The aim of the S-LCA is to identify potential social risks affecting stakeholders[3] along the supply chain, including workers, local community, value chain actors, and society. These risks are assessed using the full set of 141 risk indicators grouped into 30 subcategories or 5 impact categories provided by the SHDB [Bennema et al. 2022]:

1) Labour rights and decent work
2) Health and safety
3) Society
4) Governance
5) Community

In order to display all results in the same graph, the equally weighted sum of the category values was used to calculate a single risk value because data for an alternative normalisation approach is not available. This was done for the purpose of screening for sources of high social risks among all inputs. Contributions were additionally verified individually on the level of all 30 subcategories. Aggregation for the purpose of normative weighting of largely independent social impacts is necessarily based on value-based choices, for which each affected person may have an individual set of preferences, and therefore was not done. This procedure allows for social hotspots to be identified, but does not allow further conclusions to be drawn about the severity of potential impacts or about trade-offs, such as reducing one risk at the cost of increasing another, unless differences in results are very high.

3.2.5 Choices specific for the assessed system

Data on background system

The mass and energy balance provided by Task 7.1 and the prices of the economic assessment (Task 7.2), were used to calculate the costs of each input.

- *Conversion of prices:*
  Current prices (2024) were provided in EUR by the economic assessment (Task 7.2). To convert EUR 2024 to USD 2011, the reference of the GTAP input/output model, prices in EUR 2024 were multiplied by a factor of 0.77. This factor is based on the mean exchange rate of EUR and USD in 2024 [European Central Bank 2024] and the USD inflation between 2011 and 2024 [US Inflation Calculator 2024].

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[3] This report adopts a broad definition of stakeholders, including all groups that are affected by, or can affect the organisation's activities.

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- *Assigning inputs to country-specific sectors:*
  The sector and countries assigned to inputs in the EnXylaScope process are listed in Table 1. The country of the plant location was selected according to the defined geographical scope (section 3.1.2), i.e., Ireland. The countries were classified as 1) domestic, 2) low to medium-risk countries on the world market, and 3) high-risk countries on the world market. In this study, domestic refers to Ireland, whereas world market countries represent major suppliers to the EU based on import statistics in 2021 – 2023 [United Nations 2023]. High-risk countries are often low-income countries with poor social and labour standards. In the absence of an appropriate sector for inputs such as ethanol, a biotech sector has been constructed as an average of the chemical and sugar sectors. If the allocation to a sector is unclear, a sensitivity analysis was carried out.
- *Infrastructure:*
  Infrastructure is not included in the inventory at the current state of development. This applies to production and processing equipment, buildings and roads.

Approach to foreground system

The foreground system includes the social risks associated with the work performed in a potential future biorefinery. Data on social performance in such plants could not be collected because similar plants do not yet exist at relevant scale. For this purpose, the chemicals sector was used as a proxy for risks associated with a biorefinery according to the EnXylaScope concept. Only risks directly related to work in the chemicals sector were taken into account, not indirect risks resulting from purchases from other sectors upstream.

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Table 1: List of inputs used in the EnXylaScope process, corresponding GTAP sectors [Center for Global Trade Analysis 2019], and countries of origin classified as domestic, world market low and medium-risk, and world market high-risk.

Item	Sector(s)	Countries		
		Domestic	World market low/medium risk	World market high-risk
EnXylaScope system				
Heat	Gas distribution	Ireland		
Electricity	Electricity	Ireland		
Wheat straw	Wheat; alternative: Other crops	Ireland		
Poplar	Other crops; alternative: Wood products	Ireland	USA	Belarus
NaOH	Chemical products	Ireland	USA	Pakistan
H_2O_2	Chemical products	Ireland	Norway	Egypt
Ethanol	Ø Sugar / chemicals	Ireland	USA	Pakistan
Yeast extract	Ø Sugar / chemicals	Ireland	Ukraine	Belarus
Citric acid	Ø Sugar / chemicals	Ireland	China	India
Other chemicals	Chemical products	Ireland	China	Pakistan
Corn steep liquor	Cereal grains	Ireland		
Lactose	Dairy products	Ireland	Great Britain	Ukraine
Water	Water	Ireland		
Foreground system	Chemical products (direct work only)	Ireland		
Reference system				
Animal feed	Cereal grain	Ireland	USA	China
Glucose	Sugar	Ireland	China	Pakistan
APG, phenol, polyol, AKD	Chemical products	Ireland	China	Pakistan

3.3 Specific definitions and settings for SWOT analysis

The social life cycle assessment, the main methodology used to assess social sustainability aspects in this study, mainly covers social risks in the supply chain based on rather general sector- and country-specific data. This is supplemented by analysing social aspects, both risks and benefits, specific to the main life cycle stages of the system itself. Projects such as EnXylaScope are researching and developing technologies that are not yet implemented, which is why possibilities for stakeholder engagement as a basis for such social analysis are very limited. Therefore, an interactive SWOT workshop on **strengths, weaknesses, opportunities, and threats** regarding the social aspects of the EnXylaScope system was conducted with all project partners contributing their direct or indirect knowledge about current and future groups of stakeholders, such as biorefinery operators, enzyme developers, industrial customers, competitors, and the local community, of a potential future EnXylaScope biorefinery.

A SWOT analysis is a tool that can be used to assess the performance of any venture, whether it is a project, a product or a company or specific aspects thereof. It originates from business management and is a strategic planning tool to identify and assess the Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) of the system under study. Strengths and weaknesses are defined as internal characteristics of the assessed system, while opportunities and threats are external factors, determining the success or failure of the venture. The results of a SWOT analysis are generally summarised in a SWOT matrix. The general structure of a SWOT matrix is shown in Figure 4.

	Helpful factors to achieving the objective	**Harmful factors to achieving the objective**
Internal (attributes of the organisation/product)	Strengths	Weaknesses
External (attributes of the environment)	Opportunities	Threats

Figure 4: Structure of a SWOT matrix.

The aim of SWOT analysis in this report is to detect, and thus account for, positive and negative social aspects that are not or not fully covered by the social life cycle assessment (S-LCA; section 3.2). Thus, the function of the SWOT analysis is to make sure that no key social factors for success or failure of a socially beneficial implementation of the analysed scenarios are omitted in the integrated sustainability assessment.

Social impacts can be very diverse and depend very much on the affected stakeholders. Which stakeholders are affected in turn depends very much on the life cycle stage. Therefore, separate SWOT matrices were set up for the following life cycle stages:

- Biomass provision (section 6.1)
- Biorefinery and enzyme development (section 6.2)
- Use phase of products (section 6.3)

In terms of inputs, the focus was on the provision of biomass as a major input potentially affecting different groups of people at the local level, which is not sufficiently covered by the S-LCA. Therefore, S-LCA and SWOT analysis complement each other very well. Within each SWOT matrix, stakeholder groups were identified and all potential social impacts were assigned to a stakeholder group.

The SWOT analysis was conducted as an internal online workshop on 17 October 2024 supplemented by another round of offline additions by all partners and collation and alignment of all inputs. The outcome was SWOT matrices with statements developed jointly by all participants.

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 5 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.

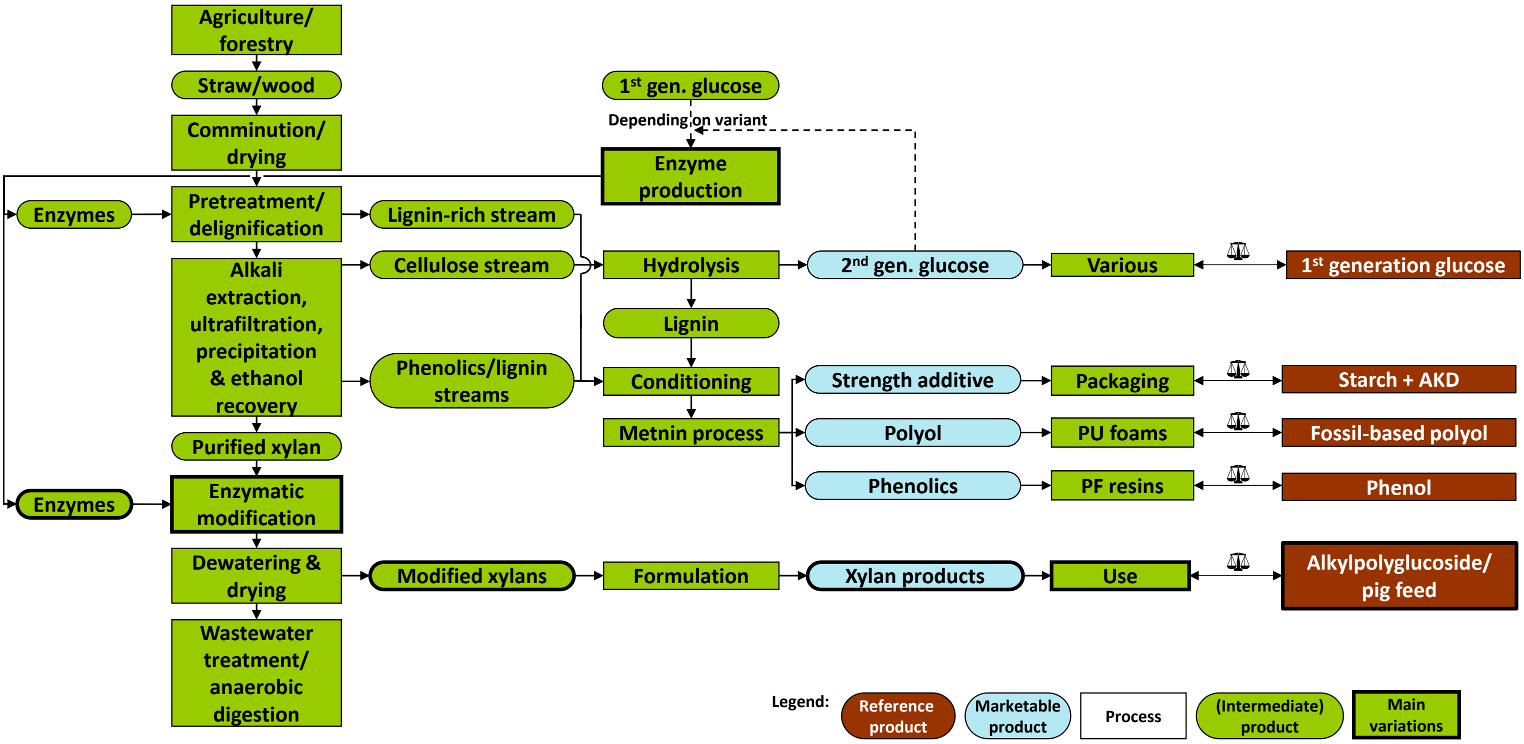

Figure 5: Simplified diagram showing the xylan extraction process in a biorefinery concept.

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

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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.

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 6) 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.

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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.

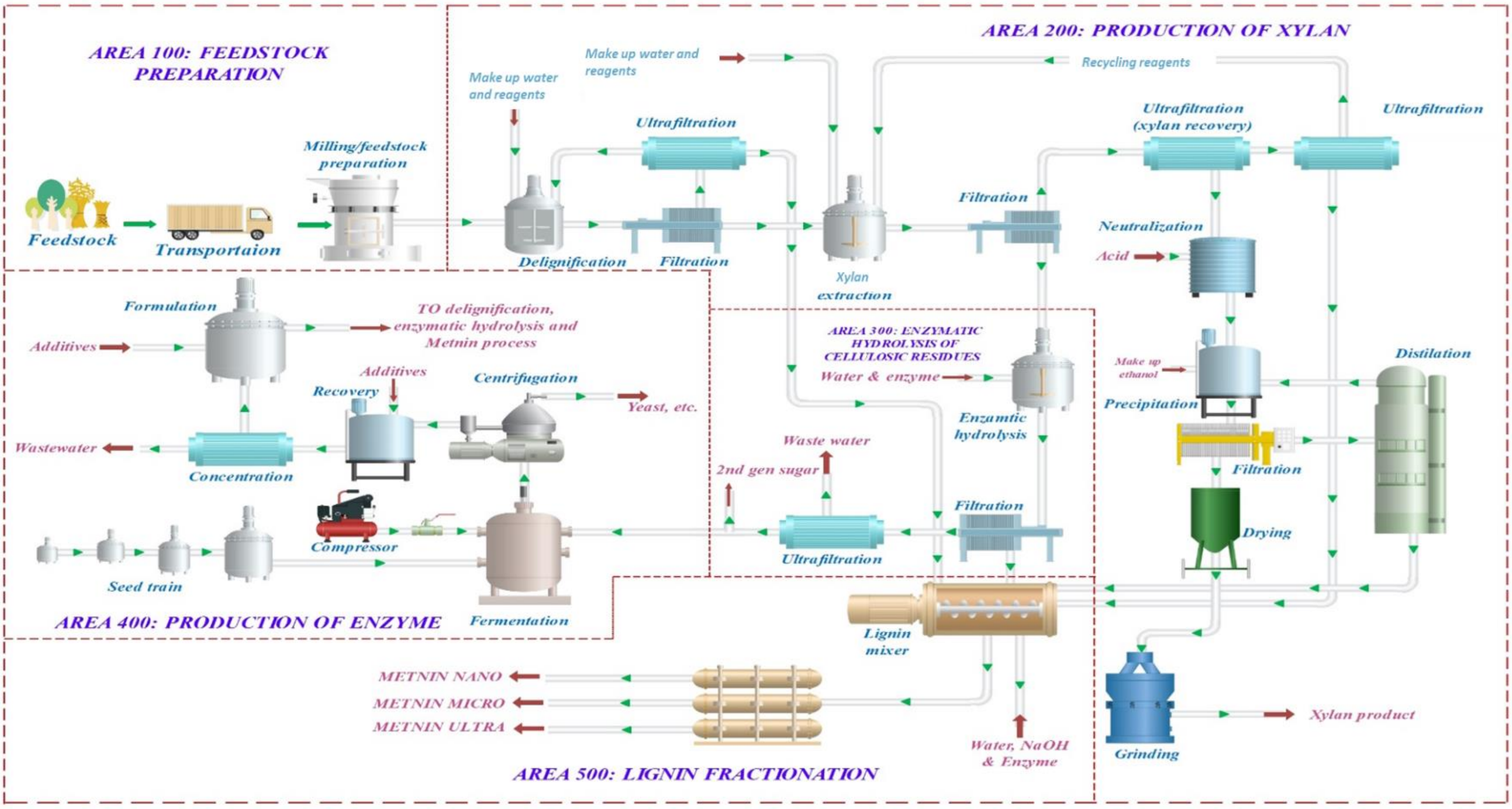

Figure 6: Simplified process flow of unmodified xylan production in a biorefinery concept.

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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.

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.

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

Ethanol recovery

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

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

4.2.4 Enzymatic hydrolysis of cellulosic residues

The cellulose rich residue from the xylan production is mixed with water in a jacketed CSTR vessel and cellulases are added. The reaction is allowed to proceed for 48 hours at 50 ^{o}C. After the reaction is completed, the reaction is briefly heated to 90 ^{o}C to stop the enzyme activity. The mixture is then cooled and filtered to separate the hydrolysate from the lignin rich solid residues. The filtered hydrolysate is further taken through a series of ultrafiltration steps to purify the stream and to also concentrate the solution to a glucose concentration of about 13 % (w/w). A portion of the glucose is allocated to

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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 7). 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.

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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.

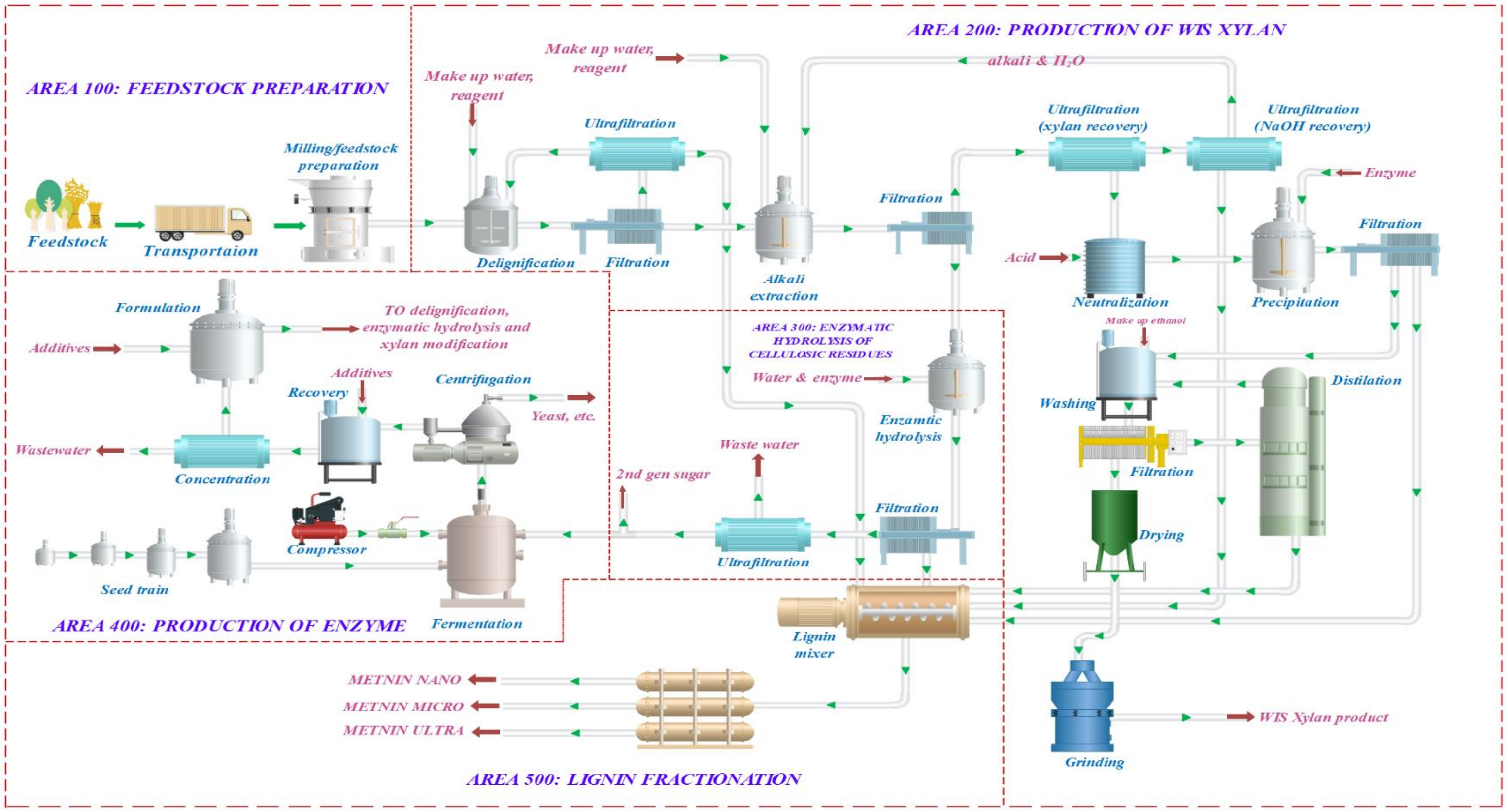

Figure 7: Simplified process flow of modified xylan production in a biorefinery concept.

4.3 Reference system

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

4.3.1 Xylan reference systems

Within EnXylaScope, two different use options for the produced xylan are investigated. The respective reference products replaced are described below. Table 2 summarises the use options represented in the analysed scenarios and the types of xylan used.

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Table 2: 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

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

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4.3.2 Co-product reference systems

The reference products replaced by the co-products 2nd generation glucose and lignin-based products are described below. The share of the replaced reference products by mass is provided in Table 3.

2nd generation glucose from cellulose

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

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 3: 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%

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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 4).

Table 4: EnXylaScope biorefinery scenarios for LCA evaluations.

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

Sub-scenarios on process efficiencies

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

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5 Results S-LCA

One objective of the social assessment was to identify social risks in the supply chain of the analysed biorefinery concept for the enzyme-based conversion of lignocellulosic biomass into xylan products for cosmetics and as animal feed supplement. Therefore, a social life cycle assessment (S-LCA) was carried out. For details on the methods and analysed systems see chapter 3 and 4, respectively. This chapter presents the S-LCA results starting with an analysis of which inputs contribute substantially to social risks (hotspots) if all inputs are sourced domestically, i.e., in Ireland (5.1). The following section shows how the origin of inputs influences the social risks of xylan production (section 5.2). Section 5.3 puts the social risks of xylan into perspective by examining those of equivalent conventional products (reference products). Section 5.4 discusses the uncertainties of the method and the related robustness of the results.

5.1 Contributions to social risks

Six scenarios depicting potential future biorefineries are analysed for the different contributions of their respective inputs to overall social risks. The scenarios differ in biomass feedstock (wheat straw or poplar from short rotation coppice) and whether the produced xylan is modified or not (see section 4.4 for an overview of scenarios). In section 5.1.1, we report social risks of unmodified and modified xylan using wheat straw to show how results vary accordingly. In section 5.1.2 and section 5.1.3, we focus on modified xylan to show the effect of biomass feedstock choice on overall social risks and to illustrate social risks across various social aspects.

The social risks associated with the various inputs to the biorefinery were assessed for all social risks provided by the background database used (Social Hotspots Database, SHDB) represented by 30 subcategories and 5 categories (see also section 3.2). In this report, most results are presented as the sum of category scores to show how the total result varies with regards to scenario selection and country of origin. In section 5.1.3, we present subcategory results to confirm the equal contribution of inputs to individual social aspects.

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5.1.1 Supply chain risks of xylan from wheat straw

In general, the extent of social risks in the SHDB, expressed in medium risk working hours equivalents (mrwh eq), depends on the (physical) quantity of inputs, unit prices, country of origin, and economic sector. Figure 8 shows the total social risk score associated with the production of one tonne of unmodified xylan and its co-products glucose and lignin-based products using wheat straw by individual inputs. The largest contributions to the overall social risks are from heat (incl. heat lignin downstream processing, referred to as METNIN heat in the system description, see chapter 4), followed by biomass, hydrogen peroxide (H_2O_2), and sodium hydroxide (NaOH), together accounting for about 80 % of the total risks. The contribution of enzymes is below 10 % and the work at the biorefinery is negligible. In this scenario, we consider inputs from domestic sources, i.e., from Ireland. This is realistic as the chemicals and biomass required in the assessed scenarios are available from Ireland.

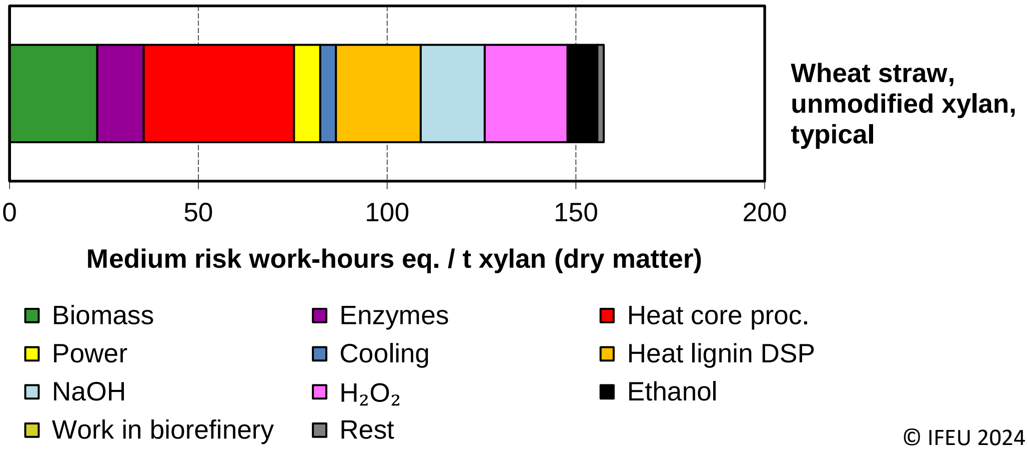

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Figure 8: Contribution of inputs to social risks of xylan. Social risks associated with inputs in the production of unmodified xylan and co-products glucose and lignin-based products from wheat straw in medium risk working hours equivalents (mrwh eq). Feedstock: wheat straw; country: domestic (Ireland); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2*: hydrogen peroxide.*

Another process scenario involves modified xylan. Comparing unmodified with modified xylan reveals slightly lower social risks for modified xylan (Figure 9). This reduction is due to lower heat demand, which compensates for the slight increase in enzyme demand, based on the selection of the underlying economic sectors (see section 5.4 for uncertainties related to the choice of economic sector).

Thus, there is a slight advantage of modified xylan, which is the focus of the following results sections.

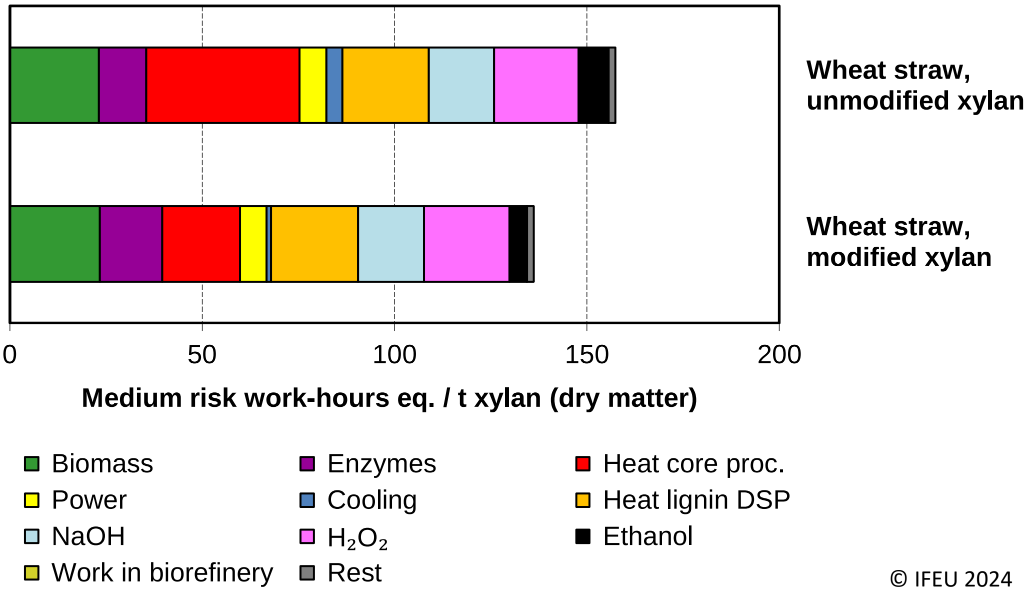

Figure 9: Difference in social risks between unmodified and modified xylan. Social risks associated with inputs in the production of unmodified and modified xylan and co-products glucose and lignin-based products from wheat straw (mrwh eq). Feedstock: wheat straw; country: domestic (Ireland); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2: hydrogen peroxide.

Enzyme production within the biorefinery requires energy and material inputs. Figure 10 shows the social risks of enzymes per tonne of xylan by individual inputs from domestic sources. Electrical and thermal energy contribute to about half of the overall risks, chemicals to about one third.

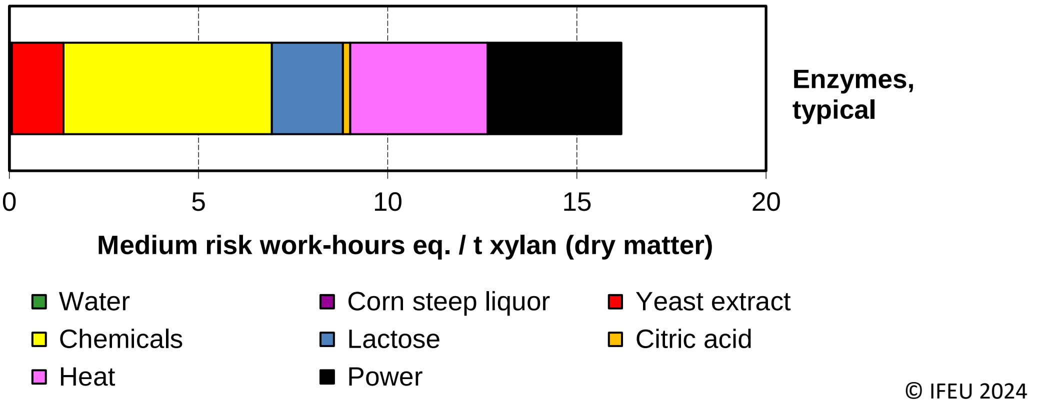

Figure 10: Social risks of enzyme production. Social risks associated with inputs in the production of enzymes for modified xylan (mrwh eq). Feedstock: wheat straw; country: domestic (Ireland); sub-scenario: typical process efficiencies.

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5.1.2 Feedstock: wheat straw vs. poplar

Wheat straw and poplar chips from short rotation coppice were considered as lignocellulosic biomass input to the biorefinery process. Comparing the social risks related to wheat straw vs. poplar relevels higher risks for poplar (Figure 11). This is due to two factors: 1) the amounts of inputs per tonne of xylan are higher for poplar due to a lower xylan output per biomass input, and 2) the social risks related to the respective economic sector are higher for the sector allocated to poplar (see section 5.4 for uncertainties related to the choice of economic sector). It is important to note that a lower xylan yield is not a disadvantage for poplar per se. Instead, more of the other co-products from poplar can be extracted in higher quantities, which may replace other high-risk products as better utilisation pathways of co-products become available.

Wheat straw and poplar are set at the same price in the analysed scenarios.

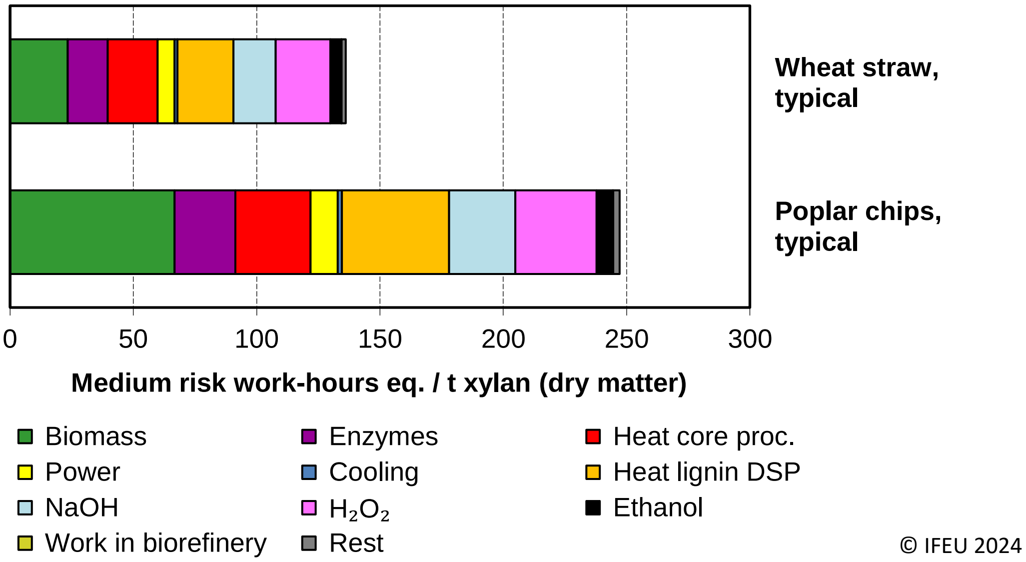

Figure 11: Difference in social risks between wheat straw and poplar. Social risks associated with inputs in the production of modified xylan and co-products glucose and lignin-based products from wheat straw and poplar (mrwh eq). Feedstock: wheat straw or poplar; country: domestic (Ireland); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2*: hydrogen peroxide.*

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5.1.3 Risk distribution over various social aspects

According to the SHDB, social risks are classified into 5 categories and 30 subcategories on various social issues. To evaluate whether inputs contribute differently to subcategories and to determine the appropriate level of analysis, we plotted the relative contribution of each input to the social risks at subcategory level (Figure 12). The result shows that all inputs contribute to a similar extent to the different subcategories, and that there is no subcategory, which is dominated by one or few inputs. This means that no input affects one stakeholder group or social aspect more than another. Therefore, the total score is sufficient to identify social risk hotspots and optimisation potentials.

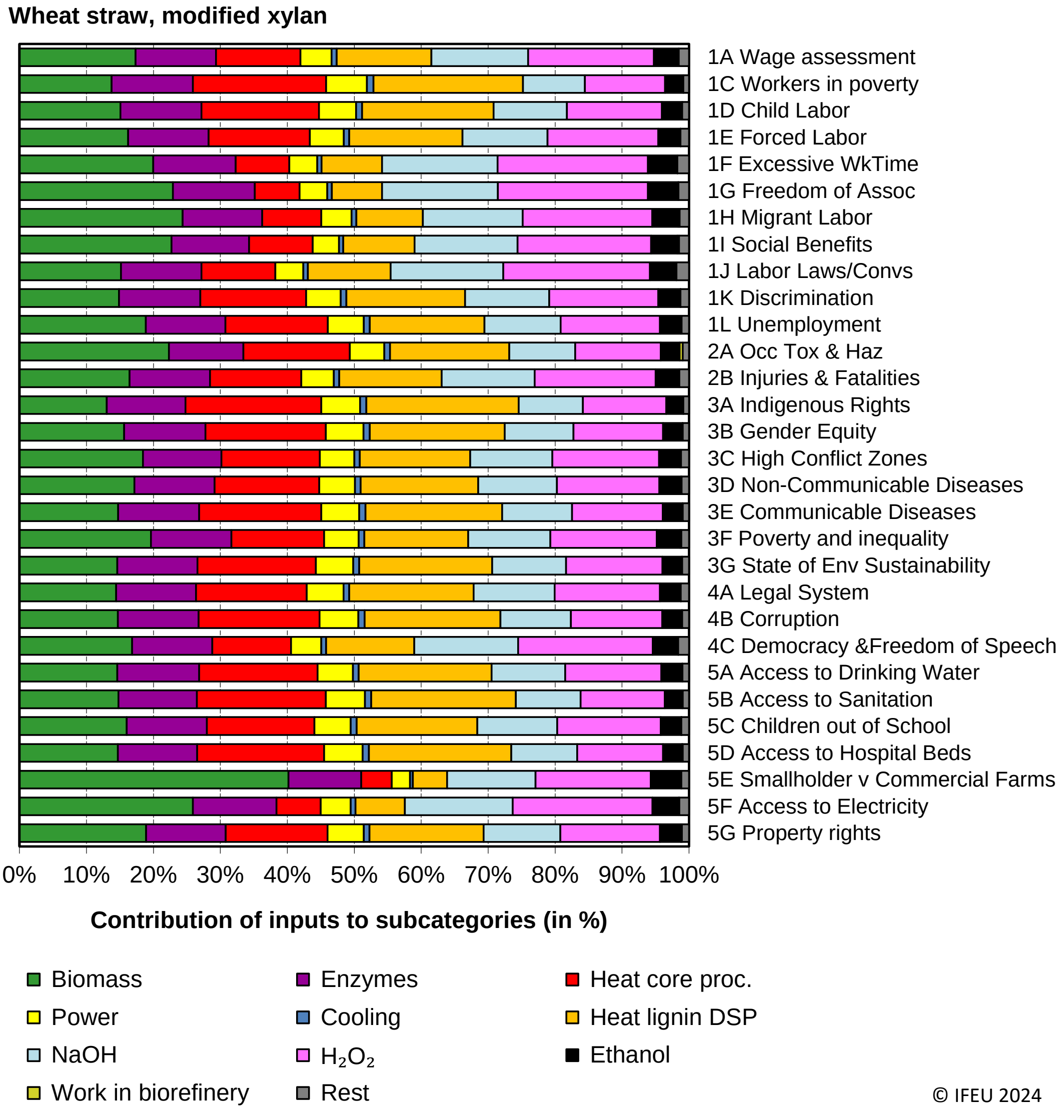

Figure 12: Contribution of inputs to subcategories (%) in the production of modified xylan and co-products glucose and lignin-based products from wheat straw. Feedstock: wheat straw; country: domestic (Ireland); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2: hydrogen peroxide.

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Key findings:

- Social risks originating from the work at the plant itself, located in the EU, are negligible. Thus, risks associated with external supplies are the hotspots to focus on.
- The largest contributions to the overall social risks of xylan are from heat (incl. heat lignin downstream processing), biomass, hydrogen peroxide, and sodium hydroxide, together accounting for 80 % of the total risks.
- The difference between unmodified and modified xylan is smaller than the difference between wheat straw or polar.
- All inputs contribute to a similar extent to individual social issues (subcategories).

5.2 Influence of choice of suppliers

While the (physical) quantity of inputs is largely determined by the biorefinery process and unit prices by the world market, countries of origin can be chosen by plant operators. This section presents the results of varying the country of origin, where applicable, by 1) domestic, 2) world market low to medium-risk countries, and 3) world market high-risk countries. High-risk countries tend to be low-income countries where social rights and labour laws are poorly regulated and/or enforced increasing the risk of companies failing to comply with international standards. Table 1 provides the country selection for the individual inputs, which is based on current (2023) import statistics to the EU.

5.2.1 Suppliers of chemicals

Figure 13 reveals that the socials risks of modified xylan production are strongly influenced by supplier countries of chemicals as the main inputs besides biomass. While social risks increase by less than 50 % when purchasing chemicals from low or medium-risk world market countries as compared to domestic sources (=Ireland), social risks can quadruple for purchasing chemicals in high-risk countries. Pakistan, the selected source country for sodium hydroxide and ethanol, has a particularly large impact on the increase. Pakistan is the largest exporter of ethanol to the EU, and the 6th largest supplier country of sodium hydroxide.

Thus, there is a risk involved in buying supplies from the world market, which may be low-priced, without considering the social risks associated with the production of such inputs most of which originate from upstream suppliers, and not from the work within the sector. It is important to note that social risks originating from high-risk countries also account for the majority of social risks in chemical products sourced from otherwise low-risk countries, although the overall level of social risk is considerably lower. For example, 99.9 % of the social risks in the chemical sector in Ireland are imported from

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countries outside Ireland while only 50% of the money spent on inputs is spent on external inputs.

Inputs needed in the biorefinery process can be sourced from many supplier countries, including low-risk supplier countries such as Ireland (section 5.1.1). This would be different if the process required certain metals or biomass from specific countries. The availability of inputs from low-risk supplier countries is an advantage of the EnXylaScope system and opens up opportunities to keep social risks low. It also means that there is no need to substitute existing inputs in the biorefinery process. However, buying from high-risk countries is not something to be avoided in general, as supply chain social risks can also be considered as an opportunity to improve living and working conditions of stakeholders along the supply chain. Rather, it entails responsibilities to people who may be affected by the production, which can be addressed by building trusting relationships with responsible producers in such countries, or by buying from certified vendors.

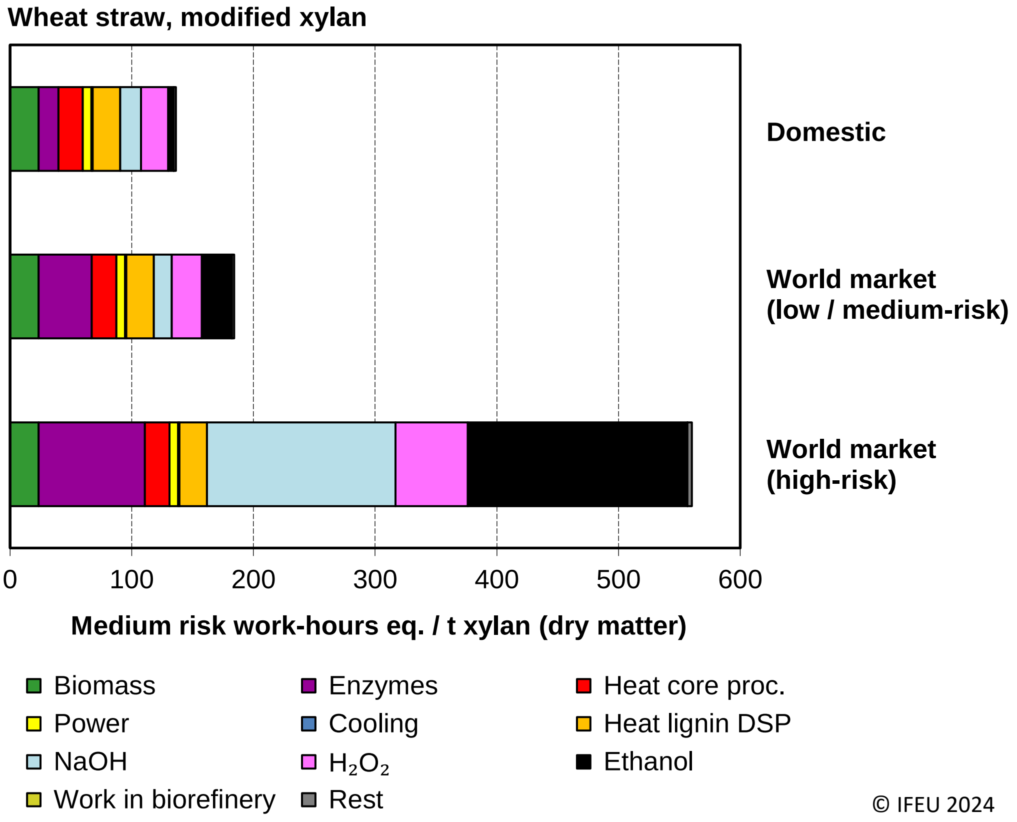

Figure 13: Difference in social risks between different supplier countries. Social risks associated with the production of modified xylan and co-products glucose and lignin-based products from wheat straw, by country of origin (mrwh eq). Feedstock: wheat straw; country: various (see Table 1); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2*: hydrogen peroxide.*

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5.2.2 Suppliers of poplar

While the difference in social risks between wheat straw and poplar is below 100%, sourcing poplar and other inputs from high-risk countries can increase the risks more than 7-fold (Figure 14). The selected high-risk country for poplar is Belarus, which was a major supplier of poplar to the EU at the time the background data is referring to. This may have changed due to sanctions imposed on Russia and its allies following Russia's invasion of Ukraine. However, risks can still be considerable when importing from other countries also given the large quantities required in the EnXylaScope process. Unlike chemicals from high-risk countries, the main risks of primary sectors, such as agriculture and forestry sectors, come from within the sector itself and not from suppliers upstream.

This means that biomass is a potential critical point of intervention when it comes to social risks and needs to be prioritised. Scenarios are based on domestic sources of wheat straw, which cannot be transported over long distances and which comes with very low social risks. Sourcing poplar from external countries is more likely because it may not be available in sufficiently large quantities in Ireland. In this case, poplar provision should be the first starting point for supplier audits. As most social risks originate in the supplier's own operations, the buyer can interact directly with the supplier and realistically influence production conditions (more feasible than for chemicals where most risks originate from purchases from other sectors).

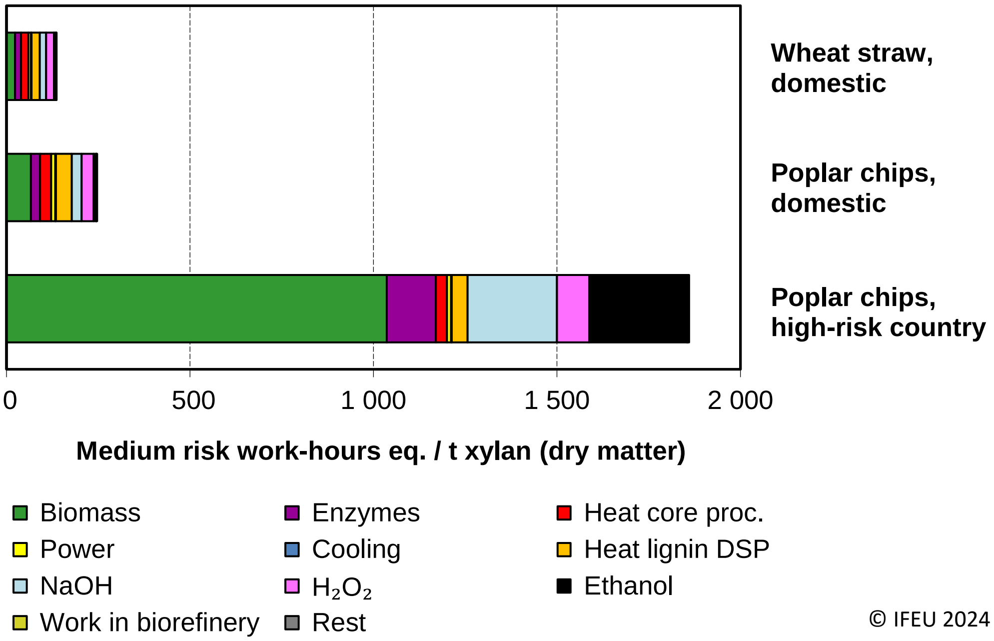

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Figure 14: Difference in social risks between wheat straw and poplar from different supplier countries. Social risks associated with the production of modified xylan and co-products glucose and lignin-based products from wheat straw and poplar chips, by country of origin (mrwh eq). Feedstock: wheat straw or poplar; country: domestic (Ireland), various (see Table 1); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2: hydrogen peroxide.

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Key findings:

- All inputs to the EnXylaScope process are available from low-risk supplier countries.
- The social risks of xylan production are strongly influenced by the countries from which biomass and chemicals are sourced.
- Most social risks associated with chemicals from high-risk countries originate from purchases from other sectors; risks associated with biomass from high-risk countries originate from the sector itself.
- To improve the living and working conditions of stakeholders along the supply chain, sourcing from high-risk countries should involve direct engagement with responsible producers in those countries or sourcing from certified suppliers.
- Working directly with biomass suppliers is easier than with chemical suppliers, where most risks arise from other sectors upstream.

5.3 Reference system

This section puts the risks associated with the production of xylan and its co-products glucose and lignin-based products produced according to the EnXylaScope concept into perspective by examining the social risks associated with the production of reference products of xylan used as cosmetic ingredient or as feed additive reducing the demand for animal feed. Figure 15 shows modified xylan from domestically sourced poplar chips as the corresponding biorefinery scenario. This is a conservative scenario, considering that the social risks associated with poplar chips are higher than with wheat straw. The results show that the social risks associated with modified xylan and its co-products are lower than those associated with purchased reference products for cosmetics and animal feed, including those for the co-products, i.e., glucose, starch, and chemicals (phenol, polyol, AKD)(Figure 15). However, a direct comparison is subject to a high level of uncertainty, due to limited robustness of results (see section 5.4).

Taking this into account, the advantage of modified xylan production over the reference products is reduced, but social risks can still be considered lower than those of the reference products.

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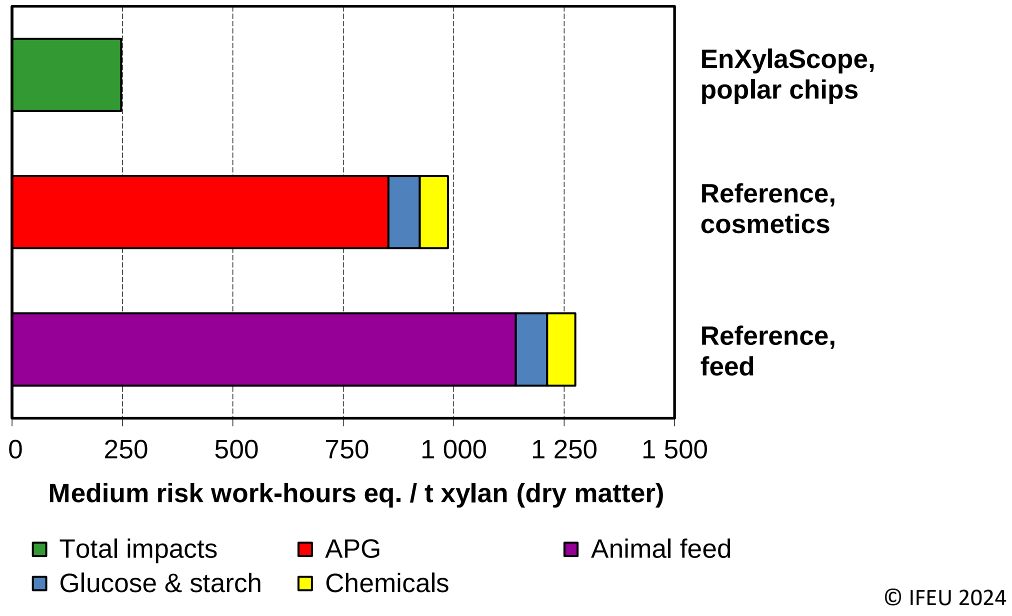

Figure 15: Social risks associated with biorefinery and reference products for domestic sourcing (mrwh eq). Biorefinery products include the production of modified xylan and co-products glucose and lignin-based products from poplar chips. The reference products of xylan used in cosmetics or as feed additive 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.

When considering high-risk countries of origin for reference products, the results provide a clearer picture: sourcing reference products of xylan used in cosmetics and as feed additive from high-risk countries can multiply social risks by more than 50 times in the case of feed compared to domestic sources (Figure 16). For the reference products of xylan used in cosmetics, social risks increase by the factor of 16. In contrast, if supplies for the biorefinery scenario based on poplar are sourced from high-risk countries, risks increase by a factor of 7.5. This difference again highlights the risks associated with the production of primary commodities in high-risk countries, due to poor working conditions in the sector, the relatively high share of labour in the sector itself per USD output, and low wages.

Overall, the modified xylan produced according to the assessed biorefinery has lower supply chain risks than the reference products, which can be associated with extremely high social risks when sourced from high-risk countries (feed in particular).

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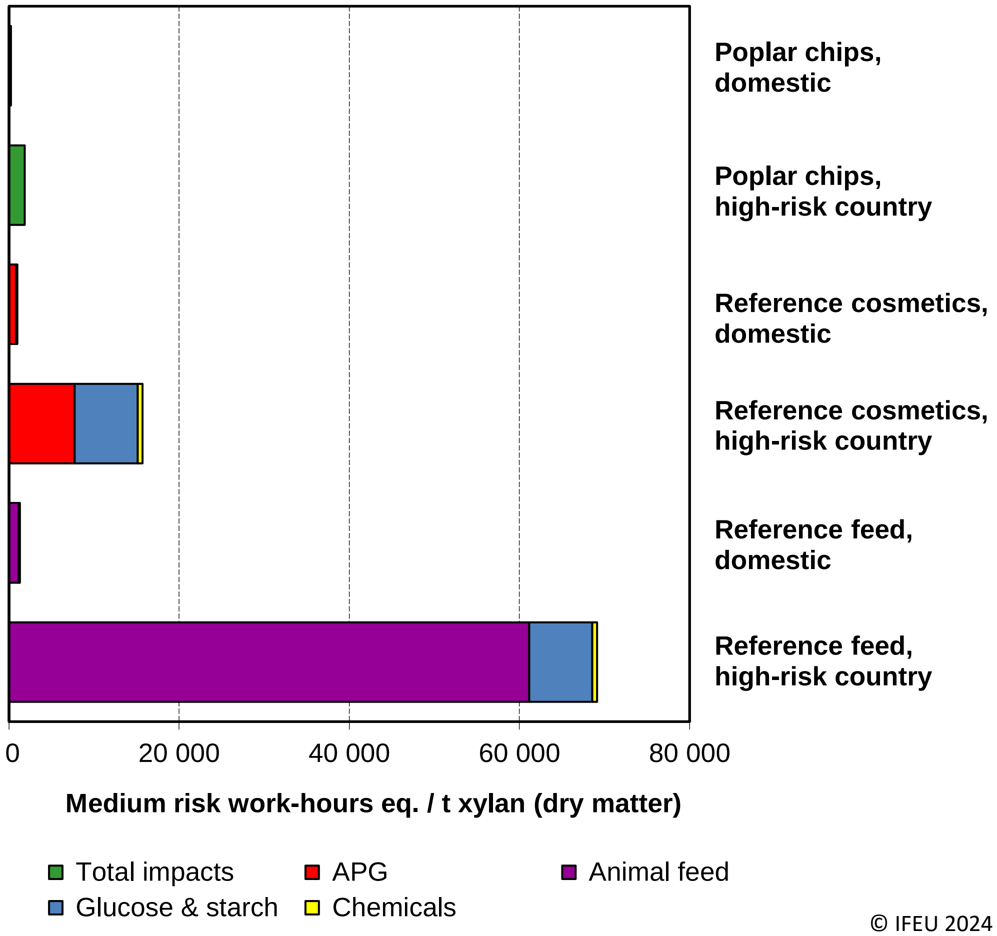

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Figure 16: Influence of procurement from high-risk countries on social risks associated with biorefinery and reference products (mrwh eq). Biorefinery products include the production of modified xylan and co-products glucose and lignin-based products from poplar chips. The reference products of xylan used in cosmetics or as feed additive reducing the demand for animal feed include conventional cosmetic ingredients from palm oil and animal feed, respectively, as well as the reference products of the co-products. Country of origin: domestic (Ireland) or high-risk country (see Table 1); sub-scenario: typical process efficiencies. APG: alkyl polyglucoside.

Key findings:

- The social risks of xylan are lower than those of reference products.
- When sourced from high-risk countries, reference products can be associated with extremely high risks.

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5.4 Robustness of results

This section describes the limitations of the S-LCA methodology, the underlying database, and the associated uncertainty in the results. The S-LCA methodology and the underlying Social Hotspots Database (SHDB, [Bennema et al. 2022]) link social risks to the production of certain inputs via an economic multi-regional input-output model (in this case GTAP [Aguiar et al. 2016], see section 3.2 for details). This means that social risks are associated with the working hours in a certain economic sector in a certain country and then to its economic turnover, but not to any specific production process. The secondary allocation of these risks to a certain input bought on the world market leads to uncertainties on the following levels:

- Is the average risk level per working hour in a certain sector, such as chemicals from China, a good representation for the risk of the biorefinery input, e.g., one particular chemical?
- Is the average number of working hours in a certain sector required to generate a certain turnover a good representation of the biorefinery input?
- Does the price level of the input that the biorefinery pays for correspond to the general price level of that economic sector in its country?

Social risks, working hours, and turnover in economic sectors: The economic sectors available in the SHDB provide information on social risks per turnover in a country-specific sector representative of an average product in that sector (see [Center for Global Trade Analysis 2019] for a list of sectors). This relationship tends to be dominated by bulk products provided by that sector, such as wheat grains in the case of the small “wheat” sector or a wide mix of specialty crops in the case of the “other crops” sector (“crops, not elsewhere classified”). For any specialty product, the social risks per turnover can vary substantially for several reasons:

- The relationship between the price of the product and the number of required working hours differs from the main product of the sector. It is likely that this relationship for a niche product such as poplar chips from short rotation coppice will be different from that for a range of other specialty products. The same applies to a specialty chemical, which probably differs from a bulk chemical in that regard.
- The risk level per working hour differs from the sector average. For example, the risk of accidents is likely to be higher when harvesting stems of poplar in short rotation coppice than when harvesting vegetables or flowers, which are in the same sector. Wheat straw and poplar, for example, are not typical of the selected sectors “wheat” in the case of wheat straw, and “crops, not elsewhere classified” in the case of poplar although these products belong to these economic sectors. In that case other sectors may even represent the risks of these products better than the sector they belong to.

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Figure 17 illustrates the effect of choosing a different economic sector for wheat straw (“crops, not elsewhere classified”) and poplar (“wood product”). On the basis of the sector combinations and the selected country of origin (“Ireland”), the difference is relatively small (a few percent to about 40 %), in particular when compared to the risk differences between different supplier countries (section 5.2). Thus, the difference between wheat straw and poplar are in the same range as the uncertainty. Thus, the difference does not allow for a clear recommendation for wheat straw or poplar from a social point of view when sourced domestically, given the uncertainties described above.

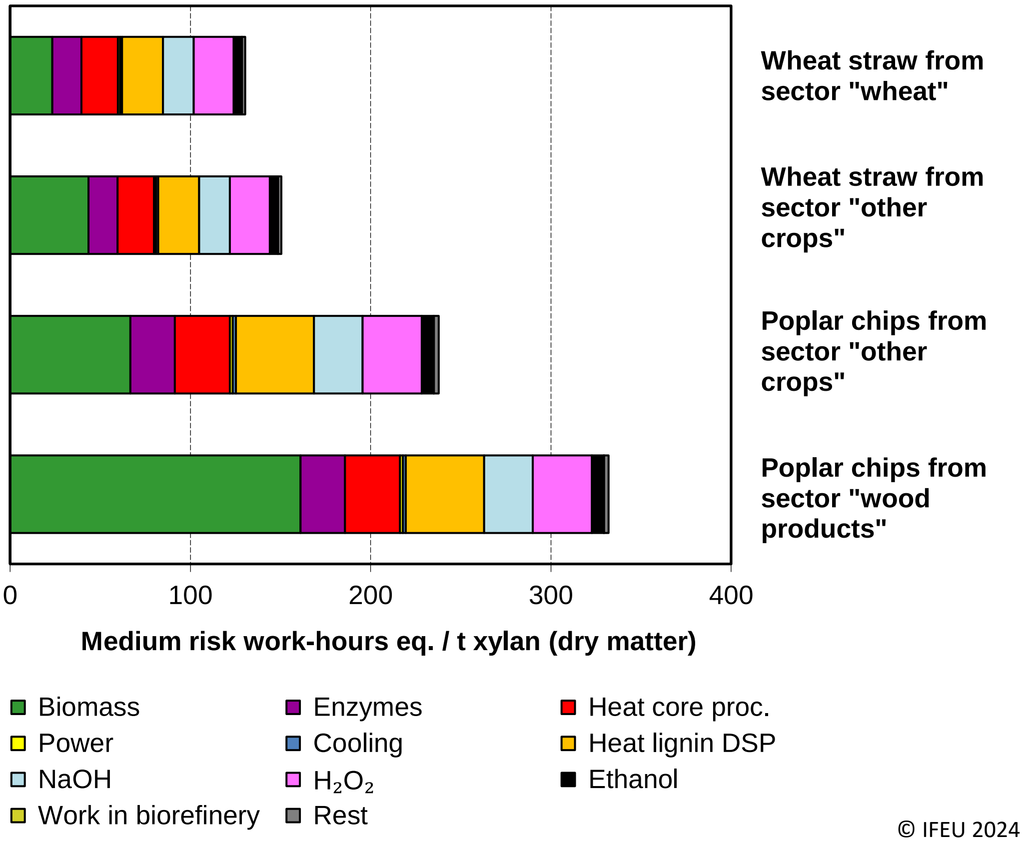

Figure 17: Influence of economic sector on social risks of wheat straw and poplar chips. Social risks associated with the production of modified xylan for different choices of economic sectors grouped by input (mrwh eq). Feedstock: wheat straw or poplar; country: domestic (Ireland); sub-scenario: typical process efficiencies. DSP: downstream processing; NaOH: sodium hydroxide; H_2O_2: hydrogen peroxide.

Price level of the purchased input: First, it is uncertain whether the price level for a certain input, as used in the economic assessment and S-LCA of this project, is representative of the price level as part of the underlying economic database. This is particularly uncertain for volatile markets and for future oriented businesses that are not yet firmly established such as poplar short rotation coppice.

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Secondly, it is uncertain to what extent the price level paid by the biorefinery reflects the price level in the country of origin of the product. This can be particularly relevant for less developed countries, which are often associated with high social risks, but also with substantial differences between domestic and world market price levels. For example, the chemical sector in Pakistan produces many products for the domestic market at a relatively low price level, while at the same time selling certain products to the world market at a higher price level. Social risks are, however, associated with an average level of working hours per turnover. Due to the higher price level of some world market products, the risks associated with them by the Social Hotspots Database tend to be overestimated. Nevertheless, the quantitative differences in social risks between low-risk and high-risk countries are usually so large that only part of this difference can be attributed to systemic overestimation. This difference in risks is confirmed when comparing the underlying qualitative risk classifications as low, high, or very-high for many social aspects between countries. Nevertheless, this increases the uncertainty for quantitative comparison of risks along the life cycle.

These uncertainties are inevitable when using secondary data and coarse economic models, but need to be taken into consideration when interpreting the results. This involves being very cautious about comparing different products, such as xylan and the reference products, which have different price levels and are reflected differently in the allocated economic sector. Comparing the same process with slightly different inputs (modified xylan using wheat straw vs. poplar) requires the variation of the influencing factors for a wider range of possible outcomes. In this report, we base our recommendations only on substantial differences in social risks, and consider smaller differences to be a potential result of the above shortcomings.

Gaps and limitations can be addressed by additionally applying other methods, such as SWOT analysis (see chapter 6 for the results), and by collection site-specific data in hotspots identified in this S-LCA, which is however, not yet possible at this stage of technology development as no site or organisation operating the biorefinery has been identified yet.

Key findings:

- Uncertainties in the methodology make it difficult to compare the social risks of different products (e.g., xylan product vs. reference product).
- Smaller risk differences between modified and unmodified xylan on the one hand, and wheat straw and poplar on the other, do not allow recommending one process scenario over another.
- Large differences from the variation in the supplier country are relevant, despite a likely systematic overestimation in the quantification of the social risks of inputs originating from high-risk countries.

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6 Results SWOT analysis

The SWOT analysis evaluates the strengths, weaknesses, opportunities, and threats (SWOT) of the analysed biorefinery concept regarding social aspects. **It complements the S-LCA** by capturing potential **social impacts, both negative and positive**, across the entire life cycle**, not just the upstream supply chain**. This also includes potential impacts that may arise at the local level from the operations of the biorefinery.

Starting with a workshop with all project partners, positive and negative social aspects affecting different stakeholder groups associated with the EnXylaScope biorefinery concept were compiled, analysed, clustered, extended, and summarised in SWOT matrices (for a detailed method description, please see section 3.3). The SWOT matrix is divided into four sections according to 1) quality and 2) origin of social impacts. The quality of social impacts includes **helpful** and **harmful** aspects to achieving the objective, i.e., the socially beneficial implementation and operation of a biorefinery according to the analysed concept; the origin of social impacts is divided according to **internal** (attributes of the organisation/product) and **external** (attributes of the environment).

The results of the SWOT analysis are structured according to life cycle stages. In that it follows the approach of the overarching integrated life cycle sustainability assessment. The three analysed life cycle stages are:

- Biomass provision, including the provision of straw and poplar (section 6.1)
- Biorefinery and enzyme development (section 6.2)
- Use phase of products (section 6.3)

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6.1 Biomass provision

Biomass, including wheat straw or poplar, is a major input to the biorefinery requiring substantial amounts of land and labour and therefore potentially affecting a wide range of stakeholders.

For biomass provision, we considered following stakeholder groups:

- Biomass supplier (i.e., farmers),
- Employees,
- Competing users
- Local communities.

The results are listed in Figure 18 (for wheat straw[4]) and Figure 19 (for poplar).

The main results of the SWOT analysis are summarised below:

- Strengths related to biomass provision include higher and diversified income for farmers, and there is an opportunity to strengthen local value chains by advanced technologies and infrastructure development in rural areas.
- The dependence on the biorefinery as one big customer to buy large shares of the biomass was identified as a weakness. Poplar production is associated with higher risks than wheat straw as a co-product of crop production because of the high investment costs, the long-term binding of land, the adoption of new agricultural practices, and the possible mismatch between biomass demand and crop maturity.
- Poplar production is potentially in direct competition with other uses of agricultural land including food production or potentially also conversion into natural reserves, which is a weakness.
- The local community can benefit from increased biomass production through the development of local value chains, but needs to be involved in the process in order to increase acceptance of new forms of production, which may be associated with changes in the landscape, increased traffic, etc.
- Concerns raised by local communities about biodiversity and increased emissions associated with a potential intensification of agricultural production.
- Seasonal workers were identified as one vulnerable group of increasing biomass production.

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[4] The results for wheat straw are based on a similar biorefinery project with wheat straw as one of the biomass inputs considered [Keller & Rettenmaier 2022].

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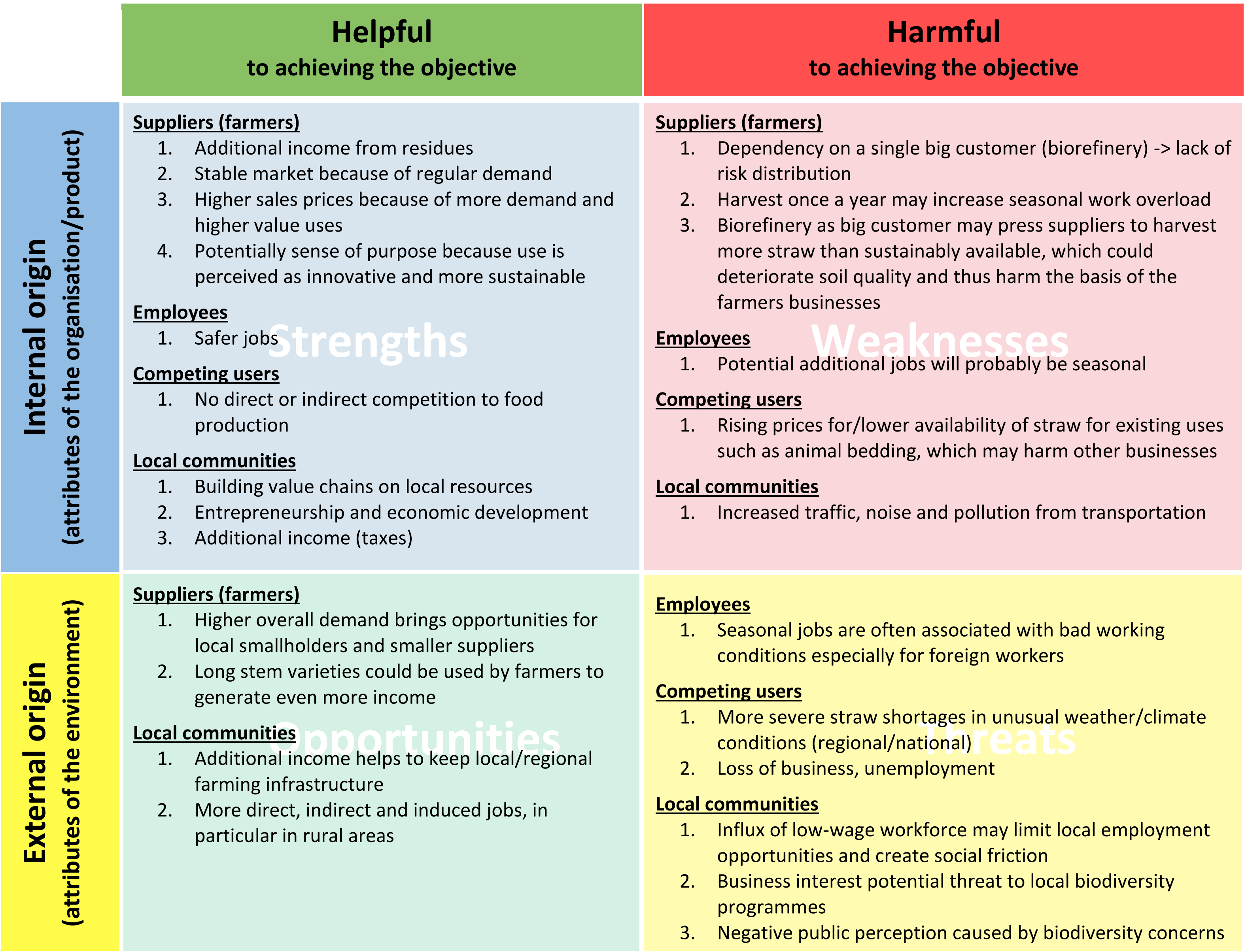

	Helpful **to achieving the objective**	**Harmful** **to achieving the objective**
Internal origin (attributes of the organisation/product)	**Strengths** **Suppliers (farmers)** 1. Additional income from residues 2. Stable market because of regular demand 3. Higher sales prices because of more demand and higher value uses 4. Potentially sense of purpose because use is perceived as innovative and more sustainable **Employees** 1. Safer jobs **Competing users** 1. No direct or indirect competition to food production **Local communities** 1. Building value chains on local resources 2. Entrepreneurship and economic development 3. Additional income (taxes)	**Weaknesses** **Suppliers (farmers)** 1. Dependency on a single big customer (biorefinery) -> lack of risk distribution 2. Harvest once a year may increase seasonal work overload 3. Biorefinery as big customer may press suppliers to harvest more straw than sustainably available, which could deteriorate soil quality and thus harm the basis of the farmers businesses **Employees** 1. Potential additional jobs will probably be seasonal **Competing users** 1. Rising prices for/lower availability of straw for existing uses such as animal bedding, which may harm other businesses **Local communities** 1. Increased traffic, noise and pollution from transportation
External origin (attributes of the environment)	**Opportunities** **Suppliers (farmers)** 1. Higher overall demand brings opportunities for local smallholders and smaller suppliers 2. Long stem varieties could be used by farmers to generate even more income **Local communities** 1. Additional income helps to keep local/regional farming infrastructure 2. More direct, indirect and induced jobs, in particular in rural areas	**Threats** **Employees** 1. Seasonal jobs are often associated with bad working conditions especially for foreign workers **Competing users** 1. More severe straw shortages in unusual weather/climate conditions (regional/national) 2. Loss of business, unemployment **Local communities** 1. Influx of low-wage workforce may limit local employment opportunities and create social friction 2. Business interest potential threat to local biodiversity programmes 3. Negative public perception caused by biodiversity concerns

Figure 18: SWOT matrix on social aspects of the provision of wheat straw (source: [Keller & Rettenmaier 2022]).

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	Helpful **to achieving the objective**	**Harmful** **to achieving the objective**
Internal origin (attributes of the organisation/product)	Strengths **Suppliers (farmers)** 1. Risk diversification 2. Stable market because of regular demand 3. Potentially sense of purpose because use is perceived as innovative and more sustainable 4. Benefits from cultivation of perennial plants and strip cultivation (soil protection, …) **Employees** 1. Safer jobs **Competing users** 1. No direct competition for poplar as biofuel, furniture or animal bedding **Local communities** 1. Building value chains on local resources 2. Entrepreneurship and economic development 3. Additional income (taxes) 4. Additional opportunity to avoid fertiliser leachate 5. Reduced migration to cities	Weaknesses **Suppliers (farmers)** 1. Dependency on a single big customer (biorefinery) -> lack of risk distribution 2. Binding land for many years 3. Demand of biorefinery for poplar may not match maturity of poplar 4. High investment costs **Employees** 1. Additional seasonal jobs including unstable contracts **Competing users** 1. Land could otherwise be used as a natural reserve, increasing overall biodiversity 2. Competition with other crops such as food **Local communities** 1. Noise and increased traffic during the harvest times
External origin (attributes of the environment)	Opportunities **Suppliers (farmers)** 1. Higher overall demand brings opportunities for local smallholders and smaller suppliers 2. Additional crop variety as safety net in the case of weather events affecting the traditional crops. 3. Subsidies for short rotation coppice **Local communities** 1. More direct, indirect and induced jobs, in particular in rural areas 2. Using poplar might provide additional benefits from using contaminated lands or waste water treatment 3. Advanced technologies on cultivation of perennial plants such as strip cultivation and infrastructure development in rural areas	Threats **Suppliers (farmers)** 1. Biorefinery operations might be discontinued 2. Ending of subsidies 3. Farmers lack skills in advanced practices incl. cultivation of perennial plants and strip cultivation, which may lead to low yields and thus low profits, as well as to reduced interest to uptake the poplar farming by other farmers **Employees** 1. Lack of local work force available during seasons and influx of migration workers which may cause housing crisis and thus bad living conditions **Competing users** 1. Loss of business, unemployment **Local communities** 1. Low acceptance of changes to traditional farming practices 2. Business interest potential threat to local biodiversity programmes 3. Negative public perception caused by biodiversity concerns

Figure 19: SWOT matrix on social aspects of the provision of poplar.

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6.2 Biorefinery and enzyme development

This section presents the social aspects that were associated with the biorefinery itself and enzyme development.

For the biorefinery, we considered the following stakeholder groups:

- Employees
- Neighbours
- Local community

For enzyme development, we considered:

- Employees
- Scientific community
- Local communities

Results are listed in Figure 20 (for the biorefinery) and Figure 21 (for enzyme development) and summarised below:

- Strengths associated with both the biorefinery and enzyme development include the creation of jobs for highly skilled technical and non-technical workers.
- Related to this are potential positive effects on the local community, including direct effect such as the provision of high-quality employment for local people requiring less commuting and indirect positive effects on the local economy, local services, and education, depending on the location and scale of the biorefinery. The latter is particularly linked to enzyme development with opportunities for research and skills development.
- The strengths mentioned above also apply to external highly-skilled workers that provide the opportunity to contribute to creating a multi-national work environment with positive feedback loop to the international scientific community driving science hubs, collaborations, and networks.
- There are also weaknesses associated with building a biorefinery in a rural community, such as potentially increasing land and housing prices, which, in combination with the influx of external workers, may cause resistance against the biorefinery and future bioeconomy projects.
- Depending on the conditions, including traffic, emissions, and aesthetics, the perception of local community and neighbours can be positive or negative.
- Risks associated with enzyme development and their use in a biorefinery include uncertain policy support, dependence on unforeseen scientific progress, regulatory challenges, uncertain product uptake by industry, and GMOs.

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	Helpful **to achieving the objective**	**Harmful** **to achieving the objective**
Internal origin (attributes of the organisation/product)	**Strengths** **Employees** 1. Job creation 2. Stable technical and non-technical jobs 3. Jobs with benefits available to local people **Neighbours** 1. Land value increases 2. Public transport and/or roads might improve 3. Sense of pride to be associated with the place for bioeconomy/biorefinery **Local community** 1. Job creation: locally, less commuting 2. Reduced migration to cities 3. Locally sourced services 4. Depending on location and scale: benefits for local economy, local services, more equal living conditions, promotion of education	**Weaknesses** **Employees** 1. Initial training activities and skill development increase workload 2. Dependency on start-up company **Neighbours** 1. Increased traffic **Local community** 1. Increase of land value affecting local low-income population
External origin (attributes of the environment)	**Opportunities** **Employees** 1. Multi-national work culture and environment with highly-skilled international workforce 2. Employees trained in advanced technologies and equipment, thus creating a positive learning work environment 3. Research focus in biorefinery may support young scientists in the field of biorefinery **Neighbours** 1. Opportunities to create new small businesses related to biorefinery 2. Good example of well managed and sustainable biorefinery with zero waste approach can spread the good word for future biorefineries in the country. **Local community** 1. Children and youth showing interest towards the courses related to biorefinery and bioeconomy 2. Benefitting from skill development programs and workshops offered by the biorefinery 3. Pride in associating with the town/place, biorefinery is located 4. Hope for their children staying close to them because of the local employment, so a sense of security and well-being for next generations	**Threats** **Employees** 1. Biorefineries located in rural areas may cause housing issues for external workers and bad living conditions **Neighbours** 1. Biorefinery causing aesthetic damage to the place and hence opposed **Local community** 1. Increased traffic might make people's everyday commuting challenging 2. Negative public perception on biorefineries and a possible waste discharge 3. High dependency on the biorefinery, so any unfortunate events (such as closure of the company) will lead to fall of local economy and will lead to mistrust on any future biorefineries.

Figure 20: SWOT matrix on social aspects of the biorefinery.

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	Helpful **to achieving the objective**	**Harmful** **to achieving the objective**
Internal origin **(attributes of the organisation/product)**	Strengths **Employees** 1. Risk reduction in chemical processes 2. Increased number of jobs in R&D&I and service sector (QM, R&I consultancy) **Scientific community** 1. Established partnerships and networks provide a robust knowledge base and collaborative opportunities to drive innovation. 2. Research and innovation opportunities in industrial setting and partnerships (e.g., research contracts from industry) **Local communities** 1. Risk reduction in chemical processes 2. The presence of biotechnology companies within enzyme-producing regions supports local employment and skill development	Weaknesses **Employees** 1. Additional training or hiring of specialized personnel to close potential knowledge gaps 2. Uncertainty for start-ups about how the new products/services will be taken up by industry **Scientific community** 1. High dependency on scientific advancements can delay product development timelines if scientific breakthroughs are slower than anticipated. **Local communities** 1. Limited awareness or support for enzyme-based biotechnology solutions in certain regions may hinder local buy-in or acceptance of biotech projects.
External origin **(attributes of the environment)**	Opportunities **Employees** 1. Opportunities for professionals passionate about environmental innovation. **Scientific community** 1. New perspectives/push for specialty enzymes: opening door for new lines of development 2. Increasing collaboration, funding, and sharing of research findings within the scientific community. 3. Knowledge gain/scientific exchange/synergies from research-industry cooperation in industrial setting **Local communities** 1. Getting used to GMOs 2. Rising consumer awareness of natural and sustainable products enhances acceptance and support for enzyme-based biotechnological developments.	Threats **Employees** 1. Competition for skilled biotech professionals may drive up recruitment and retention costs, posing challenges to maintaining a highly qualified workforce. **Scientific community** 1. Rapid advancements and patenting within global enzyme sectors, especially in North America and Asia-Pacific, could lead to intellectual property challenges and increased competition. **Local communities** 1. Worries about GMOs 2. Market fragmentation and differing regulatory requirements in various European regions may limit the widespread adoption of enzyme-based biotechnological products, affecting community support for large-scale implementation.

Figure 21: SWOT matrix on social aspects of enzyme development.

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6.3 Use of products

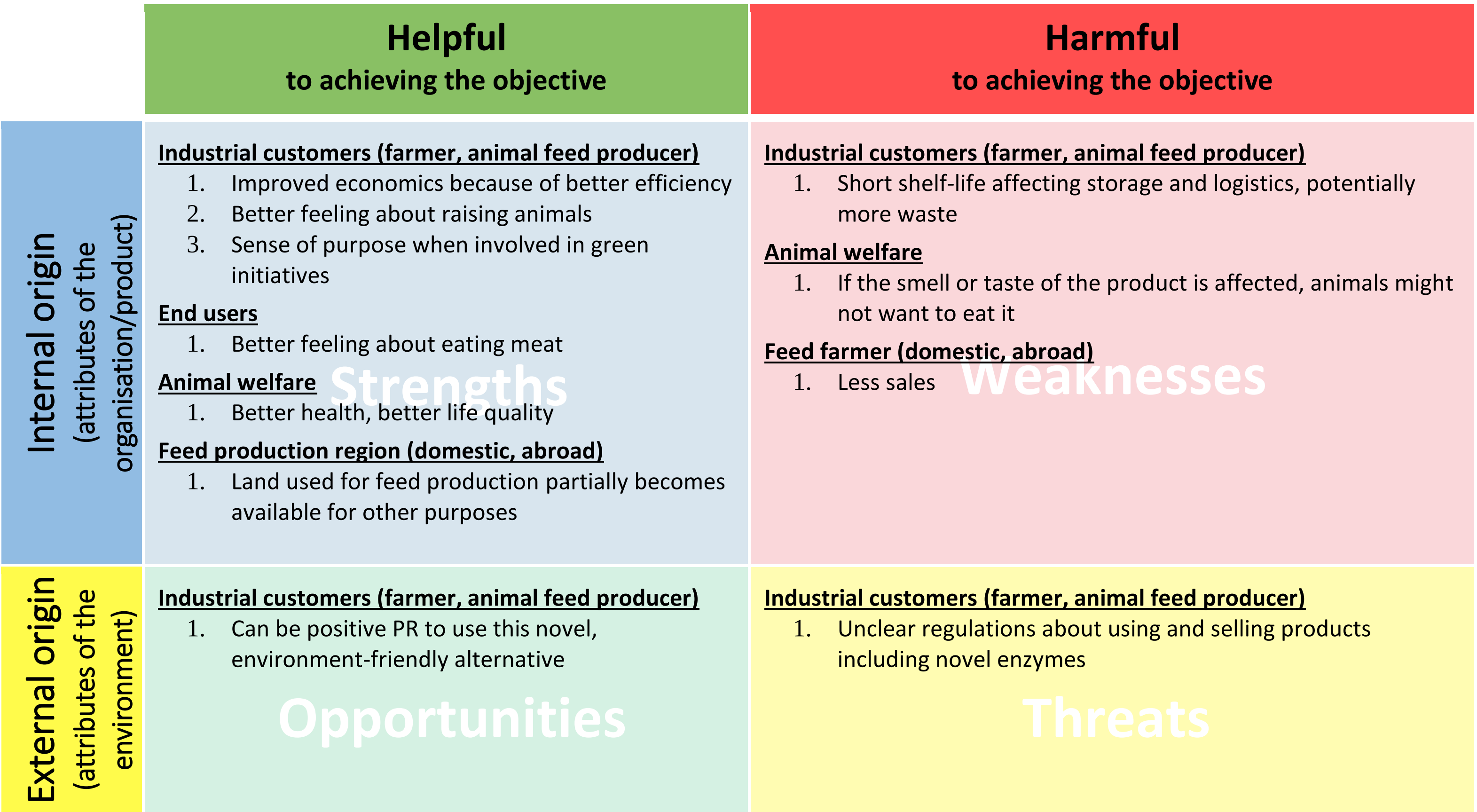
As described in section 4.3, xylan produced in EnXylaScope can be used as feed additive or in cosmetics.

For the use of xylan as feed additive, we considered the following stakeholder groups:

- Industrial customers (farmer, animal feed producer)
- End users
- Animal (welfare)

For the use of xylan in cosmetics, we considered:

- Industrial customers (farmer, animal feed producer)
- Industrial competitor
- End users



	Helpful **to achieving the objective**	**Harmful** **to achieving the objective**
Internal origin (attributes of the organisation/product)	**Industrial customers (farmer, animal feed producer)** 1. Improved economics because of better efficiency 2. Better feeling about raising animals 3. Sense of purpose when involved in green initiatives **End users** 1. Better feeling about eating meat **Animal welfare** 1. Better health, better life quality **Feed production region (domestic, abroad)** 1. Land used for feed production partially becomes available for other purposes Strengths	**Industrial customers (farmer, animal feed producer)** 1. Short shelf-life affecting storage and logistics, potentially more waste **Animal welfare** 1. If the smell or taste of the product is affected, animals might not want to eat it **Feed farmer (domestic, abroad)** 1. Less sales Weaknesses
External origin (attributes of the environment)	**Industrial customers (farmer, animal feed producer)** 1. Can be positive PR to use this novel, environment-friendly alternative Opportunities	**Industrial customers (farmer, animal feed producer)** 1. Unclear regulations about using and selling products including novel enzymes Threats

Figure 22: SWOT matrix on social aspects of the use of xylan products as feed additive.

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Results on social aspects of the use of xylan products are listed in Figure 22 (as feed additive) and Figure 23 (in cosmetics) and summarised below:

- Both the use of xylan as a feed additive and in cosmetics have in common benefits in terms of the positive perception of xylan products as environmentally friendly and sustainable by end users. However, uncertainty about whether the product is vegan and cruelty-free can hinder this positive perception.
- With regard to the end users of xylan in cosmetics, additional weaknesses and threats are related to GMOs, smell, taste, consistency, and shelf life.
- The use of xylan as feed additive has benefits for both the industrial customer and the animal, if improved animal welfare materialises. This also depends on taste and shelf life.
- Industrial customers may be concerned about regulatory challenges related to the use of GMOs and novel enzymes in their products.

	Helpful **to achieving the objective**	**Harmful** **to achieving the objective**
Internal origin **(attributes of the organisation/product)**	**Industrial competitors** 1. Labels existing to ensure “no harms” status **End users** 1. Meeting increased awareness for environmental effects of consumer products 2. Vegan? (Lactose may be a problem) 3. Cruelty free product? If not tested on animals **Strengths**	**Industrial customers** 1. Short shelf life may affect logistics and transportation arrangements **End users** 1. Maybe not vegan? (Lactose may be a problem) 2. Maybe not cruelty free product? Problem, if tested on animals 3. Maybe not fully smell-less? 4. Problems with consistency? 5. Short shelf life? **Weaknesses**
External origin **(attributes of the environment)**	**Industrial customers** 1. Reducing risks associated with imported raw materials 2. Can be positive PR to offer novel, environment-friendly products **End users** **1.** Scientific advancement like enzymes may be met positively by influencers **2.** Rising consumer awareness for natural and sustainable products **Opportunities**	**Industrial customers** 1. Unclear regulations about using and selling products including novel enzymes **End users** 1. Uncertainties about enzymes and GMOs may lead to resistance 2. Uncertainties about the product’ smell and consistency may lead to resistance **Threats**

Figure 23: SWOT matrix on social aspects of the use of xylan products in cosmetics.

7 Conclusions and recommendations

This social assessment report analyses supply chain risks in EnXylaScope using the social life cycle assessment (S-LCA) methodology. Other social implications associated with the biorefinery process were evaluated using SWOT matrices. This chapter presents conclusions from the results and recommendations for a socially beneficial future implementation of the assessed biorefinery on an industrial scale.

7.1 Conclusions

Conclusions on the major supply chain risks and other social implications are presented below.

7.1.1 Social supply chain risks

- Main contributions to supply chain risks of xylan production originate from the demand for heat, biomass and chemicals such as hydrogen peroxide, sodium hydroxide, and ethanol, while enzyme production is a minor contributor. Social risks originating from the production in the plant itself located in the EU are negligible. **Risks associated with external supplies** are therefore the social hotspots to focus on.
- All inputs to the EnXylaScope process are available with comparatively low social risks if appropriate measures are taken in procurement. There is therefore **no need to redesign the EnXylaScope process** for input substitution.
- The analysis did not reveal large differences in social risks between different process scenarios (production of modified or unmodified xylan, use of wheat straw or poplar chips from short rotation coppice). The difference in social risks between poplar and wheat straw can only be substantial if poplar is imported from high-risk countries because straw cannot be transported over long distances and must be sourced domestically. As all the options can be implemented with social risks at the lower end of the range of possible outcomes, **social risks are no major criterion for decisions between assessed process variants.**
- Social risks are strongly influenced by the countries from which in particular biomass and chemicals are sourced, with the overall risks being multiplied when sourcing from high-risk countries representing a substantial share of the global market for the respective products. Even if all inputs are sourced from suppliers within the EU, the main risks come from upstream supply chain activities outside of the EU. Therefore, **responsible sourcing beyond EU borders** was identified as the biggest lever to reduce supply chain risks.
- It is the **plant operator's freedom and responsibility to choose the input suppliers**. On average, social risks are highly dependent on the country in which the supplier is located. The higher the average risk in a certain country of origin

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is, the greater is the responsibility of the plant operator to ensure good social conditions at the particular supplier. Certain aspects of this can fall under the EU Corporate Sustainability Due Diligence Directive (CSDDD)[European Parliament & Council of the European Union 2024], which makes it the liability of large companies to identify and address negative impacts on human and labour rights in their supply chain.

- Risks associated with biomass production from high-risk countries arise from the biomass production itself, which can provide leverage for biorefinery operators to **influence biomass suppliers to engage in good social practices**. In contrast, most of the social risks associated with chemicals from high-risk countries originate from purchased inputs from other sectors in the country. This may be more difficult to trace and influence depending on the importance of the biorefinery as a customer and the ability of the supplier to change local conditions.
- Buying inputs from any kind of supplier **not only creates social risks but also jobs** and can also contribute to **local value chain and infrastructure development** particularly in rural areas. The latter are not covered by the applied S-LCA methodology but were an outcome of the SWOT analysis. Therefore, efficiency measures to reduce the demand for inputs are not only reducing the quantified risks but also benefits not visible in the respective figures. Likewise, **sourcing from high-risk countries can even improve the living and working conditions** of people if precautions are taken to reduce the risk (see section 7.2.1). Therefore, **reducing the social risk is not the primary goal** but social risks should be taken as an **indicator where in the supply chain more attention for social impacts is needed.**
- Compared to existing alternatives, the social supply chain risks associated with the assessed biorefinery process are lower for most combinations of countries, from which supplies could be sourced. This makes the **substitution of conventional products by the assessed xylan products** and their co-products a **socially less risky, acceptable choice**. If no further risk mitigation measures were taken, which is not recommended, the xylan products would be preferable for most supply chain variants. Nevertheless, **also supplies for palm oil- and soy-based conventional products can and should be sourced responsibly** to generate social benefits instead of negative social impacts in the countries of origin.

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7.1.2 Local social impacts

The SWOT analysis revealed a wide variety of both positive and negative potential impacts of several life cycle stages (biomass provision, biorefinery and enzyme development, use phase) on various stakeholder groups. This should be seen as a **starting point for more concrete stakeholder engagement at a later stage of development**, particularly when the geographical scope can be sufficiently narrowed down.

Biomass provision

- Sourcing from local biomass suppliers can lead to **higher and more diversified incomes for farmers and opportunities to strengthen local value chains in rural areas**. To achieve this, among other things it is important to minimise the risk that small-scale biomass producers, particularly poplar producers, face from being dependent on a single large customer.
- Increased biomass production can have positive and/or negative impacts on local communities, including concerns about biodiversity and increased emissions, which can be actively managed by the biorefinery, for example by supporting regenerative agriculture.
- Supplier agreements with biomass suppliers **must support human and labour rights in particular of seasonal migrant workers**, who have been identified as a potential vulnerable group in the context of increased biomass production.

Biorefinery and enzyme development

- Benefits associated with both the biorefinery and enzyme development include the creation of local jobs for highly skilled technical and non-technical workers. The biorefinery may be the only employer in the region’s bioeconomy, which requires **fair negotiations on wages and other working conditions**.
- The local community can benefit from the biorefinery through positive impacts on the local economy, local services, and education. To fully realise the potential benefits, **local employment and procurement strategies should be sought**. Thereby, it is important to minimise risks to the local community and neighbours, including increasing land and housing prices, traffic, and emissions.
- Other potential benefits could include the creation of a sense of purpose and identity for the bio-based industry within the local community.

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7.1.3 Potential impacts beyond the local level

- The conditions under which an innovative biorefinery start-up operates, including unforeseen scientific progress and uncertain product uptake by industry, **can create uncertainty for all stakeholders** and need to be taken into account and communicated accordingly.
- Risks specific to enzyme development include uncertain political support and regulatory challenges related to novel enzymes and GMOs, if applicable, which need to be managed to avoid negative impacts on local stakeholders and industrial customers.
- A new biorefinery and innovative enzyme production can **provide a positive stimulus to the scientific community**, with opportunities for research and skills development locally and elsewhere.

7.2 Recommendations

The recommendations arising from the social assessment address different stakeholders, including industrial operators who intend to take EnXylaScope to industrial scale, funding agencies, political decision makers, and the local community. These recommendations from a social perspective need to be complemented by recommendations based on other sustainability aspects.

7.2.1 To process developers

- In general, the **assessed biorefinery process should be further developed** from a social point of view because the associated products are expected to have lower social risks compared to competing conventional products.
- Decisions on possible process variants for further development should be based on sustainability indicators other than those addressed in this report, 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.
- When considering major process changes, such as affecting biomass feedstock and product portfolio, **screen for potential additional social risks.** These may include high social risks associated with biomass feedstocks that are only available from less developed countries, such as tropical regions, or lower social risks associated with competing products that would be replaced.

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7.2.2 To potential industrial operators of a future biorefinery

Supply chain

- 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
- We recommend **option 3 to improve the living and working conditions** of stakeholders along the supply chain. This requires 1) gathering first-hand information through supplier audits, complaints channels, or media reports, and 2) 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. Note that domestic biomass production can also create social risks, for example by employing seasonal migrants in poor working conditions.

Planning and operation of the biorefinery

- **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.
- Identify biomass utilisation pathways and take measures to **avoid or reduce negative impacts on existing users of the same biomass** in particular for straw as a residue with limited availability and transportability.
- If poplar is targeted as main feedstock, try to locate the biorefinery in regions with existing poplar plantations and either more supply than current demand or potential to increase plantation sizes. Connecting to flexible existing markets with several customers **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.
- Wherever possible, seek to **mitigate negative impacts on neighbours and the local community**, including increasing land and housing prices, emissions, and traffic.

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- 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.
- **Engage with local stakeholders**, including farmers, neighbours, and the local community, early on and take their needs and views into account.

7.2.3 Research funding agencies

- Provide **further funding to develop this xylan-first biorefinery concept** further to support the realisation of its potentials to provide social benefits.
- 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].

7.2.4 To political decision makers

- A carefully planned supply chain law at the national level to meet the requirements of EU's directive on due diligence can induce social improvements on a large scale. To increase its 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.
- **Support risk reduction measures for poplar farmers** investing in short rotation coppice, e.g., by subsidising initial investments in the plantation.

7.2.5 Local community

- 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, 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.

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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)
CSTR	Continuous Stirred Tank Reactor
DoA	Description of the Action
EU	European Union
EUROSTAT	European Statistical Office
GA	Grant Agreement
GMO	Genetically modified organism
GTAP	Global Trade Analysis Project
HCl	Hydrogen chloride
ISO	International Organization for Standardization
ILCSA	Integrated life cycle sustainability assessment is a methodology for comprehensive sustainability assessment of products (see [Keller et al. 2015] for details) building on the LCSA principle
iLUC	indirect Land Use Change
LCA	Life cycle assessment
LMW	Low molecular weight
MRIO	Multiregional input/output
RO	Reverse Osmosis
S-LCA	Social life cycle assessment
SHDB	Social hotspots database
SWOT	Strengths, weaknesses, opportunities, threats
WIS	Water-insoluble
WP	Work Package

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