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This deliverable has been submitted to the European Commission but has not yet received formal approval.
As such, its contents are still subject to modifications based on the outcome of the review process.

D3.1 – MCDMA inventory and benchmark analysis

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Deliverable description

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WORK PACKAGE: **WP3 - Building methods for measuring industrial symbiosis and monitoring circularity by design across regional communities**
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Glossary of terms

ANRI	Alchemia-nova research & innovation gemeinnützige GmbH
ANTEJA	Anteja ECG D.O.O.
BABEG	Kärntner Betriebsansiedlungs- und Beteiligungsgesellschaft m.b.H.
CBE	Circular Bioeconomy
CF	Potential conflict with food
CP	Circularity potential
CRP	Cost reduction potential
CSL	Corn Steep Liquor
CMU	Cardiff Metropolitan University
EH	Enzymatic Hydrolysis
EIP	Ecosystem impact potential
FCTA	Fundación Corporación Tecnológica de Andalucía
GA	Grant Agreement
GRP	Greenhouse-gas reduction potential
HIC	High Impact Commodity
LGCA	Lombardy Green Chemistry Association
MADM	Multiple-Attribute Decision-Making
MC	Market competitiveness
MCDMA	Multi-Criteria Decision-Making Analysis
MFA	Material Flow Analysis
MODA	Multi-Objective Decision Analysis
PHA	Polyhydroxyalkanoate
PLA	Polylactic Acid
RR	Regional resilience
SAW	Simple Additive Weighting
SERN	Startup Europe Regions Network
SYMBIO	Shaping symbiosis in bio-based industrial ecosystems based on circular by-design supply chains

TDP	Technological diversification potential
TS	Total Score
VC	Value creation in the region
WP	Work package

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Executive summary

This Deliverable, **D3.1 – MCDMA Inventory and Benchmark Analysis** presents the first comprehensive benchmark of circular bio-based value chains ("BioLinks®") within the SYMBIO project. Building on the 47 pathways identified in WP2, a structured Multi-Criteria Decision-Making Analysis (MCDMA) was applied to prioritise those value chains with the highest ecological, economic, and social potential across six European pilot countries as part of Work Package 3 (WP3) and specifically Task 3.1. The objective was to generate a transparent, evidence-based selection of promising symbiotic business models for subsequent in-depth analysis and replication across the EU.

The MCDMA was grounded in nine sustainability criteria and informed by regional experts through a direct weighting process. Performance was assessed using the Simple Additive Weighting method, complemented by sensitivity analyses that confirmed strong robustness of the ranking even under ±10% and ±25% weight variations. To ensure real-world feasibility, the top-performing BioLinks® underwent a dedicated validation workshop. This step proved essential for aligning methodological results with practical, technological, and market considerations.

Fourteen high-ranking BioLinks® were considered during validation, from which two were excluded due to significant constraints: Molasses → Glycerol (market saturation, limited competitiveness) and Corn residues → PHA (energy intensity, unfavourable sustainability profile, competing technologies). This refinement underscores the value of combining quantitative evaluation with qualitative expert judgement.

The final six validated BioLinks® show strong reliance on secondary biomass streams, high circularity potential, and favourable replicability across regions:

- **Forestry residues → PHA** in *Croatia* and *Andalusia*
- **Whey → Proteins** in *Friuli Venezia Giulia* and *Wallonia*
- **Corn residues → Succinic acid** in *Piedmont*
- **Barley straw → Succinic acid** in *Veneto* and *Carinthia*
- **Wheat straw → PHA** in *Piedmont* and *Slovenia*
- **Corn steep liquor (CSL) → 1,3-Propanediol (PDO)** in *Flanders* and *Brussels*

Together, these pathways represent robust, resource-efficient, and regionally adaptable opportunities for circular bioeconomy deployment.

The outcomes of D3.1 provide the strategic backbone for subsequent SYMBIO tasks. In D3.2 – Resource flow scenarios and multicriteria overviews, the selected pathways will undergo Material Flow Analysis and show a mutli-criteria overview involving economic, ecological and social parameters. Together, these insights from Task 3.1 provide the foundation for WP4, where the economic, environmental, and social impacts of the selected value chains will be assessed using the Triple Layer Business Model Canvas. Deliverable 3.4 will address regulatory enablers along the full value chains including targeted policy-expert surveys. Through regional focus groups in Task 3.3, the validated BioLinks® will be further refined into implementable business models. As a result, the findings of WP3 establish a replicable and transparent framework to guide regional decision-makers in prioritising high-impact and scalable circular value chains across Europe.

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Context and Objectives

The SYMBIO project supports 12 European pilot regions in six countries (Italy, Spain, Belgium, Croatia, Austria, Slovenia) in identifying circular, bio-based business models enabled through industrial symbiosis and circular-by-design value chains. The core purpose is to equip European regions with tools to design and validate around ten high-profitability symbiotic business models that can be replicated across the EU. The project is structured across four phases, beginning with *data-hub building* in the 12 pilot regions, moving through *value chain design* to create "BioLinks®", then developing a robust *monitoring system* using MCDMA and Material Flow analysis (MFA), and finally performing a *Triple Layer Business Model Canvas* assessment to measure the economic, environmental, and social impacts. Ultimately, SYMBIO aims to overcome current barriers, strengthen supply chain resilience, and provide actionable policy and business recommendations to accelerate the green transition. The project brings together stakeholders from across the value chain to co-create and assess circular innovations tailored to regional potentials and challenges.

Work Package 3 - Building methods for measuring industrial symbiosis and monitoring circularity by design across regional communities, focuses on identifying and evaluating symbiotic bioeconomy value chains. Building on the BioLinks® defined in WP2 using VCG.AI, it applies a multi-criteria approach that involves environmental, social, and economic indicators to identify approximately ten most promising business models with high replication potential across Europe. Central to the SYMBIO methodology are multi-stakeholder focus groups, which collaboratively elaborate and discuss the proposed business models to uncover key enablers, barriers, and real-world implementation requirements. In parallel, regulatory and institutional frameworks are assessed to understand how current policies support or hinder the implementation of these models. The insights gained will directly inform the development of an industrial symbiosis handbook with an integrated reporting system, designed to support industrial stakeholders in adopting and monitoring circular bio-based business models across diverse regional contexts.

Task 3.1 - MCDMA and MFA analysis of industrial symbiosis business models, applies a MCDMA to evaluate 48 circular BioLinks® developed in WP2. By considering environmental, economic, and social criteria, the task identifies high-potential symbiotic business models. These are benchmarked for their implementation potential and replicability across Europe. Based on these results, MFA and Sankey Diagrams will be performed to visualize the circularity potential of the identified business models. These methodologies are considered for easy adoption by local stakeholders and allow for co-implementation in different industrial sectors, thus integrating fully into reporting standards. Ultimately, this will allow stakeholders to focus on the most cost-effective and impactful solutions.

The objective of this deliverable, **D3.1 – MCDMA Inventory and benchmarks analysis**, is to present a structured methodology for evaluating circular value chains and provide an initial benchmark of up to ten high-potential symbiotic business models. These benchmarks aim to support decision-makers and stakeholders in prioritising value chains with highest potential for systemic impact and EU-wide replication. The results from this deliverable serve as a key input for the MFA assessment (D3.2) and multi stakeholder focus groups in T3.3, and Work Package 4, dedicated to measuring the economic (D4.1), environmental (D4.2), and social (D4.3) impacts of the ten selected symbiotic business models.

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1. Introduction

1.1. Circular Bioeconomy

The Circular Bioeconomy (CBE) represents a vital and innovative concept that results from the synergy between the Circular Economy and Bioeconomy agendas. This forward-thinking approach is fundamental for integrating sustainable resource management with economic growth (1). The CBE aims to transform the current linear "take-make-waste" production system into one that reduces, recycles, recovers, reuses, and regenerates wastes, while actively seeking to substitute fossil fuels with biobased products and fuels (2). This strategy emphasizes sustainability and circularity, working to decouple economic growth from resource exhaustion and subsequent environmental degradation (3,4). As the biological motor of a future circular economy, the CBE is based on the optimal use of resources derived from renewably sourced feedstock (5).

The CBE is increasingly recognized for its crucial role in addressing pressing global sustainability challenges, such as climate change, biodiversity loss, and resource depletion. This integrated strategy simultaneously works to drive economic growth and enhance societal well-being (1).

Challenges facing the CBE:

Despite the clear benefits, the transition toward a CBE is hindered by several operational, economic, and institutional challenges:

- **Complexity and Optimization**: A major difficulty lies in moving beyond a purely techno-centric approach to sustainability, which may not be economically or socially viable. It is challenging the appropriate composition of technical innovations and systemic strategies to balance the economic costs of circularity with the societal benefits associated with avoided environmental impacts (2).
- **Market Barriers and Costs:** Market barriers reduce or block the economic viability of circular products, as competing petrochemical products often remain cheaper because environmental and social costs are external to prices. Producers may initially face high costs (including capital, labor, learning, and search costs), risks, uncertainties, and inconvenience when adopting circular technologies, leading to reluctance in implementation (2,6).
- **Feedstock Supply and Competition:** The biomass supply is often uncertain due to the inherent heterogeneity and seasonal nature of the raw and secondary materials, leading to unstable and geographically dispersed supply chains. Furthermore, when biomass is sourced from agriculture, the inevitable "food vs. non-food bio products" conflict must be addressed by bioeconomy strategies (3,5).
- **Regulatory Hurdles and Framework Gaps:** The application of CBE principles in bio-based products faces obstacles due to the absence of comprehensive legal frameworks and an adequate understanding of relevant indicators (1).
- **Consumer Engagement:** A fundamental challenge involves operationalizing circularity at the consumer level, where the majority of waste is generated and where end-of-life valorization pathways are largely absent (3).

Circular Biobased Business Models and Pathways

The successful transition from a linear economy to a CBE requires a combination of technological innovation, institutional reform, and new market strategies (2).

Strategic Economic Shift and Principles: A systemic, structural shift is necessary, moving away from reliance on economies of scale (which prioritize volume and efficiency) toward economies of scope, where multiple products are produced together, leading to multiple sources of income and lower overall costs. CBE requires adherence to five key ecological principles for circular biomass use:

- **Safeguard:** Utilizing natural resources at a rate that does not exceed their regenerative and absorptive capacity.
- **Avoid:** Addressing the use and production of non-essential bio-based products and preventing losses and waste of essential ones.
- **Prioritize:** Using biomass first for basic human needs (food, pharmaceuticals, clothes) and sectors without sustainable alternatives (like the chemical industry).
- **Recycle:** Ensuring nutrients and carbon from by-products are recycled back into the bio-based system.
- **Entropy:** Minimizing overall energy use and working toward reliance on renewable energy (6).

Technological and Value Chain Innovation: Technological advances are key drivers for the transition. Emerging technologies include digital precision farming, artificial intelligence, and synthetic biology applications for converting unavoidable wastes and perennial energy crops into plant-based proteins, bioproducts, and bioenergy (2). A central link for these new value chains is the **biorefinery**, defined as a facility that integrates biomass conversion processes to produce transportation biofuels, power, and chemicals from biomass. Biorefineries valorize secondary resources by transforming organic waste/residues into valuable products, facilitating a systematic transition to the bioeconomy (3,5).

Pathways for Market and Policy Transformation: To achieve a socially optimal degree of circularity in a market economy, government intervention is often needed in the form of incentives or regulations. The economic perspective identifies five critical pathways for transformation:

- **Technological Advances:** Public investment in research and development is crucial for making circular technologies commercially available and competitive.
- **Regulatory Incentives and Institutional Change:** This requires moving beyond voluntary conservation programs to **market-based policies** that price waste generation (e.g., carbon or nitrate taxes). Institutional changes, such as modifying crop insurance and loan guarantee programs, are needed to reduce the risk associated with circular production practices.
- **Markets for Circular Products:** Credible **certification of products and processes**, branding, and labeling are necessary to enable differentiated pricing and incentivize environmentally conscious consumers to pay a premium for sustainably produced goods.
- **Public Education and Awareness:** Educating consumers about the ecosystem services provided by CBE products can lead to changes in preferences and a higher willingness to pay, creating a strong "demand-pull" for circular products.

- **Equity Considerations:** Integrating equity into the transition process is crucial to mitigate adverse impacts on vulnerable groups, which may involve establishing compensation mechanisms, safety nets, and workforce re-skilling programs (2).

The conceptual framework of Value Chains (VCs) within the CBE describes the interconnected processes designed to generate products or services by adding value to biological raw materials or feedstock (3). The CBE itself is a strategic paradigm that integrates the goals of the traditional bioeconomy—the utilization of renewable biological resources—with the principles of the circular economy (5). This dual focus aims to decouple economic growth from resource exhaustion and environmental degradation, thereby closing the loop and establishing resource efficiency, often through the development of industrial symbiosis (3). Consequently, CBE VCs center on the transformation of biomass, including agricultural by-products/waste (secondary resources), into high-value bio-based products such as biochemicals and biopolymers (7). Due to the inherent complexity and multi-dimensional nature of sustainable and circular systems, methodologies like MCDMA are recognized as valuable tools for assessing VCs. The objective of MCDMA is to systematically analyze alternatives by weighing multiple, often conflicting, parameters across criteria pertaining to technical, economic, social, and environmental impacts (3,8).

1.2. Identification of SYMBIO's 47 BioLinks®

The MCDMA carried out within Work Package 3 (**WP3**) is directly based on the results of Work Package 2 (**WP2**). The objective of WP2, documented in **Deliverable 2.2 ("Circular value chains modelling") (9)**, was the systematic modeling and prioritization of potential industrial symbiosis solutions to create a solid selection basis for the more in-depth analysis in WP3.

A total of **47 priority circular value chains (BioLinks®)** were identified and defined across the 12 European pilot regions. These BioLinks® represent the most promising symbiotic models, linking the local availability of bio-based resources with market demand for high-value platform chemicals.

The modeling of these value chains relied on the extensive harmonized data collected through **Deliverable 1.2 ("Regional Data-Hub inventory and data map") (10)** in Work package 1 (WP1).

D1.2 provided the critical data foundation by mapping and assessing the regional ecosystems:

1. **Regional Biomass Availability:** A quantitative analysis of available **bio-based raw materials** was conducted across the pilot regions, focusing on both **primary biomass** (initial plant materials directly harvested) and **secondary biomass** (residues and by-products like maize stover, wheat straw, or molasses).
2. **Technologies and Products:** D1.2 identified the main conversion routes for **12 prioritized platform chemicals** (such as Lactic Acid, Glycerol, Polylactic Acid (PLA), and PHA). It also mapped the regional technologies and companies that could potentially perform these conversions, even considering technologies as 'adaptable' if they could theoretically convert the secondary biomass into final products.

Creation and Prioritization of the 47 BioLinks®

The **creation and prioritization** of the 47 BioLinks® (9) were performed using the digital tool **VCG.AI (Value Chain Generator)**, which leverages big data and artificial intelligence to analyze regional waste streams and resources to identify feasible circular business opportunities.

The decisions regarding the modeling and ranking of the Value Chains were based on a structured approach that explicitly incorporated **feedstock sources, technology readiness, and market potential**.

The key criteria considered for prioritization included:

1. **Top Biomass Flows:** Focusing initially on the most abundant secondary biomass flows in each region, based on their production volume (tonnes), ensured the analysis targeted the most significant resources.
2. **Technological Suitability:** Identified biomass flows were matched with the **12 prioritized platform chemicals** to define technologically plausible conversion routes.
3. **Economic Viability and Synergy:** Critically, the ranking assessed the **number of engaged stakeholders** along the supply chain. Value chains were ranked higher based on the perceived "overall involvement" across three categories:

    - **Feedstock Suppliers** (waste producers).
    - **Technology Providers** (process enablers and converters).
    - **Market Partners** (offtakers/buyers for the bio-based end product).

The **47 final BioLinks®** represent the value chains identified as priority solutions that demonstrated the highest potential across these criteria and feed into the MCDMA. This analysis aims to narrow the selection down to biobased value chains deemed most profitable and sustainable for further development and replication across the EU.

1.3. Multicriteria-Decision-Making-Analysis

MCDM often referred to in the literature as Multiple-Criteria Decision Analysis, Multi-Objective Decision Analysis (MODA), or Multiple-Attribute Decision-Making (MADM), is a systematic and versatile discipline with the aim to support decision-making processes in the selection of the best alternative from several potential candidates based on multiple, often conflicting, criteria or attributes (11,12). Unlike mono-criterion methods that assess a plan against a single objective (like economic efficiency in Cost-Benefit Analysis, CBA), MCDMA is an umbrella term encompassing various techniques that explicitly consider multiple dimensions of interest simultaneously. A decision problem typically arises when several feasible options exist, each associated with various impacts, requiring the decision-maker to balance these trade-offs and identify the most appropriate alternative. However, decision-making does not only entail identifying a single “best” option; it often involves prioritising a set of alternatives by integrating multiple individual preferences into a collective judgment (12). The speciality of MCDMA lies in its ability to enhance decision-making by providing a structured, comprehensive, and inclusive approach by integrating

not only multiple criteria across various sustainability dimensions, but also by including stakeholder perspectives (13).

The MCDMA process generally involves several foundational steps: identifying the decision objective, selecting the criteria by which alternatives are judged, generating alternatives, assigning weights to the criteria to reflect their relative importance, and selecting an appropriate MCDMA technique (such as TOPSIS or SAW to evaluate and rank the alternatives (3,7,8). These steps can be combined with participatory approaches, allowing stakeholders to actively contribute to the decision-making process (14).

MCDMA is exceptionally well-suited for prioritizing value chains within the CBE, a domain inherently defined by the need to balance multiple, often conflicting, sustainability objectives (15,16). The method systematically integrates the three core pillars of sustainability (economic, social, and environmental), frequently augmented by technical/technological criteria essential for evaluating innovation potential or process scale-up feasibility. This structured approach enables decision-makers to assess complex alternatives (such as bio-based products, raw materials, or symbiotic models) against highly relevant performance indicators, which often include factors like resource efficiency, feedstock variability, multi-sector application, and a variety of end-of-life options (7,17,18).

Considering the wide range of available biomass types, conversion technologies, and end products, the preliminary selection of biomass-to-product pathways with the highest potential represents a complex yet strategic step (19).

Within SYMBIO, the application of MCDMA provides a systematic framework to support the evaluation and ranking of regional biobased value chains (BioLinks®) across ecological, economic, and social criteria, ensuring that the most promising and regionally adaptable pathways are identified for further business model development. This holistic approach aims to provide a comprehensive assessment and to prevent incomplete conclusions that might arise from evaluating alternatives based on separate, isolated analyses of single categories (17).

2. Methodology

Within this Deliverable, the MCDMA supports the identification and prioritisation of the most promising symbiotic value chains (BioLinks®) for regional CBE development. The objective is to select approximately ten regionally specific business cases that are grounded in local biomass resources and industrial structures, and that show high potential for replication across the EU. This process also serves to establish a structured evaluation methodology, generate benchmark insights, and support stakeholders in prioritising the most impactful and scalable value chains across Europe.

The methodology builds on the BioLinks® previously identified in WP2 (9) and follows a structured, multi-step process combining expert knowledge, qualitative assessment, and evidence-based scoring. As visualised in the process overview (**Figure 1**), the MCDMA in SYMBIO involves the following components:

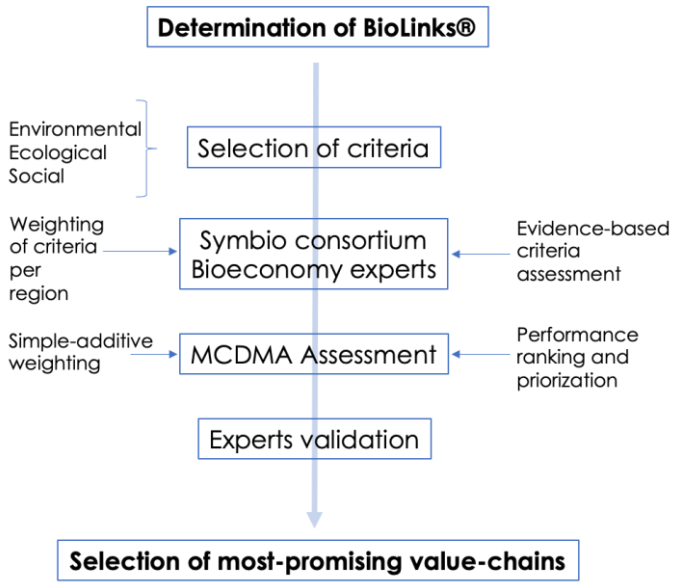

***Figure 1**: Workflow of the MCDMA process in SYMBIO for the selection of high-potential symbiotic value chains*

In MCDMA frameworks, **options** represent alternative courses of action (**in SYMBIO: the 47 BioLinks®**), and are evaluated against a set of **objectives** (e.g. economic, ecological, and social impact dimensions). These objectives are operationalised through **criteria**, which serve as measurable indicators to assess how well each option meets a specific objective. Each option's performance per criterion is captured by a **score**, typically on a normalised scale (e.g. 0 to 1), while each criterion is assigned a **weight** to reflect its relative importance in the decision-making context (eg. region-specific). The performance of an option in terms of the various criteria, to which different weightings can be assigned, is determined by scores. Formally speaking, a multi-criteria method defines the entirety of rules that determine the type of options, criteria, scores, and weightings, as well as the how they are used to evaluate, compare, select/eliminate, or rank options (20).

2.1. Criteria Identification

The identification of the evaluation criteria for the MCDMA followed a systematic and iterative process aimed to ensure that the selected criteria adequately capture the environmental, economic, and social dimensions relevant for the success of bio-based business models, while being adaptable across different regional contexts.

The criteria identification process began with monthly consortium meetings in which regional partners contributed input through a dedicated Excel template. In this template, each partner identified regionally relevant criteria. In parallel to this participatory process, a comprehensive desk-based literature review was conducted to identify additional indicators used for evaluating bio-based value chains. Combining these two sources of input resulted in a consolidated preliminary list of 28 criteria structured across the three sustainability dimensions: economic, ecological, and social.

Subsequently, this list was transformed into an excel based template, which was distributed among the partners LGCA, FCTA, and CMU that were selected as dimension-specific leads (see **Table 1**), for their evaluation. The selection followed the thematic leadership roles defined in the Description of Action (DoA) for the following impact analysis in WP4, ensuring their expertise within the assigned dimensions (see Chapter 2.3). In accordance with their roles, each partner reviewed all proposed criteria and was asked to select three most relevant criteria per dimension that they considered most relevant to assess the BioLinks® in order to enable an evaluation that supports the prioritization of those value chains with the highest potential for successful implementation and long-term sustainable impact in line with the core objective of SYMBIO.

These evaluations were consolidated and analysed by ANRI to identify overlaps and patterns of consensus. In this consolidation, particular attention was given to the degree of agreement among partners, with additional weighting given to the expertise of the dimension specific leads. The proposed final set of criteria was again reviewed in consultation with ANTEJA, whose expertise in the CBE supported the methodological validation and was finally approved by the expert partner for each dimension (see **Table 1**). This iterative consultation ensured that the final selection was both scientifically grounded and collectively endorsed.

Table 1 shows three criteria per dimension, a total of nine indicators, that were selected to form the analytical framework for the multicriteria decision making analysis, approved by all partners involved. They provide a comprehensive and balanced foundation for the evaluation and prioritisation of the BioLinks®, capturing key economic, environmental and social aspects relevant in the bio-based circular economy. A detailed description of each criterium and their individual assessment methods are explained within **Chapter 2.3**:

***Table 1**: Final set of MCDMA criteria and corresponding dimension-specific leads*

Impact dimension	Criterium	Dimension-specific lead
Economical	Cost reduction potential	FCTA
	Market competitiveness	

	Technological diversification potential	
Ecological	Greenhouse gas reduction potential	LGCA
	Circularity potential	
	Ecosystem impact potential	
Social	Regional resilience	CMU
	Value creation in the region	
	Potential conflict with food	

2.2. Criteria weighting

To determine the relative importance of the evaluation criteria in the SYMBIO MCDMA, a **Direct Assignment Technique (DAT)** was applied. This method, also referred to as **direct weighting** or **points allocation**, asks decision-makers to assign scores directly to criteria by distributing a fixed number of points (in this case, 100 points) across all attributes based on perceived relevance (21). The resulting scores are then normalised so that their sum equals one, as shown in **Equation 1**:

(1)

$$w_i = \frac{S_i}{\sum_j S_j}$$

In this equation:

- w_i is the **normalised weight** of criterion *i*,
- S_i is the **raw score** (points) assigned to criterion *i* by the respondent,
- $\sum_j Sj$ =100. The **sum of all scores** assigned across all *j* criteria by the same respondent equals 100.

This method was applied separately for each country (Italy, Spain, Austria, Slovenia, Croatia, Belgium) in order to account for regional differences in priorities, and implementation contexts. The weighting process followed a **two-step approach**:

1. **Weighting by regional project partners**:
   In a first round, project partners representing the six pilot countries were asked to allocate 100 points across the nine evaluation criteria using a standardised Excel matrix. The goal was to reflect regional specific knowledge and expertise within the consortium. Accordingly, the weighting inputs were provided by the partners responsible for each pilot region: LGCA for Italy, FCTA for Spain, BABEG for Austria, ANTEJA for Slovenia, STEEM for Croatia, and SERN for Belgium.

2. **Expert survey to broaden stakeholder input**:
   Additionally, an **online survey** was created for each pilot region using the OpinionX tool to systemically involve a borader range of local stakeholder. In these surveys, participants were asked to allocate 100 points across the predefined criteria (including their descriptions), following the same weighting logic applied by the regional project partners. The surveys were disseminated by the consortium partners to external stakeholders within their regional eco-system, thereby expanding the stakeholder input and enhancing the validity and robustness of the weighting process. ANRI screened all submissions, verified the correctness of the allocations, and included only those entries that adhered to the intended methodology. A limitation of the OpinionX tool was that the platform did not allow for technical restrictions to ensure that respondents could allocate a maximum of 100 points in total or assign a minimum of zero points per criterion. As a result, several submissions could not be used because they did not comply with the required scoring structure.

This approach was specifically chosen to address the complexity of the assessment, which involved multiple value chains across six different countries, each requiring a separate weighting of nine criteria. To manage this multidimensional decision space without overburdening participants, a simple and transparent method was selected. DAT offered the advantages of low cognitive effort, ease of replication, and clarity in interpretation (22).

Importantly, the method was chosen with the understanding that the MCDMA in SYMBIO does not aim to make binding or high-stakes decisions. Instead, it serves to **identify high-potential business models**, which will be further analysed and discussed in subsequent phases in which the purpose is to uncover regional barriers and enablers, inform policy recommendations, and support stakeholders in making informed strategic decisions. In this context, a straightforward and participatory method such as direct weighting was considered both sufficient and appropriate.

2.3. MCDMA assessment

To rank the 47 BioLinks® identified in WP2, we applied the **SAW** method—one of the most widely used and transparent approaches within the family of MCDMA (8,11,23). SAW is considered a simple and straightforward technique, particularly suitable for decision-making contexts with limited complexity. Its core principle involves multiplying the normalised score of each alternative by the respective criterion weight. The weighted scores are then summed across all criteria, yielding an aggregate score for each alternative, which can subsequently be ranked in descending order of preference. The method is described in Equation 2, where w_i stands for the normalized weight of criterion *i* and $s_{ij}$is the normalised score of BioLink® *j* under criterion *i*.

(2)

$$Total\ Score\ (TS)_j = \sum_{i=1}^{n} w_i s_{ij}$$

When the aim is to integrate different types of information into a unified ranking, SAW can only be utilized by converting heterogeneous data into a common quantitative scale (15). In line with approaches described in Äkräs et al. (2022), the scoring procedure in SYMBIO was designed to combine qualitative, semi-quantitative, and quantitative evidence derived from literature research, desk research, and project data from WP1 and WP2 by using a specific scaling technique. In this project, a **scaling technique** was applied that builds on the approach used in Äkräs et al. (2022)(8). In contrast to the binary or three-point scales frequently used in simplified MCDA applications, SYMBIO employed a **0–10 interval scale**, allowing for more fine-grained scoring of alternatives (20). This broader interval was deliberately chosen to **capture nuanced differences in performance across BioLinks®**, particularly in qualitative criteria where absolute thresholds are not easily defined. Each BioLink® was evaluated along all nine criteria using this scale, where 0 represented the lowest and 10 the highest performance within a given criterion. The resulting raw scores were subsequently **normalised to a 0–1 scale** to ensure compatibility with the SAW aggregation method.

This approach was deliberately chosen to ensure that each score was not merely based on expert judgement but additionally grounded in verifiable project data and sound scientific or technical justification. The complete MCDMA scoring matrix is found in **Annex 1**. The scoring process was designed to reduce subjectivity, especially given the relatively limited number of external stakeholders involved during this phase. In general, subjectivity is intrinsic in all decision making and MCDA does not dissolve subjectivity, but it makes the whole process transparent, where subjective judgements are considered (12).

The assessment was conducted by selected **Subject Matter Experts (SMEs)** (24) from within the SYMBIO consortium:

- **LGCA** evaluated the environmental criteria,
- **FCTA** assessed the economic dimension, and
- **CMU** was responsible for scoring the social indicators.

This division followed the thematic leadership roles defined in the Description of Action (DoA), ensuring that each criterion was assessed by the most qualified partner. In addition, the criteria themselves had been co-developed and reviewed through a structured process (see **Chapter 2.1**), which further contributed to the reliability and coherence of the scoring process.

The detailed assessment methodology applied for each impact area (economic, environmental, and social) by the responsible partners is further described in the following chapters.

2.3.1. Economic criteria

The economic criteria within the SYMBIO MCDMA framework are designed to evaluate the financial viability and market potential of bio-based value chains. Three core criteria – **cost reduction potential, market competitiveness, and technological diversification potential**—were selected through a rigorous literature review and partner consultation process. Each criterion is assessed using both qualitative and quantitative, evidence-based scoring approach and weighted according to regional priorities, ensuring that the evaluation reflects both scientific rigor and stakeholder perspectives.

Cost Reduction Potential

This criterion measures the ability of the BioLink® to minimise production costs through efficient resource use and process optimisation. High-cost reduction potential is crucial for enhancing the economic attractiveness of CBE solutions, particularly in markets where conventional petrochemical products remain price-competitive. It considers:

- Raw materials: utilization of low-cost feedstocks such as agricultural residues or industrial by-products.
- Process efficiency improvements: energy integration and reduced water or chemical consumption.
- Lower pretreatment requirements and overall operational savings.

Each criterion is scored on a scale from 0 (lowest) to 10 (highest) based on evidence from project data, literature, and expert judgment. Points were allocated based on the presence of cost-reducing factors. Each positive factor contributes 2.5 points, leading to a maximum of 10.

- The process uses less water
- The process requires fewer reagents
- The process uses less energy
- The process requires less equipment

Market Competitiveness

Market competitiveness evaluates the capacity of a BioLink® to succeed in existing or emerging markets. This criterion reflects the importance of aligning bio-based products with market trends, consumer preferences, and policy frameworks to ensure commercial viability and long-term sustainability. It includes:

- Demand for bio-based products and alignment with market trends.
- Price competitiveness compared to conventional alternatives.
- Supply chain robustness and scalability.
- Regulatory incentives and policy support.

Each criterion is scored on a scale from 0 (lowest) to 10 (highest) based on evidence from project data, literature, and expert judgment. The scoring logic was established as:

- 0 = The final product is not competitive in the market, facing only disadvantages.
- 5 = Moderate competitiveness, with some advantages.
- 10 = Strong market attractiveness and clear competitive advantage.

With the possibility to use intermediate scoring.

Technological Diversification Potential

This criterion evaluates the potential of a BioLink® to produce multiple products, thereby fostering innovation and resilience. Technological diversification enhances the ability of business models to respond to changing market conditions and supports the development of integrated biorefinery concepts. It considers:

- Ability to generate co-products (e.g., PHA, lactic acid, succinic acid).
- Adaptability of technology to various biomass sources.
- Potential for innovation and integration into biorefinery concepts.

For the assessment of this criterion, the total number of products that could be obtained through a cascade approach was identified.

The scoring logic was defined as:

- 10 points were allocated to the BioLink® with the highest number of products
- 1 point for the one with the minimum number of products
- For the other BioLinks®, the score was interpolated.

2.3.2. Ecologic criteria

The ecological evaluation was structured around the **three core dimensions** (Greenhouse-Gas reduction potential (GRP), Circularity potential (CP), and Ecosystem impact potential (EIP)) each representing a key aspect of environmental performance within bio-based value chains. Each dimension was further disaggregated into three sub-axes designed to capture the main drivers influencing ecological outcomes. The assessment followed a qualitative approach, supported by quantitative references and expert-based reasoning, allowing for a comprehensive yet consistent evaluation across the 47 BioLinks®.

Scale and Scoring Logic

Each BioLink® was assessed across the three ecological core dimensions (GRP, CP and EIP), composed of its three sub-axes. Every sub-axis was individually evaluated according to defined qualitative criteria, and the resulting three sub-scores were averaged to obtain a single composite score representing the overall performance of that dimension. This approach ensures that each dimension's score reflects a balanced consideration of all relevant ecological aspects while minimising bias toward any single factor.

All ecological criteria core dimension were evaluated using a **qualitative 0–10 scale**, where the score reflects the relative environmental performance of each BioLink® within its category. The scale was designed as follows:

- **0** = low ecological performance or poor alignment with sustainability principles,

- **5** = moderate performance, representing partial alignment or mixed ecological outcomes,
- And **10** = high ecological performance or strong alignment with sustainability objectives.

Although qualitative in nature, the scoring was anchored in data-based thresholds, literature evidence, and expert interpretation of bio-based process characteristics. Each of the three ecological dimensions was scored according to its specific sub-axes as described below.

Greenhouse-gas reduction potential

The GRP dimension assessed the ability of each BioLink® to reduce greenhouse gas emissions in comparison with conventional fossil-based or incumbent value chains. Three sub-axes were considered:

1. ***Country Energy Mix***

Country Energy Mix accounted for the share of renewable electricity in the regional grid, which directly affects life-cycle emissions of bio-based processes. This aspect was quantified using Eurostat data on national renewable energy shares, ensuring consistency and comparability across regions.

The scoring logic was defined as:

- 10 = High renewable share (>40%).
- 5 = Medium renewable share (20–40%).
- 3 = Low renewable share (<20%).

Data from was used to define the score per country.

Table 2: *Share from renewables per country in % and MCDA score used in ecological impact assessment.*

Country	Share from renewables (%)	Score
Austria	40,8	10
Croatia	28,1	5
Slovenia	25,1	5
Spain	24,8	5
Italy	19,6	3
Belgium	14,7	3

2. ***Process Complexity***

Process Complexity reflected the relationship between processing intensity and energy demand: mild, biological conversions such as enzymatic hydrolysis and fermentation were associated with lower emissions due to their moderate temperature and pH conditions, whereas chemical-intensive processes

like acid hydrolysis or solvent-thermal conversions typically operated under harsher conditions (>120 °C, strong acids or solvents) and entailed higher energy consumption (25).

The scoring logic was defined as:

- 10 = Single-step mild (fermentation, membrane separation).
- 7 = Two-step mild (enzymatic hydrolysis + fermentation, enzymatic hydrolysis + saponification).
- 5 = Mixed mild + chemical (fermentation + polymerization; EH + transesterification).
- 3 = Chemical-intensive (acid hydrolysis, catalytic hydrogenation, solvent–thermal).

3. *Feedstock Type*

Feedstock Type captured the effect of raw material origin on the emission profile. By-products and residues generally avoid upstream agricultural burdens, while dedicated crops carry additional emissions from cultivation and harvesting (26).

The scoring logic was defined as:

- 10 = By-product/residue (e.g. whey, molasses, straw, sawdust).
- 3 = Dedicated primary crop (e.g. corn, sugar beet, soybean, rapeseed).

Circularity potential

The CP dimension evaluated how effectively a BioLink® aligns with circular economy principles by considering feedstock sourcing, supply stability, and valorisation of side-streams:

1. *Feedstock Type and Pretreatment Requirement*

Feedstock Type and Pretreatment Requirement examined whether the feedstock originated from by-products or residues, which enhance circularity, and whether it requires energy-intensive pretreatment. The classification reflects established understanding of feedstock characteristics and processing intensity as described in bio-based conversion and LCA literature: feedstocks like molasses, which can be directly fermented without pretreatment, were seen as highly circular, while lignocellulosic materials such as straws or forestry residues require more extensive conversion steps. Animal fats and other livestock-derived by-products were recognised for their potential in circular systems, yet their link to high-impact livestock agricultural activities is associated with high greenhouse gas emissions, land use, water use, and biodiversity impacts. This evaluation synthesised multiple publicly available sources (including internal deliverables from the SYMBIO project) together with domain expertise on biorefinery approaches to ensure representativeness and methodological robustness.

The scoring logic was defined as:

- 10 = By-product/residue with little or no pretreatment (molasses).
- 7 = By-product/residue requiring pretreatment (lignocellulosic straws, forestry residues).
- 5 = Animal fats and by-products.
- 3 = Dedicated primary crop (sugar beet, corn).

2. *Seasonality Management*

Seasonality Management considered the temporal availability of feedstocks, acknowledging that seasonal or weather-dependent materials require additional strategies, such as storage or blending, to maintain year-round operations. The evaluation was informed by general agronomic data and technical knowledge on the cropping cycles and harvesting periods of the main European feedstocks considered in the assessment, complemented by expert judgment regarding their practical implications for year-round supply and storage requirements.

The scoring logic was defined as:

- 8 = Steady or year-round supply (whey, molasses, CSL, sawdust, animal fats, soybean meal, rapeseed oil).
- 5 = Seasonal (straws, sugar beet, corn residues, alfalfa fiber, forestry residues which are not always continuous and can be weather-dependent).

3. *Valorisable Process Side-Streams and By-Products*

Valorisable Process Side-Streams and By-Products evaluated the extent to which process residues could be reintegrated into other value chains or converted into secondary products, thereby enhancing resource efficiency and minimizing waste (26).

The scoring logic was defined as:

- 8 = Easily valorisable by-products that can contribute to the creation of new value chains (e.g. lignin for energy from fractionation of lignocellulosic biomasses).
- 5 = Neutral, by-products that don't have potential to create new value chains (e.g. wastewater from fermentative processes that can be manageable but not value-adding).
- 3 = Problematic side-streams and by-products (e.g. acidic effluents, heavy metals).

Ecosystem impact potential

The EIP dimension captured broader ecological risks beyond greenhouse gas emissions, encompassing effects on land use, water systems, toxicity, and biodiversity. This dimension considered the following sub-axes:

1. *Process Complexity*

Process Complexity paralleled that of the GHG dimension, as simpler, biologically based processes were deemed less ecologically disruptive than multi-step or chemical-intensive operations (25).

This axis is aligned with GHG scoring for consistency. The scoring logic was defined as:

- 10 = Single-step mild (fermentation, membrane separation).
- 7 = Two-step mild (enzymatic hydrolysis + fermentation, enzymatic hydrolysis + saponification).
- 5 = Mixed mild + chemical (fermentation + polymerization; EH + transesterification).
- 3 = Chemical-intensive (acid hydrolysis, catalytic hydrogenation, solvent–thermal).

2. *Chemical Input Requirements*

Chemical Input Requirements assessed the type and quantity of chemical substances involved in the process, recognising that minimal use of benign agents such as enzymes and buffers poses lower ecological risks than processes dependent on strong acids, solvents, or heavy metals, which may introduce toxicity and effluent burdens.

The scoring logic was defined as:

- 8 = Minimal (enzymes, nutrients, buffers, water).
- 5 = Moderate (solvents, neutralization agents).
- 3 = High (strong acids, heavy metals).

3. *Feedstock Type and Commodity Classification*

Feedstock Type and Commodity Classification evaluated the ecological implications of the feedstock's origin, with particular attention to its association with high-impact or conversion-driving commodities as identified by the Science Based Targets for Nature (SBTN) High-Impact Commodity list. By-products derived from low-impact sources were rated most favourably, while dedicated crops linked to high-impact commodities (such as corn, soy, or sugar beet) were considered to have higher ecological risk profiles due to their land and resource intensity.

This sub-axis is based on the SBTN High Impact Commodity (HIC) List. The scoring logic was defined as:

- 10 = By-product/residue, not tied to high-impact commodities (barley straw, alfalfa fiber).

- 5 = By-product/residue from a high-impact commodity (e.g. sugar beet pulp, molasses, soybean meal, rice straw, poplar sawdust, forestry residues).
- 3 = Dedicated crop or feedstock in high-impact commodity list (corn, rice, wheat, sugar beet, rapeseed, soybean, timber, dairy and animal products).

2.3.3. Social criteria

Three social criteria were selected for study in the MDCMA: regional resilience; value creation in the region; and potential conflict with food. Each BioLink® was assessed against the three criteria using a qualitative 0 - 10 interval scale.

Regional resilience

Regional resilience is defined as *"the extent to which the BioLink® strengthens the regional economy's ability to withstand external shocks such as supply chain disruptions, price volatility or global market dependence"*. Factors identified as influencing the regional resilience of the BioLinks® included: The resilience of the feedstock to climate change (27); market trends and predictions for feedstock and end-product (28) existing farming practices and regional value chains dependent on the feedstock (29,30); the extent to which the value chain currently exists within the region; and the strength of the regional innovation ecosystem, including policy, funding, education and research commitment (31).

The interval scale for regional resilience spanned the following range:

- 0 = BioLink® increases dependency on external markets / value chains
- 5 = Partial resilience - dependencies exist
- 10 = Very resilient to external shocks due to high local anchoring

Value creation in the region

Value creation in the region is defined as "*the degree to which the BioLink® generates socio-economic value locally, including job creation with living wage, SME involvement, local processing and the retention of value added in the region"*. Factors identified as influencing value creation in the region include: Average, size, organisational structure and salaries of businesses similar to those in the BioLink®, based on profiles developed in Symbio Deliverables 1.1 and 2.2; the extent to which the value chain currently exists in the region as demonstrated in Symbio Deliverable 2.2; regional economic policy, including provision for minimum and living wage (32); strength of the regional innovation ecosystem (33), and the existence of collective bargaining organisations (32).

The interval scale for value creation in the region spanned the following range:

- 0 = No value added to the region
- 5 = Moderate - some local jobs or services/products added
- 10 = Strong local processing, jobs, reinvestment, SME involvement, local market demand.

Potential conflict with food

Potential conflict with food is defined to "*the extent to which the biomass feedstock used in the BioLink® competes with food or feed production*". Factors identified as influencing the potential conflict with food include: existing end uses for the feedstock (34); and regional land-use trends (35,36).

The interval scale for potential conflict with food spanned the following range:

- 0 = Biomass is a primary crop used for food or feed
- 5 = Biomass is a co-product or by-product of a food/ feed system
- 10 = Biomass is an unused residual or waste stream with high utilisation potential and no direct food/ feed competition.

2.4. Sensitivity analysis

To assess the robustness of the MCDMA, a sensitivity analysis was carried out by systematically varying each criterion's weight by ±10 % and ±25 %, while proportionally adjusting the remaining criteria to maintain a total weight of 1. To ensure regional consistency, the country-specific weightings were matched to the corresponding regional BioLinks®. The ±10 % variation represents a moderate uncertainty range, whereas the ±25 % variation was included to capture potential deviations stemming from the relatively small number of expert assessments available per country (7). This dual-step approach allows both the stability of the model and its responsiveness to more substantial weight fluctuations to be examined. The analysis was performed in Python (version 3.14.0 using automated scripts developed specifically for this project).

Overall, this Deliverable establishes a replicable and transparent framework to guide regional decision-makers in prioritising high-impact and scalable circular value chains across Europe.

2.5. Validation Workshop

A validation workshop with selected experts from the CBE domain was designed and facilitated by ANRI to review the procedure and results of the MCDMA and to minimise methodological bias in the prioritisation of high-potential bio-based value chains (37). The three-hour session, moderated by ANRI, was conducted online via Microsoft Teams and supported by transparently structured workshop materials prepared in MIRO, an online collaborative whiteboard platform enabling synchronous, structured input. Participants included representatives from CTA, LGCA, and CMU – as SMEs each responsible for one assessment dimension of the MCDMA - the advisory board from the project, as well as 17 additional

external experts in bioeconomy providing independent perspectives. External experts were invited directly via the project consortium's network, actively also involving SYMBIOs sister project SIMBA.

The workshop followed a structured agenda consisting of three steps. First, ANRI introduced the project and workshop objectives and presented the MCDMA methodology, including criteria selection, as well as weighting and scoring procedures. CTA, LGCA, and CMU each briefly outlined the methodological procedures and underlying rationales applied in the economic, ecological, and social dimensions. Second, the MCDMA results, which yielded in top 14 regional BioLinks®, and 8 high-promising value chains (see **Chapter 3.2**), were presented. Third, participants engaged in a 105-minute validation exercise using MIRO, where they reviewed each value chain, commented on the justification tables (see **Chapter 3.3**) using colour-coded digital sticky notes (agreement, disagreement, or additional input), completed an integrated poll (yes or no) on the suitability of each value chain for developing a high-value, replicable business model, and subsequently provided brief written rationales for their votes using additional sticky notes.

All inputs, including the poll outcomes, were documented directly on the MIRO board (see **Annex 2**) to ensure full traceability for subsequent analysis. To comply with data protection requirements, all individual responses and identifying information were anonymised before inclusion in this Deliverable.

3. Results and Discussion

This chapter presents and discusses the main outcomes of the assessment, beginning with the aggregated results of the criteria weighting, followed by the ranked performance of all BioLinks® and the selection of the most promising value chains to be further elaborated into replicable business models.

3.1. Criteria Weighting

The weighting of the nine evaluation criteria represents a key step in the MCDMA process, as it determines the relative importance of each sustainability dimension in assessing and ranking the BioLinks®. The weighting was conducted using DAT, as described in **Chapter 2.2**, and was applied separately for each SYMBIO pilot country (Italy, Spain, Austria, Slovenia, Croatia, and Belgium). This ensured that regional priorities and contextual differences were reflected in the assessment.

A total of 35 experts participated in the weighting process. Each respondent was asked to distribute 100 points across the nine evaluation criteria. The resulting raw weights were normalised to a scale from 0 to 1 to ensure comparability across countries. **Table 3** presents the averaged, normalised weights per country, together with the number of stakeholders involved in each case. The stakeholders participating in the validation workshop represented a diverse mix of expertise across the CBE, including biotechnology, bioprocessing, sustainability, circular economy, food and energy systems, funding and project management.

Table 3: *Criteria weights per country and number of experts involved. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP –*

circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.

Country	CRP	MC	TDP	GRP	CP	EIP	RR	VC	CF	Sum	Local Stakeholders involved
Croatia	0,12	0,12	0,08	0,13	0,12	0,12	0,11	0,12	0,08	1	8
Slovenia	0,10	0,13	0,13	0,13	0,13	0,11	0,08	0,12	0,07	1	5
Austria	0,10	0,11	0,09	0,15	0,14	0,13	0,12	0,12	0,04	1	5
Italy	0,11	0,08	0,10	0,16	0,12	0,14	0,08	0,13	0,09	1	6
Spain	0,17	0,18	0,13	0,10	0,11	0,07	0,09	0,10	0,08	1	4
Belgium	0,13	0,11	0,10	0,10	0,16	0,10	0,13	0,12	0,06	1	7

The number of respondents per country ranged from **four in Spain** to **eight in Croatia**, with most countries represented by five to seven experts. While this distribution allowed for comparability between regions, the overall number of expert inputs per country remained relatively limited. Despite several rounds of invitations to local stakeholders to participate in the online survey, circulated through the partners' networks, the number of completed responses remained modest. As a result, the weighting outcomes should be interpreted as indicative rather than statistically representative. Nevertheless, they provide valuable insights into regional tendencies and reflect the informed perspectives of experts directly involved in bio-based value chain development across the SYMBIO pilot regions.

Across all regions, **GRP** and **CP** appear consistently among the higher-weighted criteria, confirming that ecological performance was generally considered important. **GRP** received its highest weights in **Italy (0.16)** and **Austria (0.15)**, indicating that these countries attached particular importance to emission reduction. In contrast, **Spain** and **Belgium** assigned only **0.10** to GRP, which is among its lowest scores, showing a relative prioritisation of economic over environmental factors.

The **economic dimension** shows more variation. **Spain** stands out with clearly dominant weights for **cost reduction potential (CRP)** and **market competitiveness (MC)** (0.17 and 0.18), which are the two highest single values in the entire table. This pattern highlights a strong economic orientation in the Spanish weighting profile. A similar, though less pronounced, trend is visible in **Belgium**, where **CP (0.16)** and **CRP (0.13)** received the highest attention, reflecting a balanced interest in circularity and cost efficiency. In contrast, **Italy** and **Austria** show a more distributed weighting across ecological and economic criteria, suggesting a less pronounced focus on short-term market competitiveness.

Croatia exhibits the most even distribution across all criteria, with weights fluctuating only between **0.08 and 0.13**. This uniformity indicates that no single sustainability dimension was strongly dominant. A similar but slightly more differentiated picture is visible in **Slovenia**, where **market competitiveness (0.13)**, **technological diversification potential (0.13)**, and **greenhouse gas reduction potential (0.13) and circularity potential (0.13)** share equal importance, suggesting a balanced approach that values both economic and environmental impact.

The **social criteria**—**regional resilience (RR)**, **value creation (VC)**, and **conflict with food (CF)**—generally received lower weights across all regions. **RR** and **VC** mostly range between **0.08 and 0.13**, while **CF** consistently ranks lowest, between **0.04 and 0.09**. The lowest weight overall (**0.04**) was assigned to **CF in Austria**, while the highest for social indicators (**0.13**) appears in **Belgium (RR)**, showing some variation but confirming that social aspects were generally considered less decisive compared to ecological and economic factors.

In summary, the weighting results demonstrate a shared emphasis on environmental performance, particularly on circularity and emission reduction, alongside notable national differences in economic focus. Spain places the strongest emphasis on market-related aspects, whereas Italy and Austria prioritise environmental criteria. Croatia and Slovenia follow a more balanced approach, and Belgium shows a dual focus on circularity and social resilience. This diversity of priorities underscores the relevance of region-specific conditions and perceptions in shaping the evaluation of bio-based value chains.

Building on the established weighting profiles, the subsequent MCDMA assessment applied these normalised criteria weights to evaluate the performance of the identified BioLinks® across all SYMBIO pilot regions. By integrating the regional weightings with the qualitative assessment scores provided by the respective domain experts, the analysis produced a comprehensive ranking of BioLinks® reflecting their overall sustainability potential.

3.2. MCDMA Assessment

Table 4 presents the overall ranking of the BioLinks® derived from the application of the MCDMA. Each BioLink® received a final Total Score (TS) resulting from the weighted aggregation of its performance across the nine criteria, taking into account the region-specific weighting profiles described in the previous section. The table displays the BioLinks® in descending order according to their TS, alongside their respective regions. This ranking provides a consolidated overview of how the different value chains perform relative to each other across economic, ecological, and social dimensions, highlighting those with the highest overall potential for further development within SYMBIO.

The statistical distribution of the total MCDMA scores (Min = 43.14, Max = 68.33, Average = 56.17, Median = 55.3) indicates that the majority of BioLinks® cluster around the mid-range performance level. The third quartile (Q3 = 62.9) marks the threshold above which the top 25% of all BioLinks® are located. According to this quantile-based classification, BioLinks® with scores higher than approximately 63.6% can be considered as the top-performing group. However, for the subsequent selection of BioLinks® to be further developed into SYMBIO business models, we deliberately extended the inclusion threshold slightly below this quartile to encompass all BioLinks® with a TS above 61%. This broader range (top 14) still represents the upper performance segment, while ensuring to represent all SYMBIO pilot countries.

Based on this procedure, we identified eight high-potential value chains (**Table 5**) where some of them are represented multiple times within the top-performing BioLinks® and thus demonstrate both a high performance and replication potential across the SYMBIO regions. The detailed assessment matrices containing the individual scores, justifications, and literature references used by the responsible partners during the evaluation process are provided in **Annex 2** for full transparency and traceability of the MCDMA results.

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Table 4: *Results of the MCDMA: ranked BioLinks® across SYMBIO pilot regions*

Rank	Region		Feedstock(s)	Product	Key Technology Steps	Total Score
1	**Spain**	Andalusia	Forestry Residues	PHA	Enzymatic Hydrolysis (EH) + Fermentation	**68,33**
2	**Belgium**	Brussels Capital	CSL	1,3-Propanediol	Fermentation	**67,31**
3	**Belgium**	Brussels Capital	Molasses	Glycerol	Fermentation	**66,78**
4	**Belgium**	Wallonia	CSL	1,3-Propanediol	Fermentation	**65,63**
5	**Croatia**	Croatia	Corn Stover; Forestry Residues	PHA	EH + Fermentation	**65,56**
6	**Italy**	Emilia Romagna	Wheat Straw	PHA	EH + Fermentation	**65,52**
7	**Italy**	Piedmont	Corn Residues	Succinic Acid	EH + Fermentation	**64,65**
8	**Italy**	Friuli Venezia Giulia	Whey	Proteins	Ultrafiltration / Membrane Separation	**63,87**
9	**Austria**	Carinthia	Barley Straw	Succinic Acid	EH + Fermentation	**63,69**
10	**Italy**	Piedmont	Corn Residues (Stover & Straw)	PHA	EH + Fermentation	**63,32**
11	**Belgium**	Brussels Capital	Whey	Proteins	Membrane Separation (e.g., ultrafiltration)	**63,32**
12	**Italy**	Friuli Venezia Giulia	Barley Straw	Succinic Acid	EH + Fermentation	**63,11**
13	**Italy**	Lombardy	Corn Residues	PHA	EH + Fermentation	**62,82**
14	**Slovenia**	Slovenia	Wheat Straw	PHA	EH + Fermentation	**62,41**
15	**Austria**	Carinthia	Corn	PHA	EH + Fermentation	**60,29**

16	**Croatia**	Croatia	Corn	PLA	Fermentation + Condensation + Polymerization	**60,04**
17	**Belgium**	Brussels Capital	Corn Stover	Succinic Acid	EH + Fermentation	**59,48**
18	**Austria**	Carinthia	Forestry Residues & Maize Cobs	Furfural	Acid Hydrolysis or Catalytic Systems or Solvent–Thermal Conversion	**57,91**
19	**Italy**	Veneto	Corn Residues	Acetic Acid	EH + Fermentation	**57,90**
20	**Belgium**	Flanders	Wheat Straw	Acetic Acid	Fermentation	**57,09**
21	**Spain**	Andalusia	Rice Straw	Sorbitol	(a) EH + Fermentation, or (b) Catalytic Hydrogenation	**56,73**
22	**Slovenia**	Slovenia	Barley Straw	Succinic Acid	EH + Fermentation	**55,90**
23	**Belgium**	Flanders	Wheat Straw	Succinic Acid	EH + Fermentation	**55,68**
24	**Italy**	Lombardy	Alfalfa Fiber	Lactic Acid	EH + Fermentation	**55,33**
25	**Italy**	Emilia Romagna	Wheat Straw	Succinic Acid	Fermentation	**55,26**
26	**Slovenia**	Slovenia	Forestry Residues	Furfural	Acid Hydrolysis or Catalytic Systems or Solvent–Thermal Conversion	**54,58**
27	**Italy**	Veneto	Poplar Sawdust	Acetic Acid	EH + Fermentation	**54,39**
28	**Belgium**	Wallonia	Sugarbeet	Glycerol	EH + Fermentation	**54,38**
29	**Belgium**	Wallonia	Sugarbeet	Glycerol	EH + Fermentation	**54,29**
30	**Spain**	Andalusia	Barley Straw	Acetic Acid	EH + Fermentation	**54,10**
31	**Italy**	Friuli Venezia Giulia	Alfalfa Fiber	Lactic Acid	EH + Fermentation	**54,01**
32	**Belgium**	Flanders	Wheat Straw	Lysine	Fermentation	**53,41**

33	**Austria**	Carinthia	Soybean Meal	Glycerol	EH + Transesterification	**51,55**
34	**Italy**	Veneto	Alfalfa Fiber	Lactic Acid	EH + Fermentation	**50,71**
35	**Italy**	Lombardy	Rice Straw / Husks	Furfural	Acid Hydrolysis or Catalytic Systems or Solvent–Thermal Conversion	**50,62**
36	**Belgium**	Brussels Capital	Sugarbeet	PLA	Fermentation + Condensation + Polymerization	**49,81**
37	**Italy**	Emilia Romagna	Alfalfa Fiber	Lactic Acid	EH + Fermentation	**49,39**
38	**Croatia**	Croatia	Forestry Residues; Maize Cobs; Corn Stalks & Cobs	Furfural	Acid Hydrolysis or Catalytic Systems or Solvent–Thermal Conversion	**49,37**
39	**Italy**	Piedmont	Corn Residues	1,3-Propanediol	EH + Fermentation	**49,31**
40	**Belgium**	Flanders	Sugarbeet	Glycerol		**49,31**
41	**Spain**	Andalusia	Sugarbeet	Glycerol	EH + Fermentation	**49,06**
42	**Croatia**	Croatia	Corn	Glycerol	EH + Fermentation	**49,01**
43	**Italy**	Piedmont	Corn Residues (Stover & Cobs)	Furfural	Acid Hydrolysis or Catalytic Systems or Solvent–Thermal Conversion	**48,34**
44	**Italy**	Emilia Romagna	Rapeseed	Glycerol	EH + Saponification + Transesterification	**48,32**
45	**Italy**	Friuli Venezia Giulia	Rice Straw	Sorbitol	Catalytic Transfer Hydrogenation or EH + Fermentation	**48,25**
46	**Slovenia**	Slovenia	Animal Fats	Glycerol	EH / Saponification	**47,51**
47	**Italy**	Veneto	Oil Crops: Soybean	Glycerol	EH / Saponification / Transesterification	**45,48**

48	**Italy**	Lombardy	Sugarbeet	PLA	Fermentation + Condensation + Polymerization	**43,14**

To provide a more strategic overview, the 14 highest-scoring BioLinks® were consolidated into eight distinct value chains. This aggregation was carried out to account for overlaps where similar biomass-to-product pathways appeared across different regions. By grouping these BioLinks® under common technological and feedstock pathways, the analysis enabled a clearer identification of the value chains that combine both high performance and strong replication potential across multiple SYMBIO regions. The following table summarises these top-ranked value chains:

Table 5: *Consolidated list of top-ranked value chains derived from the 14 highest-scoring BioLinks®*

Top ranked value chains	
Forestry Residues	PHA
Corn Steep Liquor	1,3-Propanediol
Molasses	Glycerol
Corn residues	PHA
Wheat straw	PHA
Corn residues	Succinic Acid
Whey	Proteins
Barley Straw	Succinic Acid

These eight top-ranked value chains identified through the MCDMA formed the basis for the discussions held during the SYMBIO Validation Workshop (see **Chapter 2.5**). In this workshop, the results were jointly reviewed with bioeconomy experts and project partners to critically reflect on their practical relevance. The following chapter provides a detailed discussion of these value chains, drawing on the feedback and insights gathered during the workshop, which helped contextualise the quantitative findings with expert perspectives on technological feasibility, market potential, and regional applicability and to confirm the top-ranked value chains as **high-potential and replicable value chains** within the SYMBIO framework.

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3.3. High-promising value chains

The validation workshop described in **Chapter 2.5** brought together a diverse group of experts and stakeholders to qualitatively complement the MCDMA-based prioritization of bio-based value chains. In total, 20 participants joined the online session, including two ANRI moderators, two additional ANRI staff members, and 17 experts from research organizations, innovation clusters, and industrial actors across Europe (including consortium members and advisory board). However, a key limitation of the workshop is that regional experts were not systematically invited for each specific regional BioLink®; instead, the focus was placed on gathering expertise at the European level, which means that the validation reflects cross-European perspectives rather than region-specific stakeholder insights. Regional insights and more detailed contextual discussions will be addressed in **Task 3.3** through the upcoming **multi-stakeholder focus groups** conducted in **each SYMBIO pilot region**.

To document the professional backgrounds of the participants, a Mentimeter survey was conducted at the beginning of the workshop (see **Table 6**). Seventeen attendees provided their job titles and fields of expertise, spanning functions such as project leads and managers in the CBE, LCA specialists, applied researchers in agriculture and environmental engineering, and innovation consultants. This diverse cluster of expertise ensured a broad and multidisciplinary knowledge base for subsequent qualitative validation.

Table 6: *Mentimeter results from validation workshop – Job titles and fields of expertise*

Nr.	Job Title	Field of Expertise
1	Project Lead	CBE
2	Technical Assistant	CBE
3	CEO	RDI in Bioeconomy
4	Team Lead	CBE
5	Project Coordinator	CBE
6	Ass. Professor	Chemical and Environmental Engineering Department (University of Seville)
7	/	Expert in Agriculture
8	Innovation Consultant, PhD in Installations and Systems for the Industry	Circular Economy
9	Prof. at University of Zagreb	Faculty of Agriculture Bioeconomy
10	Junior Researcher	/
11	Project Manager	Circular Economy
12	Project Manager	Circular Bioeconomy
13	LCA Specialist	Bioeconomy
14	/	CBE
15	Area Manager at Wood K plus	Research Institute for wood and related renewable materials

16	Senior Researcher	Bioeconomy
17	CEO	CBE

Of the 17 participants present, 8 engaged actively in the MIRO-based validation exercise by contributing comments, sticky-note feedback, and poll inputs. These active participants formed the core analytical group whose qualitative assessments were combined with the quantitative MCDMA scores.

While the workshop provided valuable insights from a diverse group of practitioners and researchers, it must be acknowledged that the number of external experts was inevitably limited. A broader participation — whether in terms of disciplinary backgrounds, geographical coverage, or industry segments — could have further enriched the discussion and potentially strengthened the robustness and completeness of the qualitative validation. This constraint does not undermine the relevance of the collected expert perspectives but should be considered when interpreting the results, as they reflect the viewpoints of those present rather than the full spectrum of stakeholders active in the European bio-based sector. Future validation rounds or complementary consultations could therefore expand expert involvement to enhance representativeness and triangulation.

The MCDMA assessment initially identified eight top-ranked value chains (see **Table 5**). During the expert discussions and voting in the workshop, **two of these eight value chains were not confirmed** (see **Chapter 3.3.7**) for further development and were subsequently excluded from the high-potential set. The following chapter presents the remaining six validated high-potential value chains in a consistent analytical structure. Each subsection begins with a brief introduction to the respective value chain, followed by the corresponding MCDMA tables that were validated during the workshop. For value chains that consist of multiple BioLinks®, i.e., those applicable in several SYMBIO pilot regions, each BioLink® is displayed in a separate table reflecting its region-specific scores, criteria weights, and underlying rationales. After the tabular presentation, each subsection concludes with a dedicated discussion, synthesizing the qualitative inputs generated during the expert validation workshop. This includes the arguments raised through sticky-note feedback and voting rationales (anonymized), which are further contextualized and critically examined through relevant academic literature. The discussion sections therefore integrate expert judgement with evidence from existing research to assess the potential, feasibility, and replicability of each value chain. All six value chains received positive voting results in the workshop, confirming their relevance for further development. The following section begins with the value chain that achieved the strongest overall performance across both the MCDMA assessment and the expert validation.

3.3.1. Forestry residues in PHA

The value chain Forestry residues → PHA is present in the SYMBIO pilot regions of Andalusia (Spain) and Croatia. Both regions ranked among the top-performing cases in the MCDMA assessment (**Table 4**) and were therefore selected for expert validation. **Table 7** presents the corresponding BioLink®, including region-specific scores, criteria weights and methodological rationales. A consolidated discussion integrates all expert comments and voting inputs from the validation workshop.

Table 7: *MCDMA Results - Forestry Residues in PHA using enzymatic hydrolysis and fermentation in Andalusia (Spain): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification*

explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.

	Score	Weight	Rationale	References
CRP	0,75	0,17	Low raw material cost, Solid state fermentation (SSF), efficiency, needs pretreatment	Du et al. 2012, Govil et al. 2020, Rodriguez-Perez et al. 2018, Oliveira et al. 2004, Soccol et al. 2017, Yazid et al. 2017, Chen and Liu 2017, Koppram et al. 2014, Modenbach and Nokes 2013, Singhvi and Gokhale 2013, Zytner et al. 2023
MC	0,6	0,18	Material potential, price and availability, processing efficiency, biomass availability, feedstock competition	Martínez-Avila et al. 2021, Kumar et al. 2020, Raza et al. 2018, Koller 2018, Koller et al. 2010, Koller and Mukherjee 2022, ?ACCESS DENIED?
TDP	0,6	0,13	PHA, lactic acid, succinic acid, acetic acid, adipic acid, furfural	Tandon
GRP	0,7	0,10	Medium renew-able energy mix share. Mild process complexity (two-step), by-product as feedstock type	Eurostat 2025
CP	0,7	0,11	By-product with pre-treatment and seasonality dependent, easy valorizable by-products	González-Rojo & Díez-Antolínez 2023, Mujtaba et al. 2023, SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025
EIP	0,6	0,07	Mild process complexity, moderate chemical input requirements, by-product from a high-impact commodity	SBTN HIC List
RR	0,7	0,09	Regional resilient biomass when sustainably managed, policy support, deforestation, aridity	Herriaz et al. 2025; Spanish Forest Strategy, 2022; Rural Development Plan of Andalusia'
VC	0,7	0,10	Multiple players in forestry management and timber processing, unionised industry, higher-salaries, coordination complexity, market potential	SYMBIO Deliverable 2.2 2025; Roca, 2014; Akimova et al., 2024; Metastat 2025
CF	0,9	0,08	No direct conflict with food. Potential reduction in local soil health and future forest food products due to removal of residues	Symbio Deliverable 2.2; VCG.ai, 2022; Limenih et al., 2024
TS	0,683			

The expert validation highlighted several factors that complement and refine the MCDMA assessment of the value chain Forestry residues → PHA. Across all dimensions, the comments converge on the view that the value chain is promising, yet subject to a set of structural constraints that must be addressed to ensure feasibility and replicability.

From an economic perspective, experts pointed to the competitive pressure arising from existing markets for forestry residues, particularly sawdust and pellets. Such competing uses may elevate feedstock prices and reduce the cost advantage typically assumed for lignocellulosic by-products. The economic viability of sourcing lignocellulosic by-products is directly impacted by the existing competitive utilization of forestry residues. Wood processing residues, such as sawdust and bark, are currently diverted toward established markets like pulp, paper production, and chipboard manufacturing. Considering these competing demands, along with alternative uses such as fertilizer and bedding, it's necessary to accurately evaluate the cost-effectiveness and overall supply of these biomass resources. In addition, participants emphasized the volatility of biomass prices, suggesting that fluctuations in the supply of forestry residues can influence the long-term cost stability of PHA production. The long-term cost stability of biomass-dependent processes is fundamentally compromised by the variability in feedstock availability. Forestry residues, which include dead wood generated by unpredictable natural disturbances like storms and insect outbreaks, are explicitly defined as an irregular source of production. This irregularity in supply contributes to the difficulty in accurately estimating the future volume and regional distribution (38).

Several contributions stressed the importance of evaluating process costs in relation to the market price of PHA, as the polymer competes primarily with low-cost fossil plastics. The primary challenge hindering the widespread commercial adoption of PHA biopolymers is the significantly high cost of production compared to traditional synthetic plastics. While conventional plastics are characterized as relatively inexpensive, the high cost associated with PHA production, specifically related to substrate materials and downstream processing, acts as a persistent constraint on commercial utilization. Consequently, current research is strategically focused on developing improved extraction technologies and utilizing cheap raw materials to regulate cost-effectiveness and establish PHA as a feasible alternative to commercial synthetic plastic (39).

Experts noted that current demand for PHA is strongly shaped by regulatory incentives, most prominently EU packaging legislation—rather than an established market pull. This reliance on regulatory drivers introduces uncertainty regarding the long-term competitiveness of PHA-based value chains. Policy instruments are fundamental for driving demand-side transformation, as demonstrated by the potential application of taxes on non-renewable products and the introduction of quota systems for sustainable alternatives. If consumer lifestyles remain business-as-usual and resist changes in consumption, policies focused primarily on the supply side necessitate more extensive and expensive supply-side measures to achieve climate objectives. This reliance on supply-side policy for expansion in sectors like bioplastics introduces the risk of negative trade-offs and challenges to social acceptance because high costs are incurred without market pull (40). One expert therefore suggested that PHA production routes may need to focus on high-value or specialized applications, such as coatings, to maintain price competitiveness in niche markets. The strategy of prioritizing high-value markets is supported by evidence that consumer segments, such as those aligning with the Lifestyle of Health and Sustainability, are willing to pay a premium for products perceived as sustainable and health-aligned. This preference for conscientiously consumed goods, which recognizes the consumer's responsibility toward society and the environment, drives the utilization of bio-based materials in premium segments. Consequently, the expansion of mass-balanced bio-based products is envisioned to be specifically driven by end-consumer preferences within these higher-priced market segments (41).

Technical aspects of the conversion pathway were also highlighted. Although fermentable sugars from forestry residues are recognized platform chemicals, experts noted that the pretreatment and hydrolysis steps required to obtain these sugars remain complex and resource intensive. The recalcitrant nature of lignocellulose necessitates multi-step processing to achieve high sugar yields, typically involving sequential chemical pretreatments before enzymatic saccharification. Optimization of these resource-intensive steps requires careful evaluation of parameters such as catalyst concentration, residence time, and solid-to-liquid ratios. When processed optimally, high efficiency is possible, with yields reaching 93.11% cellulose conversion and monomeric sugar concentrations up to 88.91 g/L, demonstrating favorable input-output ratios for feedstock utilization. Furthermore, maintaining non-aggressive process conditions is crucial to prevent the formation of inhibitory compounds that could interfere with downstream biological conversion steps (42). In this context, the need to account for mass balance considerations was emphasized, as the volume of residues required to produce a target amount of PHA directly determines reagent, water and energy demands throughout the process.

Ecological comments were broadly aligned with the MCDMA results. Experts reaffirmed the GRP associated with replacing petrochemical plastics with and noted that the conversion pathway operates under relatively mild conditions. Comparative Life LCA's examining bio-based and fossil-based polymers reveal substantial variation in climate change results between different studies, which prevents definitive conclusions regarding which polymer type offers the lowest environmental impact. This difficulty in assessment is partly due to methodological choices, particularly the common practice of crediting the carbon dioxide absorbed by growing biomass to the polymer product, which frequently results in calculated negative climate change values for bio-based cases. Such practices are considered potentially misleading, especially when utilized in cradle-to-gate studies that do not account for the eventual emission of CO_2 at the end-of-life stage. Although biological feedstocks provide a lower feedstock carbon emission burden due to their rapid growth cycle compared to fossil reserves, the inconsistent use of carbon crediting highlights a challenge in accurately assessing the full lifetime climate impact of bio-based alternatives (43).

The social and regional feedback focused particularly on Andalusia, where experts observed a relatively limited number of forestry-sector actors. This constraint may affect both feedstock mobilization and the coordination of supply chain activities. Additional uncertainty was raised regarding the presence of local end-users capable of absorbing PHA or intermediate materials, which could limit the development of regionally anchored markets. Optimization models evaluating the integration of PHA into packaging systems emphasize that the regional viability of these bio-polymers relies critically on the local presence of end-of-life infrastructure. For instance, a candidate biorefinery site near Tarragona, despite offering access to southern feedstocks, exhibited reduced environmental performance when compared to Milan due to the latter's proximity to established industrial composting facilities. This disparity translated into quantifiable economic factors, as investments in composting infrastructure generated an 18% higher return on investment in Milan compared to Tarragona, underscoring the vital need for robust regional waste management networks to absorb the material output. Consequently, successful PHA deployment requires strategies that integrate localized feedstock access with established or subsidized waste-handling capabilities, rather than relying solely on material substitution (44).

Despite these concerns, no fundamental objections were expressed against the social assessment, and one expert explicitly confirmed the reasoning as straightforward.

Finally, the voting results showed unanimous support for the replicability of this value chain. Participants emphasized the widespread availability of forestry residues across Europe and highlighted the relevance of this pathway for regions with strong forestry sectors, such as Central and Northern Europe. Lignocellulosic materials derived from wood processing and primary forestry residues are considered abundantly available across the EU, with the realistic potential for forestry residues estimated at 43.5 million tons per year. However, the successful replication of such a value chain relies heavily on managing the upstream supply chain to overcome major drawbacks related to transport and handling logistics. Several experts also noted that determining minimum annual feedstock volumes will be essential for assessing the scalability of future replications (45).

Overall, the expert comments and the voting outcomes provide consistent and well-founded qualitative confirmation of the MCDMA results. While the value chain faces economic and logistical challenges related to market conditions, process complexity and regional constraints, the workshop's feedback strongly supports its classification as a high-potential pathway within the SYMBIO project.

3.3.2. Corn Residues in Succinic Acid

The value chain Corn residues → Succinic Acid is represented in the SYMBIO pilot region of Piedmont (Italy). The following table summarises the region-specific BioLink®, including its MCDMA scores, weighting factors and the underlying methodological rationales. A consolidated discussion then integrates and analyses all expert comments and voting inputs from the validation workshop.

Table 8: *MCDMA Results - Corn Residues in Succinic Acid using enzymatic hydrolysis and fermentation in Pietmont (Italy): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	0,80	0,11	High-solid enzymatic hydrolysis, less water and reagents, integrated CHP energy use, lower equipment demand	Lu et al. 2020, Wu et al. 2013, Luque et al. 2009, Datta et al. 1992, Kosamia et al. 2024, Tomczyk et al. 2022
MC	0,80	0,08	Growing EU bio-succinic acid market, bioplastics demand, green regulations, higher costs than petro route, strong Piedmont bio-clusters, Reverdia plant know-how	GMI Insights 2025-2034, Lin et al. 2024, Cluster SPRING 2023, DSM 2019
TDP	0,30	0,10	Lignin, cellulose, fixed CO_2 providing environmental benefit	Luo et al. 2022, Yang et al. 2016, Lin et al. 2024,
GRP	0,67	0,16	Low renewable share, mild process complexity (two-step), by-product as feedstock type	Eurostat 2025

CP	0,67	0,12	By-product/residue requiring pretreatment, seasonal residue and can be weather-dependent, easily valorisable by-products	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025, Tomczyk et al. 2022
EIP	0,57	0,14	Mild process complexity, moderate chemical input requirements, by-product from a high-impact commodity	SBTN HIC List
RR	0,80	0,08	Established corn sector and supply chains; moderate climate risk mitigated by innovation; strong institutional and research support for bioeconomy enhances resilience.	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025; Edwards, 2022; Mereu, 2021; OECD,2021
VC	0,80	0,13	Existing firms and cooperatives enable local value retention and potential business growth through substitution of imports.	Symbio Deliverable 2.2, 2025; Universita di Scienze Gastronomiche de Pollenzo, 2014; Dansero & Puttilli, 2013
CF	0,40	0,09	Feedstock competes with livestock feed and biofuel uses, creating potential conflicts over residue allocation.	Galindo, 2022; Olagunjo et al, 2023; Bagagiolo et al, 2022; Symbio Deliverable 2.2, 2025.
TS	0,656			

The expert feedback on the value chain Corn residues → Succinic Acid provided several critical reflections on the economic, ecological and social dimensions of the assessment. While the overall workshop sentiment was positive, especially regarding regional value chain potential, several participants raised questions about specific assumptions in the justification, contributing to a more nuanced understanding of the pathway's strengths and limitations.

From an economic perspective, multiple experts expressed uncertainty regarding the actual yields achievable from corn residues under the described process conditions. This concern was raised both in the main validation comments and again during the voting discussion, indicating that yield performance constitutes a key parameter requiring further clarification or empirical support. At the same time, several contributions highlighted that the underlying conversion pathway is well developed and relies on standardized process equipment, suggesting technological maturity and reduced implementation risk. The fermentative production of succinic acid is classified as a mature technology, having been established by multiple manufacturers at scales of 10 kilotons per annum or greater. When utilizing common first-generation feedstocks such as starch-derived sugars, this process is highly efficient, with reported yields reaching up to 1.1 grams of succinic acid per gram of glucose. Despite this technological readiness, historical efforts by commercial producers have faced challenges in establishing consistent and economically viable operations due primarily to strong competition from petrochemical synthesis routes (46). Recent experimental studies provide quantitative insights into the overall yield performance of converting corn residues into succinic acid, thereby directly addressing the experts' request for empirical data on the hydrolysis–fermentation sequence. In integrated Simultaneous Saccharification and Fermentation (SSF) systems, processing corn stover with Actinobacillus succinogenes has achieved succinic-acid yields of approximately 0.72 g g^{-1}, with final concentrations around 47.4 g L^{-1}. In Separate

Hydrolysis and Fermentation (SHF) configurations, anaerobic fermentation of corn-fiber hydrolysate has produced up to 70.3 g L^{-1} succinic acid at yields of 0.96 g g^{-1}, illustrating the high efficiency attainable once fermentable sugars are available. High-solid SHF experiments further demonstrate the dependence of overall process yields on pretreatment performance: steam-exploded corn stalk at 30% WIS reached a 73.6% cellulose conversion, generating 97.5 g L^{-1} glucose, which was subsequently transformed into 38.6 g L^{-1} succinic acid (≈0.40 g g^{-1} relative to glucose input). Notably, unwashed hydrolysates containing inhibitors such as acetic acid and furfural failed to ferment entirely, underscoring the sensitivity of lignocellulosic succinic-acid production to pretreatment-derived by-products and confirming that achievable yields depend strongly on biomass quality, inhibitor removal and hydrolysate composition (47–49).

Some participants emphasized the regional suitability of the value chain for Piedmont, noting the strong agricultural sector and the presence of relevant actors along the supply chain. This positive assessment was accompanied by a follow-up comment asking for clarification on why the value chain is particularly promising for the region, indicating a desire for more explicit justification of region-specific comparative advantages.

A cluster of comments focused on justification related to carbon flows. Experts questioned the statement regarding "fixed CO_2", asking from which process step this carbon would originate and expressing skepticism about the underlying rationale. This critique highlights the need for clearer communication of carbon balance assumptions in succinic acid production from lignocellulosic residues. Succinic acid fermentation exhibits high carbon efficiency, a result of the process actively incorporating CO_2 as a substrate alongside fermentable sugars under anaerobic conditions. The stoichiometry illustrates this capture, requiring seven moles of glucose and six moles of CO_2 to generate twelve moles of succinic acid, yielding a calculated carbon efficiency up to 98% (46,50). Another comment challenged the claim that cellulose-derived sugars constitute a "by-product", noting that cellulose is in fact the primary carbon source for fermentation. This point underlines the importance of using terminology that accurately reflects the feedstock hierarchy in lignocellulosic processing. When utilizing second-generation feedstocks, like lignocellulosic residues, the biomass must undergo processing to liberate monomeric sugars, including glucose derived from the cellulose component. This requirement establishes the cellulose fraction as a primary source of fermentable carbon necessary for the successful conversion pathway (46).

Ecological feedback included the observation that competition for by-products is high in Piedmont, due to the region's advanced bioeconomy sector and established industrial utilization pathways. This remark suggests that although corn residues serve as an abundant agricultural by-product, the regional context may introduce constraints on residue availability due to competing uses.

The social dimension generated the highest number of comments and a lively discussion among participants. One expert disagreed with the justification describing "moderate climate risk", arguing that it is not possible to make such a statement with certainty at this point in time. Other contributions introduced new evidence and interpretations: one expert noted that climate models currently suggest moderate impacts for the region, while another argued that emerging insights into accelerating climate feedback loops may soon challenge existing modelling assumptions. Additional comments clarified that the climate risk in the MCDMA relates specifically to future land-use resilience and the ability of the region to sustain corn cultivation under projected climate conditions. This distinction indicates that participants

broadly agreed that climate risks exist but differed in how these risks should be weighed between ecological and regional resilience dimensions. The development of lignocellulose biorefineries is largely driven by the urgent global requirement for sustainable approaches that diminish climate change and facilitate the decarbonization of the fossil economy. However, despite being a solution to greenhouse gas emissions, climate change is identified as a geopolitical weak point contributing to the sector's high capital and operational investments and overall process uncertainty. This complex dual role highlights that the efficacy and viability of bio-based systems remain exposed to the very climate instability they are designed to mitigate (51). One participant suggested explicitly that climate risk may be more appropriately discussed under ecological impact, indicating a need for methodological transparency in how climate-related factors are allocated across criteria.

Several positive comments were made regarding the strength of the regional actor landscape. Participants emphasized that Piedmont has the unusual advantage of hosting all necessary value chain actors, processors and end-usersm, within the same region. This was considered a significant enabling condition not commonly found in other European contexts.

As a critical platform chemical, bio-based succinic acid is produced via one of seven fermentative processes identified as technologically mature enough for industrial-scale bulk chemical production. This compound is convertible into renewable polyesters, such as polybutylene succinate, which are highly desirable for circular economy applications, particularly in short-cycle products like convenience food packaging (46). Successfully deploying such bio-based platforms requires prioritizing integrated regional configurations that coordinate feedstock supply, logistical networks, and local end-of-life capabilities to ensure sustainable and cost-effective market penetration (44). A related comment highlighted the presence of strong supply chains and established cooperatives, reinforcing the region's favorable structural conditions for implementing this value chain.

The voting statements further reinforced these insights. While the yield uncertainty was reiterated by one participant, others expressed confidence that the value chain can truly be regional, emphasizing the presence of integrated supply systems and market demand. Another comment pointed to increasing demand for biobased packaging and other applications of succinic acid, underscoring the relevance of this platform chemical for growing EU bioproduct markets. Succinic acid is recognized as one of the seven fermentative processes sufficiently mature for industrial-scale bulk chemical production, establishing it as a critical platform molecule for bioeconomy. These mature fermentation routes include ethanol, lactic acid, succinic acid, 1,3-propanediol, itaconic acid, 1,4-butanediol and PHA, all of which have demonstrated industrial-scale operation at or above the 10 kt yr^{-1} threshold and are therefore classified as technologically robust within the CBE (46). Succinic acids classification within this group reflects decades of industrial demonstration, with multiple companies operating fermentative succinic-acid processes at capacities between 10,000 and 30,000 tonnes per year. This high level of technological maturity, combined with its exceptional carbon efficiency and established downstream conversion routes, further reinforces succinic acid's status as a strategically important platform chemical within the evolving European bioeconomy (48). Its conversion into renewable polyesters, such as polybutylene succinate, aligns directly with the increasing market demand for bio-based packaging solutions desirable for CBE applications (46).

Taken together, the expert feedback highlights the strong regional embeddedness and technological maturity of this value chain while also identifying specific technical and conceptual issues requiring clarification – particularly regarding yield expectations, carbon flow assumptions and the allocation of climate risks. Despite these concerns, the overall validation remained positive, and the voting results underline the perception that Corn residues → Succinic Acid represents a feasible and regionally anchored pathway for further development within SYMBIO.

3.3.3. Wheat Straw in PHA

The value chain Wheat straw → PHA occurs in the SYMBIO pilot regions of Piedmont (Italy) and Slovenia. The following tables summarize the region-specific BioLinks®, including their MCDMA scores, weighting factors, and underlying methodological rationales. The consolidated discussion then integrates and analyses all expert comments and voting inputs from the validation workshop.

Table 9: *MCDMA Results – Wheat Straw in PHA using enzymatic hydrolysis and fermentation in Piedmont (Italy): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	0,75	0,11	Low raw material cost, lignocellulosic feedstock, SSF/SSEH low energy and water use, high yields, needs pretreatment	Du et al. 2012, Govil et al. 2020, Rodriguez-Perez et al. 2018, Oliveira et al. 2004, Soccol et al. 2017, Yazid et al. 2017, Chen and Liu 2017, Koppram et al. 2014, Modenbach and Nokes 2013, Singhvi and Gokhale 2013, Zytner et al. 2023
MC	0,70	0,08	Biodegradable and biocompatible polymer, UV and hydrolysis resistant, high biomass availability, local feedstock and market, cost and processability limits	Martínez-Avila et al. 2021, Kumar et al. 2020, Raza et al. 2018, Koller 2018, Koller et al. 2010, Koller and Mukherjee 2022,
TDP	0,60	0,10	PHA, lactic acid, succinic acid, acetic acid, adipic acid, furfural	Tian et al., 2018
GRP	0,67	0,16	Low renewable share, mild process complexity (two-step), by-product as feedstock type	Eurostat 2025
CP	0,67	0,12	By-product with pre-treatment and seasonality dependent, easy valorizable by-products	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025 González-Rojo & Díez-Antolínez 2023, Mujtaba et al. 2023,
EIP	0,57	0,14	Mild process complexity, moderate chemical input requirements, by-product from a high-impact commodity	SBTN HIC List

RR	0,60	0,08	Wheat straw availability supports feedstock use; climate impacts and bioenergy competition may affect long-term resilience.	Symbio Deliverable 1.1; Symbio Deliverable 1.2; Symbio Deliverable 2.2 2025; Pulighe et al, 2024; BBM, 2025; IEA Bioenergy, 2018; ENI, 2022
VC	0,80	0,13	Strong cooperatives and existing processing capacity enable small-farmer inclusion and job creation in new bio-based value streams.	SYMBIO Deliverable 2.2 2025; Universita di Scienze Gastronomiche di Pollenzo' ; Dansero & Puttilli, 2013
CF	0,50	0,09	Wheat straw competes with existing low value uses that indirectly influence food and feed chains such as animal bedding and compost.	Giannocaro et al, 2017
TS	0,655			

Table 10: *MCDMA Results – Wheat Straw in PHA using enzymatic hydrolysis and fermentation in Slovenia: Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	0,75	0,10	Low raw material cost, lignocellulosic feedstock, SSF/SSEH low energy and water use, high yields, needs pretreatment	Du et al. 2012, Govil et al. 2020, Rodriguez-Perez et al. 2018, Oliveira et al. 2004, Soccol et al. 2017, Yazid et al. 2017, Chen and Liu 2017, Koppram et al. 2014, Modenbach and Nokes 2013, Singhvi and Gokhale 2013, Zytner et al. 2023
MC	0,70	0,13	Biodegradable and biocompatible polymer, UV and hydrolysis resistant, high biomass availability, local feedstock and market, cost and processability limits	Martínez-Avila et al. 2021, Kumar et al. 2020, Raza et al. 2018, Koller 2018, Koller et al. 2010, Koller and Mukherjee 2022, ?ACCESS DENIED?
TDP	0,60	0,13	PHA, lactic acid, succinic acid, acetic acid, adipic acid, furfural	Tian et. al, 2018
GRP	0,73	0,13	Medium renewable energy mix share. Mild process complexity (two-step), by-product as feedstock type	Eurostat 2025
CP	0,67	0,13	By-product with pre-treatment and seasonality dependent, easy valorizable by-products	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025 González-Rojo & Díez-Antolínez 2023, Mujtaba et al. 2023,
EIP	0,57	0,11	Mild process complexity, moderate chemical input requirements, by-product from a high-impact commodity	SBTN HIC List

RR	0,50	0,08	Strong domestic corn production; existing processing capacity not yet at scale but supports potential resilience through higher-value markets.	Symbio Deliverable 1.1; Symbio Deliverable 1.2; Symbio Deliverable 2.2; Giannocaro et al, 2017
VC	0,50	0,12	Moderate job creation potential linked to technological development for conversion.	Symbio Deliverable 2.2; de Souza Vandenberghe et al, 2016; Molina Penate et al., 2024; Ghinea et al., 2025; Gatto & Re, 2021.
CF	0,50	0,07	Corn residues compete with traditional uses in animal feed and fertilizer.	Galindo, 2022; Olagunjo et al, 2023; Bagagiolo et al, 2022; Symbio Deliverable 2.2, 2025
TS	0,624			

While experts broadly agreed with many aspects of the assessment, they identified several economic, ecological and social considerations that influence the feasibility of this pathway across both Piedmont and Slovenia.

From an economic perspective, concerns were raised regarding the assumption of high yields, particularly given that pretreatment conditions can strongly influence overall conversion efficiency. One expert explicitly questioned whether pretreatment may reduce yields, thereby challenging the justification of consistently high process performance. The difficulty in establishing cost-effective pretreatment methods represents a major economic bottleneck, requiring high chemical and energy inputs which contribute substantially to overall capital and operational expenditure. Another comment expressed doubt about the general economic feasibility and competitiveness of PHA production from wheat straw, signaling the need for more robust cost–benefit comparisons with existing uses or alternative bio-based products. Crucially, the degradation products formed during pretreatment may subsequently inhibit crucial downstream hydrolysis and fermentation steps, negatively affecting the yields of second-generation sugars necessary for commercial processes. Consequently, the slow commercial progress of microbial PHAs is linked to the high price of lignocellulosic substrates, demanding optimal economic viability for successful industrial application (51).

Ecological feedback included both supportive and critical perspectives. One expert considered the ecological justification “reasonable”, indicating alignment with the MCDMA assessment. However, several participants highlighted that wheat straw already fulfils important ecological functions in its current uses. In many farming contexts, crop residues such as wheat straw are essential resources for animal bedding, a low-processing pathway that supports compost formation and contributes to soil fertility and ecological balance. Proper residue management in this context promotes nutrient recycling, carbon sequestration, and the maintenance of soil organic matter. This implies that existing pathways may, under certain conditions, offer sustainability advantages for farmer groups (52).

At the same time, experts emphasized that bedding alone cannot absorb the full volume of wheat straw generated in the region, indicating the need for additional valorization pathways. This concern is supported by evidence that hundreds of millions of tons of crop residues are generated annually, far exceeding the capacity of traditional agricultural or household uses. As a result, excess straw often accumulates, reinforcing the notion that multiple valorization routes can coexist without undermining soil health (51).

One participant also noted that illegal open burning of straw persists in parts of the EU, a practice driven by limited management alternatives and the low cost and convenience of burning. This phenomenon contributes to pollution, biomass loss and soil degradation, underscoring the environmental relevance of developing more sustainable utilization options (52).

The social dimension elicited a mixture of agreement and clarification. One participant affirmed the general reasoning provided in the MCDMA. However, another disagreed with the justification that wheat straw valorization competes with human food systems, noting that wheat straw does not directly interact with food supply chains except indirectly through its use as animal bedding. This feedback stressed the need for precision when discussing resource competition in social assessments. A further comment explained that, in the MCDMA, resource competition was assessed to capture potential implications for other users of the residue rather than competition with food production. This distinction highlights the importance of differentiating between direct and indirect social interactions associated with agricultural residues (52).

The voting comments reiterated economic concerns, particularly regarding whether the value chain is competitive and sustainable when compared to current, well-established uses. This final remark reinforces the previously raised issues surrounding yield, cost-efficiency, and alternatives such as bedding or composting. Overall, the expert discussion confirms the relevance of this value chain but also highlights uncertainties regarding yield assumptions, economic competitiveness, and interactions with existing ecological and social functions of wheat straw. These insights complement the MCDMA assessment and provide direction for further refinement of economic modelling, sustainability comparison and feedstock mobilization strategies in both Piedmont and Slovenia.

3.3.4. Corn Steep Liquor in 1,3-Propanediol

The value chain CSL → 1,3-PDO is represented in the SYMBIO pilot regions of Flanders and the Brussels Capital Region (Belgium). The following tables summarize the region-specific BioLinks®, including their MCDMA scores, criteria weights, and underlying methodological rationales. The consolidated discussion then integrates all expert comments and voting inputs from the validation workshop.

Table 11: *MCDMA Results – CSL in 1,3-PDO using fermentation in Flanders (Belgium): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	1,00	0,13	Low energy and water use via liquid fermentation with CSL, simplified recovery, moderate temperature, reduced nitrogen cost.	Wang et al. 2020, Ju et al. 2020,Posada et al. 2013
MC	0,85	0,11	Growing EU market for textiles, cosmetics, biopolymers. Flanders: strong bioeconomy strategy, major	Coherent Market Insights (2025-2032), Grand View Research (2024-2030), Departement Omgeving 2014, Flemish

			chemical cluster, low-cost feedstock. High competition, Bio- PDO cost > Petro-Popanediol	Government Environment, Nature and Energy Department 2013, Flanders Investment & Trade 2025, Posada et al. 2013
TDP	0,20	0,10	Organic acids and residual CSL	Zhang et al. 2023, Ren et al. 2021
GRP	0,77	0,10	Low renewable energy share mix, low process complexity (single-step), by-product as feedstock type	Eurostat 2025
CP	0,77	0,16	By-product/residue with little or no pretreatment, Steady or year-round supply, by-products that don't have potential to create new value chains	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025Li et al. 2024
EIP	0,77	0,10	Low process complexity (single-step), minimal chemical input requirement, By-product/residue from a high-impact commodity	SBTN HIC List
RR	0,60	0,13	Strong corn production base; limited wet milling and fermentation capacity but available feedstock for valorisation.	Symbio Deliverable 1.1, 2025; Symbio Delierable 1.2, 2025; Symbio Deliverable 2.2 2025, Catalisti, 2018; Bio-Base Europe, 2020.
VC	0,50	0,12	Moderate potential for value creation through existing technological and knowledge infrastructure; opportunities for mid- to high-tech job growth.	Symbio Deliverable 2.2; Bio-Base Europe, 2020; Biobase4SME, 2018
CF	0,40	0,06	CSL likely already used as livestock feed supplement, limiting availability.	Chang et al, 2025; Lee et al., 2025; Pharazyn & Noughty, n.d.
TS	0,673			

Table 12: *MCDMA Results – CSL in 1,3-PDO using fermentation in Brussel Capital (Belgium): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	1,00	0,13	Low energy and water use via liquid fermentation with CSL, simplified recovery, moderate temperature, reduced nitrogen cost.	Wang et al. 2020, Ju et al. 2020, Posada et al. 2013
MC	0,75	0,11	Growing EU market for textiles, cosmetics, biopolymers. Belgium: strong chemical hub, active R&D, supportive bioeconomy policies. Low-cost feedstock (glycerol, CSL), but high	Coherent Market Insights (2025-2032), Grand View Research (2024-2030), European Chemical Industry Council, Brussels-Capital Region, Posada et al. 2013

			competition and Bio-PDO cost > Petro-PDO	
TDP	0,20	0,10	Organic acids and residual CSL	Zhang et al. 2023, Ren et al. 2021
GRP	0,77	0,10	Low renewable energy share mix, low process complexity (single-step), by-product as feedstock type	Eurostat 2025
CP	0,77	0,16	By-product/residue with little or no pretreatment, Steady or year-round supply, by-products that don't have potential to create new value chains	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025, Li et al. 2024
EIP	0,77	0,10	Low process complexity (single-step), minimal chemical input requirement, By-product/residue from a high-impact commodity	SBTN HIC List
RR	0,50	0,13	Low regional corn production; dependency on other Belgian regions, mainly Flanders, for feedstock supply.	Symbio Deliverable 1.1, 2025; Symbio Delierable 1.2, 2025; Symbio Deliverable 2.2 2025, Catalisti, 2018; Bio-Base Europe, 2020.
VC	0,50	0,12	Limited local production capacity; small to moderate value creation potential via existing 1,3-PDO users.	Symbio Deliverable 1.1, 2025; Symbio Deliverable 1.2, 2025; Symbio Deliverable 2.2, 2025;.
CF	0,50	0,06	CSL competes with established uses in animal feed and bait additives.	Chang et al, 2025; Lee et al., 2025; Pharazyn & Noughty, n.d.
TS	0,656			

The expert validation generated a broadly positive assessment with respect to economic potential, technological simplicity and replicability. At the same time, participants identified several cross-cutting constraints linked to feedstock competition, existing circular uses and regional processing capacities. Together, these insights critically analysed the MCDMA results and highlighted key considerations for future deployment.

From an economic perspective, experts consistently agreed that CSL represents a low-cost feedstock and that market dynamics for 1,3-PDO are strongly positive, with growing demand across cosmetics, textiles, polymers and biotechnology sectors. Several participants highlighted this as a high-trend market, reinforcing the argument that the value chain aligns with broader EU bioeconomy growth trajectories. At the same time, experts noted that price exposure remains a critical factor, as PDO competes both with petrochemical PDO and with other bio-based production routes. The 1,3-PDO market demonstrates strong positive dynamics, serving as a vital bi-functional compound with widespread industrial applications in polymer, pharmaceutical, food, and cosmetic industries, with the polytrimethylene terephthalate segment driving substantial growth. Achieving economic sustainability is critically dependent on raw material costs, which typically account for over half of total production expenditures, thereby necessitating the utilization of inexpensive carbon sources. The bio-based route must compete with established chemical synthesis methods, which, although yielding the final product, often require exclusive catalysts, high pressure, and generate toxic intermediates that raise environmental concerns. CSL, for

example, has been evaluated successfully as a low-cost replacement for nutrient sources like yeast extract to improve productivity and cell growth in crude glycerol fermentations (53).

Participants also highlighted the high competition for CSL as a feedstock, acknowledging that CSL attracts multiple users and therefore may be more constrained than suggested in the justification. The specific conversion of CSL to 1,3-PDO involves an industrially mature fermentation technology, yet such microbial production methods are heavily constrained by high feedstock costs, which often account for more than 50% of the total production expenditure. The reported high competition for CSL feedstock reflects acknowledged market saturation for both the input material and the resulting product (46). Despite this, the overall economic reasoning was perceived as “straightforward”, and several experts explicitly agreed with the assessment.

Ecological feedback focused on the simplicity and efficiency of the process. Experts agreed that the conversion operates at very low energy input, consistent with single-step fermentation using CSL. One comment emphasized that CSL already participates in a simple circular value chain as a livestock feed supplement, which raises questions about opportunity cost and whether the ecological case for PDO production should explicitly account for displacement effects. The ecological and economic assessment of converting CSL into 1,3-PDO requires careful consideration of how the substrate’s existing uses influence the net benefits of the pathway. Because CSL already functions as a co-product in established value chains — most notably as a livestock-feed supplement—its diversion into PDO production necessitates evaluating potential displacement effects rather than energy substitution. In this context, experts emphasized that the CSL-to-PDO route is characterized by a relatively simple, low-energy fermentation process with few ecological alternatives, reinforcing the view that the conversion itself is operationally robust and environmentally modest in impact. At the same time, identifying the most beneficial use of CSL depends on understanding the opportunity costs associated with diverting it from feed systems into biochemical production, particularly in regions with high feed demand. Overall, the environmental relevance of the CSL - to-PDO pathway therefore hinges on the comparative ecological performance and systemic consequences of reallocating CSL within existing circular resource flows. (54).

The overarching ecological message was that the process has low energy requirements and minimal chemical input, aligning with the high level of agreement expressed across multiple green stickies in the workshop meeting.

The social dimension was particularly important given the regional context of Flanders and Brussels. One participant pointed to the protein shift – the transition toward more plant-based diets—which could reduce livestock production and thereby decrease feed demand. This shift may, in the long term, increase CSL availability, representing a structural opportunity for the PDO value chain. Another comment observed that because CSL is a co-product of wet milling, regions with limited wet-milling capacity may face constraints in establishing a strong regional feedstock base, particularly outside Flanders. This suggests that regional feedstock mobilization strategies would need to account for structural differences in corn processing infrastructure. The CSL feedstock is identified as a common byproduct of the corn wet-milling process. Establishing economically viable, large-scale cereal-based biorefineries requires considerable improvements in established processing strategies and must account for the complexity and geographic variations in biomass feedstocks. Moreover, the availability of grains like maize, which drives CSL production, is influenced regionally by environmental factors such as water availability and

temperature. This dependency highlights that feedstock mobilization is tightly coupled to localized infrastructure and agricultural conditions (55).

Multiple experts agreed that the value chain benefits from local production loops, existing biotechnology employment opportunities and a generally favorable innovative ecosystem in both regions. These factors were consistently described as "straightforward", reinforcing the MCDMA findings on value creation and regional skills.

The voting comments further strengthened the economic and market-oriented arguments. Participants agreed that the value chain is supported by a strong and diverse market, with broad applicability across consumer goods, materials and specialty chemicals. However, one comment voiced concern about current competing uses, such as livestock feed, again raising the question of which circular pathway should be prioritized under future policy or sustainability frameworks. The final comments emphasized that the feedstock is simple, the conversion process is operationally straightforward, and the overall replicability is high, supported using standard industrial equipment.

The qualitative expert feedback confirms that CSL → 1,3-PDO represents a highly feasible and market-aligned pathway, particularly in bioeconomy-intensive regions such as Flanders and Brussels. The discussion highlights that feedstock competition, regional wet-milling capacity and the evolving protein shift will shape the long-term potential of this value chain, but none of these considerations undermine its strong performance across economic, ecological and social dimensions.

3.3.5. Barley Straw in Succinic Acid

Barley straw as a feedstock for bio-based succinic acid was assessed for two regions — Veneto (Italy) and Carinthia (Austria) — both of which host established barley cultivation systems and active bioeconomy actors. **Table 13** and **Table 14** summarize the region-specific MCDMA results, including criteria scores, weights, and underlying rationales. The discussion integrates all expert comments from the validation workshop to critically evaluate the opportunities and limitations of this value chain in both regions.

Table 13: *MCDMA Results – Barley Straw in Succinic Acid using enzymatic hydrolysis and fermentation in Veneto (Italy): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	0,80	0,11	Less water, reagents, and energy use; integration with CHP; fewer equipment needs depending on process design.	Kim et al. 2024, Kosamia et al. 2022, Tomczyk et al. 2022, Luque et al. 2009, Cheng et al. 2012
MC	0,70	0,08	Growing EU market; still costlier than petro route. Veneto: strong chemical and biotech clusters, supportive policies, and high agri-residue availability.	GMI Insights 2025-2034, Lin et al. 2024, Cluster SPRING 2023, The Business Year 2020, Ruggeri et al. 2025, Apollo Reports 2024

TDP	0,20	0,10	Lignin and fixed CO_2 (environmental benefit, not commercial product).	Kosamia et al. 2022, Lin et al. 2024
GRP	0,67	0,16	Low renewable share, mild process complexity (two-step), by-product as feedstock type	Eurostat 2025
CP	0,67	0,12	By-product with pre-treatment and seasonality dependent, easy valorizable by-products	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025, Narisetty et al. 2022, Zhou et al. 2023
EIP	0,73	0,14	Mild process complexity, moderate chemical input requirements, by-product from a high-impact commodity	SBTN HIC List
RR	0,60	0,08	Climate risks affect barley production; limited processing technology may increase external dependence, though regional bioinnovation capacity is strong.	Symbio Deliverable 2.2 2025; Pulighe et al., 2024; Straffelini & Tarolli, 2023
VC	0,70	0,13	Diverse farming structure with procurement models supporting farmers; potential for high- and mid-tech job creation and local value retention through biobased production.	Symbio Deliverable 1.2, 2025; Symbio Deliverable 2.2, 2025; Veneto Green Cluster, n.d.
CF	0,50	0,09	Barley straw used in animal feed with low nutritional value.	Giannocaro et al, 2017
TS	0,631			

Table 14: *MCDMA Results – Barley Straw in Succinic Acid using enzymatic hydrolysis and fermentation in Carinthia (Austria): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	0,80	0,10	Less water, reagents, and energy use; CHP integration; fewer equipment needs depending on process design.	Kim et al. 2024, Kosamia et al. 2022, Tomczyk et al. 2022, Luque et al. 2009, Cheng et al. 2012
MC	0,60	0,11	Growing EU market; still costlier than petro route. Carinthia: strong bioeconomy focus, active green clusters, and good biomass base, though logistics remain challenging	GMI Insights 2025-2034, Lin et al. 2024, Carinthia 2023, Carinthia
TDP	0,20	0,09	Lignin and fixed CO_2 (environmental benefit, not commercial product)	Kosamia et al. 2022, Lin et al. 2024
GRP	0,90	0,15	High renewable share, Two-step mild Process, By-Product/Residue	Eurostat 2025

CP	0,67	0,14	By-product with pre-treatment and seasonality dependent, easy valorizable by-products	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025, Narisetty et al. 2022, Zhou et al. 2023
EIP	0,73	0,13	Mild process complexity, moderate chemical input requirements, by-product from a high-impact commodity	SBTN HIC List
RR	0,60	0,12	Decline in traditional barley production; winter barley and straw remain regionally available with suitable technology providers and end-users supporting resilience.	Symbio Deliverable 2.2 2025;
VC	0,50	0,12	Limited potential for primary production jobs; moderate potential for mid- to high-tech employment in conversion technologies.	Symbio Deliverable 2.2, 2025;
CF	0,50	0,04	Barley straw used as low-nutrition roughage in animal feed.	Giannocaro et al, 2017
TS	0,637			

On the economic dimension, several experts questioned whether pretreatment requirements could negatively affect achievable yields, emphasizing that high yields should not be assumed without considering pretreatment. Participants also raised concerns regarding the overall economic feasibility and competitiveness of barley straw compared with other lignocellulosic feedstocks, such as corn residues. In addition, workshop participants highlighted logistical challenges associated with seasonal straw residues, referring to cost-intensive storage, transport constraints, and variability of supply. Some experts further questioned the relevance of CO_2-fixation statements within the economic rationale, noting that such environmental benefits do not automatically translate into economic value. The economic viability of converting lignocellulosic biomass is significantly challenged by upstream processes, as pretreatment often represents the primarily capital-intensive step, constituting 30–50% of total equipment costs or 20–25% of operational costs in lignocellulose biorefineries. The competitive price point for biorefineries is fundamentally linked to feedstock cost, which can account for more than 50% of total production expenditure, making the consistent, year-round availability of biomass at a competitive price a paramount concern. Furthermore, the logistics of transport and handling for highly dispersed, seasonally available agricultural residues present major drawbacks that delay their utilization for commercial purposes. Ultimately, although bio-based processes provide environmental benefits like GHG reduction, these advantages do not automatically translate to economic success in the competitive market (51,45).

Although no ecological comments were provided directly for barley straw, several environmental considerations emerged by analogy to related residue streams. Barley straw is a soft, absorbent, and durable bedding material for small animals like rabbits, guinea pigs, and chickens that provides comfort, insulation, and odor control (40). Experts highlighted that barley straw has established uses as animal bedding that requires little processing and returns organic matter to soils, contributing to soil fertility and carbon cycling. At the same time, participants noted that residue availability often exceeds bedding demand, indicating that complementary valorization routes may still be needed. Discussions from related

value chains also pointed to the persistence of illegal straw burning in some areas, an environmentally harmful practice that underscores the need for improved valorization strategies (56,52).

Social considerations differed across regions. In Veneto, the assessment statement on crop resilience prompted debate. Some experts argued that barley should not be considered inherently resilient, as climate change increasingly affects all major crops. Others pointed out that, relative to other feedstocks examined in the workshop, barley may still exhibit comparatively higher resilience, although this does not eliminate exposure to climatic variability. Overall, the social rationale for Veneto was viewed as plausible. Future climate projections indicate that barley production across the Mediterranean basin, including Italy, faces significant negative consequences, with overall grain yield reductions of approximately 9% predicted due to drier and hotter conditions. This vulnerability is characterized by strong location-specific variability, as the impact on yield is heavily influenced by the interaction between extractable soil water content and the occurrence of severe heat stress (days above 34 °C). Inter-annual weather variability is a fundamental source of yield fluctuation for barley, consistently impacting outcomes regardless of the future climate projections (57).

In Carinthia, participants scrutinized the assessment reference to a decline in traditional barley production, questioning whether this trend should be interpreted positively or negatively. Clarifications indicated that the issue relates to shifts between early and winter barley, which influence seasonal residue availability and local land-use patterns. Experts also agreed that species differences are unlikely to substantially affect straw supply, if winter barley remains widely cultivated. The cultivation of winter barley serves as a strategic feedstock, utilizing land that would otherwise be fallow during the winter season by planting in late October and harvesting prior to summer crops in mid-June. Although major policy analyses often aggregate spring and winter barley, making it difficult to evaluate shifts, these models generally project that land expansion is primarily driven by spring barley acreage, not winter barley. While studies frequently assume barley straw is left on the land to enhance soil organic carbon, demand for straw as animal bedding and mushroom compost creates large, established markets in certain regions (58).

Finally, concerns were raised regarding replicability and scalability. Some participants pointed to regulatory uncertainty at the regional level, suggesting that bioeconomy policy frameworks may not yet fully support the deployment of this pathway across the EU. Others questioned feedstock availability in various European regions, noting that while Veneto and Carinthia may sustain the chain locally, residue volumes could be more limited elsewhere. The competitive nature of lignocellulosic feedstock requires policy intervention to promote the most efficient and advantageous utilization concepts, indicating that regulatory support is crucial for scaling up new bio-based pathways. Geographically, while barley straw is recognized as a major source for high value-added products with a total sustainable bioeconomic potential of 16 Mt across the EU, this volume is regionally concentrated, with the highest amounts available in regions such as the Bassin Parisien and Central Spain (59).

Overall, expert feedback suggests that barley straw represents a plausible but constrained feedstock pathway for succinic acid. Strengths include established residue availability in the assessed regions and supportive infrastructural contexts. Main limitations relate to pretreatment sensitivity of yields, economic competitiveness, seasonal logistics, differential regional resilience, and uncertainties regarding feedstock security in other EU contexts.

3.3.6. Whey in Proteins

Whey valorisation through membrane-based protein extraction was assessed for two regional BioLinks® — Friuli Venezia Giulia (Italy) and Wallonia (Belgium) — both characterised by established dairy sectors and existing industrial infrastructures relevant for processing whey streams. **Table 15** and **Table 16**summarize the region-specific MCDMA results, including criteria scores, weighting factors, and justifications. The following discussion synthesises all expert feedback from both regions to critically assess the economic, ecological, and social implications of this value chain, and to evaluate its replicability and strategic positioning within the European CBE.

Table 15: *MCDMA Results – Whey in Proteins using ultrafiltration and membrane separation in Friuli Venezia Giulia (Italy): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS) results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	1,00	0,11	Water reuse, no aggressive chemicals, low energy, modular process	Cinar 2022, Synder, Brião et al. 2024, Reig et al. 2021
MC	0,75	0,08	Growing European dairy protein market; strong dairy tradition, clusters, and incentives. Risks: plant-based competition and sustainability pressure	Mordor Intelligence (Europe_Diary 2025-2030), Mordor Intelligence (Italy 2025-2030), Venerus 2008, Fondazione Agrifood & Bioeconomy FVG, Mordor Intelligence (Europe_Plants 2025-2030), Journal of the American Center for Nutrition
TDP	0,10	0,10	Lactose	Brião et al. 2024
GRP	0,77	0,16	Low renewable energy share mix, low process complexity (single-step), by-product as feedstock type	Eurostat 2025
CP	0,60	0,12	By-product, Steady or year-round supply, Neutral (by-products that don't have potential to create new value chains)	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025, Cinar 2022, Synder, Reig et al. 2021
EIP	0,77	0,14	Low process complexity (single-step), minimal chemical input requirement, By-product/residue from a high-impact commodity	SBTN HIC List
RR	0,40	0,08	Strong dairy sector with policy support and regional provenance; limited technology providers and geographic barriers may constrain processing resilience.	Symbio Deliverable 2.2 2025, IO SONO FVG, n.d.; European Commission, 2025; Mainardis et al. 2019
VC	0,60	0,13	Growing food ecosystem and demand for protein-rich products; potential for limited job growth in production,	Symbio Deliverable 1.1, 2025; Symbio Deliverable 1.2, 2025; Symbio Deliverable 2.2; Mainardis et al. 2019;

			though skills gap hinders advanced conversion roles.	
CF	0,60	0,09	Whey traditionally used in animal feed; unvalorised residual whey remains due to logistical constraints.	Mainardis et al. 2019;
TS	0,639			

Table 16: *MCDMA Results – Whey in Proteins using ultrafiltration and membrane separation in Wallonia (Belgium): Rows: (1) Normalized assessment scores and (2) normalized criteria weights specific for this region. (3) Rationale refers to the justification explaining the summarized reasoning behind the assigned criterion scores. The final TS results from the multiplication of the criterion score by its respective weight. Criteria abbreviations: CRP – cost reduction potential; MC – Market competitiveness; TDP – Technological diversification potential; GRP – Greenhouse-gas reduction potential; CP – circularity potential; EIP – Ecosystem impact potential; RR – Regional resilience; VC – Value creation in the region; CF – Potential conflict with food.*

	Score	Weight	Rationale	References
CRP	1,00	0,13	Water reuse; no aggressive chemicals; low energy use; modular process	Cinar 2022, Synder, Brião et al. 2024, Reig et al. 2021
MC	0,70	0,11	Strong dairy industry; protein innovation clusters; local biomass and market; competition from plant proteins; sustainability pressure.	Mordor Intelligence (Europe_Diary 2025-2030), Mordor Intelligence (Europe_Plants 2025-2030), I4CE – Ingredients for a Circular Economy, Journal of the American Center for Nutrition
TDP	0,10	0,10	Lactose	Brião et al. 2024
GRP	0,77	0,10	Low renewable share, Mild Process Complexity (Single-step), By-Product as residue type	Eurostat 2025
CP	0,60	0,16	By-product, Steady or year-round supply, Neutral (by-products that don't have potential to create new value chains)	SYMBIO Deliverable 1.2 2025, SYMBIO Deliverable 2.2 2025, Cinar 2022, Synder, Reig et al. 2021
EIP	0,77	0,10	Mild Process complexity (Single step), Minimal Chemical Input requirements, By-product/residue from a high-impact commodity	SBTN HIC List
RR	0,60	0,13	Stable dairy production with regional processing capacity and policy support for whey valorisation; dependencies on Flanders, lock-ins and market fluctuations may affect resilience. A number of existing projects focused on valorisation.	Feed Magazine 2025; SYMBIO Deliverable 2.2 2025; Plan Regal, n.d.; CRA-W, n.d; AgriChemWay, n.d; de Herde et al, 2019; de Herde et al., 2020.
VC	0,50	0,12	Consolidated dairy sector with limited small-scale participation; moderate potential for job creation in product manufacturing within existing bioeconomy framework.	The Brussels Times April 2024; Regional Policy Declaration, 2024 ; Circular Wallonia, 2021.

CF	0,60	0,06	Whey by-product is used in food and feed, but excess available for valorisation without major impact on food markets.	Symbio Deliverable 2.2 ; Buchanan et al., 2023 .
BTS	0,633			

From an economic perspective, experts largely confirmed the advantages attributed to membrane-based filtration technologies, noting that these processes typically require low energy and minimal chemical inputs, and support internal reuse of effluents. Several participants characterized whey protein extraction as one of the strongest value-chain opportunities for Friuli Venezia Giulia, but simultaneously cautioned that existing processing plants already operate in the region and surrounding areas, raising questions about whether sufficient additional feedstock would be available to support new industrial capacity. The confirmed economic advantages of the process are technically supported by membrane filtration pre-treatment, which is crucial for recovering whey protein concentrates and enabling process water recirculation. This technological integration contributes to lower operational costs by minimizing the demand for thermal regulation utilities, particularly when fermentation occurs at higher temperatures. However, the concentration of whey feedstock presents a significant regional challenge, as the majority of Italian production (61%) is centralized in Lombardy, Emilia-Romagna, and Veneto, potentially limiting the accessible raw material for new facilities in adjacent areas (60).

Another recurring theme was competition from plant-based protein markets, which experts viewed as increasingly influential in shaping demand and market positioning for animal-derived proteins. At the same time, participants emphasized that the overall protein market continues to grow, indicating a broader expansion of demand rather than a purely substitutive dynamic.

Additional comments highlighted potential side-stream opportunities, including the extraction of bioactive peptides with nutraceutical applications and the recovery of lactose as a usable sugar. The dynamics of the protein market are influenced by the increasing scrutiny of animal production systems, particularly concerning associated environmental consequences such as high GHG emissions and intensive land usage. Consequently, a necessary market transition entails developing vegetal protein products that are accepted by consumers as direct competitors to animal-derived offerings. However, projections indicate that global protein demand, driven by demographic and socio-economic changes, is likely to increase by more than one-third in the foreseeable future, suggesting substantial overall market growth. This expansion creates opportunities for value enhancement within existing protein industries, such as the dairy sector, where the ability to valorize permeate streams — by-products generated from the removal of lactose and salts during protein concentration — is key to the business model. Furthermore, leveraging side-streams from marine materials and cereals to extract high-value bioactive peptides offers significant potential for nutraceutical and functional food applications. More specifically, the valorization of protein- and lipid-rich by-products from fisheries, aquaculture and farmed algae to produce high-value compounds such as bioactive peptides. These marine residues—including fish-processing by-catch, rest raw material generated through EU landing obligations, and protein-rich seaweeds or microalgae—constitute an emerging resource base for nutraceutical and functional-food ingredients with significantly higher market value than their conventional low-grade uses. (40,61).

Experts from both SYMBIO regions noted that the pathway is already implemented in parts of Belgium and Italy, reflecting a high degree of technological maturity and existing industrial deployment.

On the ecological dimension, the discussion centered primarily on energy intensity and renewable-energy dependence. Experts highlighted that processes involving drying steps can significantly increase energy demand, making the renewable-energy share of the regional grid a critical determinant of net GHG-reduction performance. The energy intensity of ingredient production is heavily driven by refinement steps, as drying is typically the major contributor to overall energy use during isolation. For highly purified products such as protein isolates, the spray drying process requires large quantities of energy, often supplied by fossil fuels, significantly increasing the environmental impact. Consequently, the resources consumed during processing can sometimes surpass the environmental impacts related to raw material cultivation, underscoring the benefits of utilizing tailored processes that minimize drying and dissolution (62).

A second ecological consideration related to the current high level of whey valorization by large dairy companies, particularly in Northern Italy, participants noted that in these regions' whey is already extensively processed, limiting the availability of residual streams that could serve as feedstock for new. Others stressed that this situation differs significantly between European regions, with less developed utilization patterns in parts of Eastern Europe, where additional valorization capacity may still be needed.

This led to the broader methodological question of whether the analyzed BioLink® represents a genuinely new value chain or a well-established pathway being replicated, a point that experts considered relevant for interpreting its innovation potential. The global utilization of whey as a resource has driven its transition from a high-load effluent toward a flexible feedstock for foods and bio-based manufacturing. Scalable industrial processes, including membrane separation techniques such as ultrafiltration, nanofiltration, and electrodialysis, are routinely applied to recover valuable components like whey protein concentrates, protein isolates, and lactose derivatives (63).

Social-impact feedback was provided exclusively for the Italian BioLink®, as no social-dimension comments were submitted for Wallonia during the workshop. Discussions for Friuli Venezia Giulia highlighted potential geographical and infrastructural barriers, noting that many dairy farms are located in mountainous areas where transport and aggregation of whey streams may be more challenging. Experts also observed that the region contains numerous small and dispersed dairy farms, which may introduce coordination challenges for feedstock collection. Logistical challenges are a defining factor in mountainous farming systems, where transport and aggregation activities face difficulties due to terrain complexity and the typical dispersion of small-scale farms. These constraints, which contribute to complex social and economic factors, must be addressed by integrating logistical aspects and cooperative models into sustainability assessments to improve the resilience of short food supply chains. Optimizing farming systems by considering the logistics of transport is necessary to solve the complex transport issues often found in mountain regions (64).

Finally, comments linked to replicability and strategic positioning emphasized the strong market outlook for whey-derived proteins and the high attractiveness of this pathway in regions where it is not yet implemented. Experts characterized the value chain as easily replicable, technologically non-complex, and often considered a "low-hanging fruit" due to standardized equipment and robust demand in food, nutraceutical, and material applications. Several participants highlighted that the pathway can be highly

profitable, though this depends strongly on regional availability of available whey streams and competition from plant-based proteins. The global production of dairy protein ingredients is supported by a highly developed manufacturing infrastructure that relies on scalable membrane separation techniques, such as micro- and ultra-filtration, to generate a diverse array of protein products with tailored functional and nutritional attributes. This value chain is attractive due to sustained global demand for high-value fractions, including whey protein isolates, which are essential for growing market segments such as performance nutrition and specific medical purposes. Nevertheless, the local economic profitability of manufacturing these concentrates relies heavily on securing sufficient regional supplies of unvaporized whey streams to feed processing capacity. Strategic positioning must also account for increasing market competition arising from the development of highly sustainable, plant-based proteins favored in the shifting landscape of consumption patterns (60,64).

Concerns were again raised that in highly industrialized dairy regions, whey may already be extensively valorized, potentially limiting feedstock accessibility for new installations. This tension—between high replicability and locally constrained feedstock—was considered a key determinant of regional suitability. Extensive industrial application has established whey as a valuable raw material, resulting in roughly half of the residual volume being recycled into high-value food and chemical products. Despite this widespread utilization, however, the continued disposal of large quantities of unmanaged whey remains a significant source of serious environmental pollution, indicating that the potential for new valorization schemes is highly dependent on securing available, unprocessed feedstock (65). The environmental severity of unmanaged whey disposal arises from its exceptionally high organic load, with biochemical and chemical oxygen demand values far exceeding those of typical dairy effluents. When released into surface water or soils, this oxygen-depleting mixture of lactose, proteins and fats rapidly disrupts aquatic ecosystems, leading to eutrophication, biodiversity loss and, in some cases, groundwater contamination (63,65).

Overall, expert feedback presents whey-protein extraction as a technologically mature, market-driven, and scalable value chain with strong potential in regions where whey streams remain underutilized. However, its expansion may be constrained in areas with already extensive valorization capacity, and its long-term competitiveness will depend on energy-system characteristics, structural features of regional dairy sectors, and evolving dynamics in plant-based protein markets.

3.3.7. Excluded BioLinks®

To provide transparency regarding their rejection and to contextualise the final selection, this section summarises the two BioLinks® that, despite being included in the expert validation workshop, were ultimately excluded from further prioritisation. The BioLinks® **Molasses → Glycerol** (Brussels) and **Corn residues → PHA** (Croatia, Emilia-Romagna, Veneto) are not considered as high-potential value chains in further steps of the SYMBIO project because expert feedback consistently identified fundamental structural, economic and ecological constraints that limit their feasibility within their potential to form a high value replicable business model, see **Annex 2**.

For Molasses → Glycerol, stakeholders repeatedly emphasised that the glycerol market is already saturated, with low demand for additional volumes and strong competition from biodiesel production, which generates large quantities of inexpensive glycerol as a by-product.

Several comments underscored the absence of a robust market, concerns about high price competition, and anticipated low production volumes, all of which directly undermine economic feasibility. Region-specific ecological limitations were also raised: Brussels would require cross-regional transport of molasses from Flanders, increasing environmental burdens; separation and purification challenges for glycerol were flagged; and although molasses being a good fermentation feedstock, experts called for a more explicit comparison of its GHG profile against business-as-usual scenarios. All vote-derived comments stressed unstable value creation, competition with biofuel pathways, and likely supply constraints. Collectively, this positioned the BioLink® as neither economically promising nor regionally suited to the Brussels Capital Region. The voting results reflected this consensus: only 2 out of 7 participants supported the value chain, while 5 voted against its potential to form a high-value replicable business model, making it the lowest-scoring case in the workshop. Additional concerns included significant feedstock and product competition, uncertainties surrounding future sugar-beet cultivation in parts of the EU, and doubts expressed by participants on how this BioLink® advanced to validation given its low social-impact scores.

For Corn residues → PHA, expert comments across the three pilot regions converged on feedstock and soil-health constraints that critically limit the replicability and sustainability of the pathway. Croatian participants stressed that residue collection is difficult for non-existent or dispersed value chains and highlighted the need to leave substantial fractions of corn residues on the field to maintain soil organic matter and future crop productivity. Linked comments reinforced that residue removal reduces soil health and narrows sustainable harvestable volumes — an issue particularly relevant in Croatia's large, heterogeneous agricultural landscapes. Further ecological concerns included transportation burdens between fields and processing sites, seasonality affecting feedstock availability (raised explicitly for Emilia-Romagna), and uncertainties about long-term residue consistency. Economically, experts questioned the competitiveness of residue-based PHA, repeatedly suggesting that converting residues into biofuels may generate higher value. Participants also requested deeper insights into market competitiveness, signalling that residue-based PHA may be economically fragile in regions with established alternative uses. Social-dimension comments noted that residues do not compete with food in Croatia, but that large and diverse regional areas pose coordination challenges for feedstock aggregation.
The poll outcome confirmed these concerns, with 3 participants voting "yes" and 5 voting "no," indicating that a majority did not perceive this value chain as capable of forming a high-value replicable model. Several vote comments further emphasised earlier concerns raised for Belgium — economic infeasibility and soil-health impacts — suggesting cross-regional evidence of limited viability.
Together, these arguments point to a value chain facing fragile economics, strong ecological constraints and insufficient scalability across the SYMBIO pilot regions.

Overall, the exclusion of these two BioLinks® reflects a robust convergence of expert judgment highlighting insufficient market stability, feedstock and sustainability limitations, and mismatch with regional industrial infrastructures. Incorporating these insights ensures that only those value chains with credible economic potential, sustainable biomass mobilisation and strong regional feasibility progress to the next phase of SYMBIO's business-model development.

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3.4. Sensitivity analysis

The results shown in **Figure 2** indicate that the ranking of BioLinks® remains largely stable under both variation levels. At ±10 %, the average absolute rank change was below 0.3 across all criteria, confirming the high robustness of the prioritization. Even under the more extensive ±25 % variation, the average rank changes remained below 0.6, showing that no major reordering of BioLinks® occurred. Criteria C3 (technological diversification potential) and C1 (cost reduction potential) exhibited the highest sensitivity, indicating that changes in these weights have a relatively stronger effect on the ranking. In contrast, C4 (greenhouse gas reduction potential) and C5 (circularity potential) showed very low sensitivity, suggesting that their influence on the overall ranking is comparatively stable.

Overall, the analysis demonstrates that the MCDMA results are robust despite limited expert input, and that the prioritisation of the BioLinks® is not significantly affected by moderate or even larger changes in the weighting scheme.

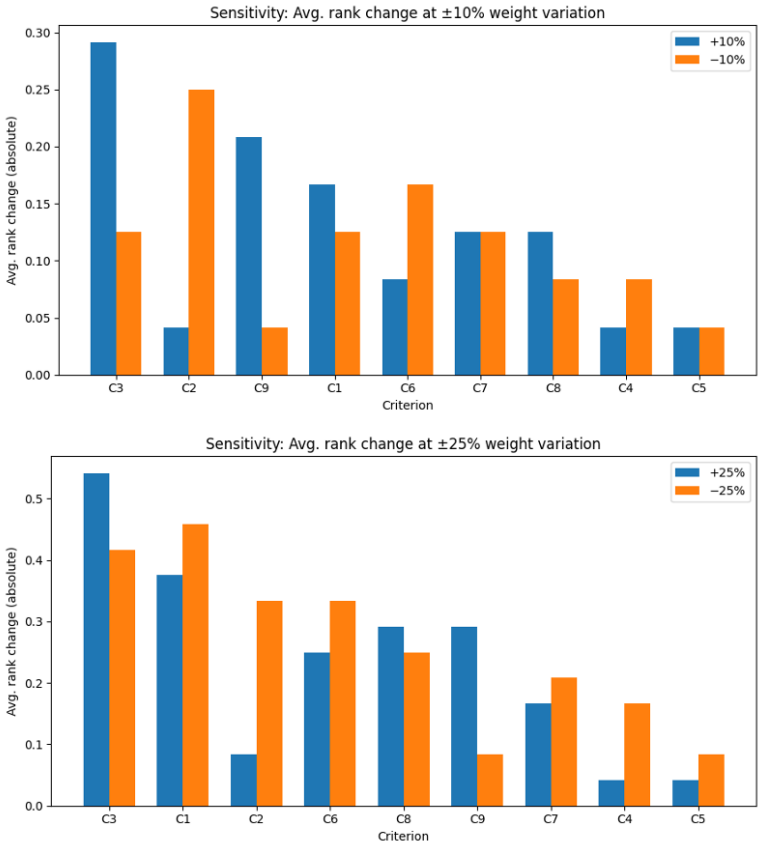

Figure 2: *Sensitivity of MCDMA rankings to ±10% and ±25% weight variations. Criteria abbreviations: C1 – cost reduction potential; C2 – Market competitiveness; C3 – Technological diversification potential; C4 – GRP; C5 – circularity potential; C6 – Ecosystem impact potential; C7 – Regional resilience; C8 – Value creation in the region; C9 – Potential conflict with food.*

4. Limitations of the study

The assessment presented in D3.1 provides a structured and transparent approach for prioritising circular bio-based value chains; however, several methodological and data-related limitations must be acknowledged when interpreting the results. These limitations stem both from inherent constraints of Multi-Criteria Decision Analysis (MCDA) as a decision-support tool and from the practical design of this study within the SYMBIO project context.

Methodological limitations of MCDMA:

Different MCDA methods (e.g., SAW, AHP, TOPSIS, PROMETHEE) often yield different results when applied to the same decision problem (15,66). This lack of methodological consistency leads to a certain degree of subjectivity in the choice of method, which is often influenced more by the analyst's experience, the availability of software, or consistency with previous studies than by objective methodological considerations. Consequently, MCDA results must be interpreted as model-dependent and not as definitive. As emphasised in decision-analysis literature, MCDA does not identify a single objectively optimal solution. Instead, complex sustainability problems fall into a "multi-criteria imbroglio," where outcomes represent trade-offs between conflicting criteria (7,11–13,66). The use of an additive model (SAW) implies compensability: strong performance in one criterion can offset weak performance in another. While this is transparent and easy to interpret, it also risks oversimplifying non-negotiable barriers (e.g., cost reduction potential and technological diversification potential). This structural feature limits the extent to which critical bottlenecks can be fully reflected in the final ranking (11,13,67). MCDA techniques, such as SAW, generally require quantitative data. Converting qualitative or semi-quantitative data into numerical values via scaling techniques is necessary, however this process of quantification risks homogenizing and distorting the original information (15). When objective measurements are not possible, experts must directly rate the performance of options (direct rating). These subjective judgments can be inaccurate and are prone to inconsistency, leading to less precise and less reliable results (66,68).

Limitations concerning stakeholder involvement:

Stakeholder participation forms a core component of MCDA, particularly in defining weights, yet this introduces several challenges. The main weakness of the entire approach is the practical impossibility of determining criterion weights objectively. Weighting is a process heavily dependent on subjective value judgments, meaning the resulting weights tend to be arbitrary and primarily reflect the priorities of the specific individuals involved in the process. The complexity of current environmental problems, which involve multiple conflicting values and scientific uncertainties, necessitates sophisticated tools that can navigate both technical and social incommensurability (11,68). However, the inclusion of stakeholders exponentially increases the complexity, making management difficult. The constraint of running a manageable process often involves a small number of stakeholders, limiting representativeness and such limited participation may introduce potential bias. The practical need for a workable process limits the number of participants, risking a failure to satisfy the requirements of statistical representativeness (11).

In the context of the SYMBIO project, these methodological challenges are further amplified by the structural complexity of the assessment framework. The 47 BioLinks® were developed across six different countries, each characterised by distinct regional priorities, data availability, technological landscapes, and

market conditions. This heterogeneity complicates the weighting process, as ideally each pilot region would require a sufficiently large and diverse group of stakeholders to ensure representative regional perspectives. Despite repeated outreach efforts through local partner networks, only a limited number of experts per country contributed to the weighting exercise, increasing the risk of bias and reducing the statistical robustness of the criterion weights. The BioLinks® also vary significantly in terms of feedstock type, conversion technology, and final product, which inherently limits comparability. To maintain a workable evaluation framework across such diverse cases, SYMBIO necessarily employed generic criteria that could be applied to all value chains. Further, the 47 value chains included in this MCDMA did not originate from an in-depth techno-economic or environmental assessment; instead, they were derived from the data-driven screening processes in D1.2 (feedstock and ecosystem availability) and the automated value chain generation in D2.2. As a result, the BioLinks® represent high-level conceptual chains rather than fully elaborated, operationally validated value chains. This structural characteristic of the dataset restricted the ability to tailor criteria directly to each individual value chain. To address these uncertainties and strengthen the plausibility of the ranking, the project conducted a dedicated expert validation workshop, an approach widely recommended in MCDA to review model-based outcomes and align them with real-world feasibility. It is important to emphasise that the detailed assessment of the high-potential business models identified through the MCDMA will take place in subsequent project steps. These shortlisted value chains will be further examined using Material Flow Analysis in D3.2 and subjected to a more comprehensive environmental, economic, and social impact assessment within WP4. This staged approach ensures that the preliminary prioritisation conducted in D3.1 is followed by deeper, data-rich analyses, enabling more accurate validation of feasibility and systemic impact.

5. Conclusion and Outlook

This Deliverable, D3.1 – MCDMA Inventory and benchmark analysis, provides a systematic prioritisation of circular bio-based value chains within the SYMBIO project. By applying a transparent MCDMA, supported by expert validation, D3.1 establishes a robust foundation for identifying high-potential symbiotic business models with relevance across diverse European regional contexts.

The analysis demonstrates that value chains based on **secondary biomass streams**—such as forestry residues, agricultural by-products, and whey—consistently achieve high performance across ecological, economic, and social dimensions. Their strong results reflect three common characteristics:

1. **high feedstock availability and low opportunity cost**,
2. **technologically mature conversion routes**, and
3. **strong regional embeddedness and replicability potential**.

Based on the MCDMA ranking, fourteen top-performing BioLinks® were shortlisted for expert validation. During the validation workshop, two of these models were **excluded** due to critical technological and market-related barriers:

- **Molasses → Glycerol**: excluded because the **glycerol market is saturated**, with strong competition from low-cost petrochemical and biodiesel-derived glycerol, limiting economic viability and reducing innovation potential.
- **Corn residues → PHA**: excluded due to **sustainability concerns**, particularly **high energy intensity**, competing technology routes, and limited comparative advantages relative to other PHA pathways.

The exclusion of these pathways illustrates the importance of combining the assessment with **qualitative expert judgement**. The validation workshop thus served as a critical decision-making filter to align the final selection with real-world feasibility, regional constraints, and market dynamics. Only through this additional layer of expert reflection was it possible to ensure that the prioritised BioLinks® are not merely high-ranking on paper, but **genuinely implementable, scalable, and strategically sound**.

Following this process, six high-potential BioLinks® were confirmed as the core set for further development. **Figure 3** summarises the final validated pathways:

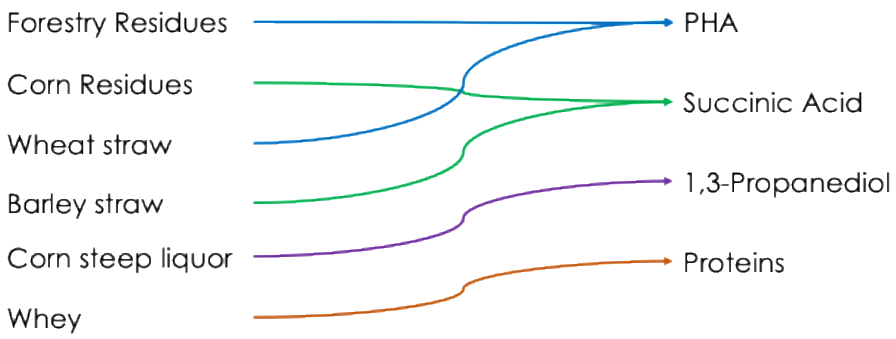

Figure 3: *Selected high-potential value chains linking biomass streams to their corresponding bio-based products.*

At the same time, the assessment highlights methodological constraints. As the weighting of criteria is inherently subjective, the limited number of available regional experts restricts representativeness. Moreover, the 47 underlying BioLinks® are conceptual models based on feedstock availability, existing infrastructure and market demand, rather than fully validated industrial value chains. As such, the current prioritisation should be understood as a **strategic preselection**, to be further substantiated through more detailed analyses.

Outlook

The results of the MCDMA and the qualitative expert validation serve as a strategic foundation for the subsequent phases of Task 3.1 of the SYMBIO project. The identified highly promising regional value chains will now be intensively developed further and form the focus for the detailed MFA in D3.2. The goal of this analysis is to visualize the circularity potential of these business models through the material flows (Sankey Diagrams).

In the next phase, the prioritized value chains identified through the MCDMA and expert validation will be examined within the broader regulatory context analysed in Deliverable 3.3 – Policy overview and recommendations – Preliminary version. The insights from D3.3 will be linked with the selected 14 BioLinks® to assess regulatory barriers and enabling conditions along the full value chain, with particular attention to key EU policy frameworks such as the Waste Framework Directive and the updated EU Bioeconomy Strategy 2025 to form D3.4 – Policy overview and recommendations – Final version. To validate these findings and ensure policy relevance, Task 3.2 will also implement a targeted policy survey involving regional and EU-level policymakers.

In Task 3.3, multi-stakeholder engagement will intensify through regional focus groups, aiming to involve in total 100 stakeholders from the 12 pilot regions. These focus groups are crucial for a collaborative analysis and validation of the regional Biolinks® as successful circular business models, including defining measurement points, elaborating appropriate funding pathways, and regulatory constraints. The goal is to ensure the intuitiveness of the proposed solutions and facilitate their easy adoption by local and regional actors. The outcomes of these focus groups are summarized in Deliverable D3.5, forming an industrial symbiosis handbook.

Furthermore, the insights gained in T3.1 will directly feed into Work Package 4 (WP4), where the economic (D4.1), environmental (D4.2), and social (D4.3) impacts of the ten selected symbiotic business models will be comprehensively measured using a Triple Layer Business Model Canvas assessment.

Long-term, the SYMBIO project aims to enable active political and entrepreneurial measures through the establishment of these validated, replicable symbiotic business models. The ultimate goal is to overcome structural barriers and provide an industrial symbiosis handbook with an integrated reporting system, thereby accelerating the adoption of circular bio-based business models across the EU and making a systemic contribution to the green transformation by working toward decoupling economic growth from resource exhaustion and environmental degradation.

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9. Annex

Annex 1: MCDMA Assessment

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Annex 2: Expert Validation Workshop – MIRO Board