Copyright

Statement of responsibility

This document engages only its author

European Master in Biological and Chemical Engineering for a Sustainable Bioeconomy

Master thesis report

Submitted to obtain the degrees of:

Master in Biology AgroSciences (BAS) of the University of Reims Champagne-Ardenne

Master in Integrative Biology and Physiology (BIP) of the University Paris-Saclay, operated by AgroParisTech

Master in Bioengineering: Chemistry and Bioindustries of the University of Liège

Multi-Criteria Analysis for Assessing and Classifying Sustainability Indicators for the European Bioeconomy in the frame of Multi-Stakeholder CALIMERO project

Presented by**: MALEKZADEH Sajjad**

Defended the 25/06/2024

Supervised by

Dr. SZABLEWSKI Carolina

Dr. ADIBI Naeem

at: **WeLOOP**

254 rue du Bourg, 59130 Lambersart

From: 02/02/2025 to 01/07/2024

Bioceb supervisors:

Dr. RICHEL Aurore, Université de Liège

Dr. BENOIT Gabrielle, AgroParisTech

Confidentiality: Yes No ☑ Privacy expiration date: …/…/…

Table of Contents

List of Figures

List of Tables

List of Abbreviations

GHG	Green House Gas
EU	European Union
BMS	Bioeconomy Monitoring System
MS	Member States
JRC	Joint Research Center
MCA	Multi-Criteria Analysis
MCDM	Multi-Criteria Decision Making
SDGs	Sustainable Development Goals
CRMs	Critical Raw Materials
ICDM	Incentives and Decision-Making Support
DQA	Data Quality and Availability

Abstract

The European Union's transition towards a sustainable and circular bioeconomy requires robust monitoring to guide policy and industry actions. The existing EU Bioeconomy Monitoring System (BMS), while comprehensive at a macro level, has limitations in providing sector-specific and practical guidance for stakeholders. This results in a gap between high-level monitoring and the operational needs of companies within key bio-based sectors.

This thesis, conducted within the EU-funded CALIMERO project, presents a harmonized methodology to address this gap by assessing and classifying sustainability indicators for the European bioeconomy. The research employs a participatory framework, engaging academic and industrial experts to identify and select relevant indicators for the textile, woodworking, construction, and biochemical sectors.

The core of the methodology is a Multi-Criteria Analysis (MCA) where shortlisted indicators are evaluated against two primary dimensions: Incentives and Decision-Making Support (IDMS) and Data Quality and Availability (DQA). A weighted scoring system is used to aggregate expert judgments, allowing for a nuanced classification of indicators based on their practical utility and data robustness.

Due to the timeline of data collection, this report presents the complete methodology and an illustrative analysis based on partial data. The results are visualized in a four-quadrant matrix that categorizes indicators, identifying those that are immediately usable, those that require improved data, and those that hold high value for specific, specialized applications.

Ultimately, this work provides a transparent and collaborative methodology that complements the EU BMS. It offers a crucial tool for policymakers and companies to select meaningful, sector-specific indicators, thereby fostering better alignment with EU sustainability goals and supporting the transition to a competitive European bioeconomy.

Keywords:

Bioeconomy, Sustainability Assessment, Sustainability Indicators, Multi-Criteria Analysis (MCA), Multi-Criteria Decision Making (MCDM), Participatory Approach, Decision Support, European Union

1. Introduction

The global economy faces major sustainability challenges, requiring a significant shift from standard linear economic models. The growing climate crisis, mainly due to Green house gas (GHG) emissions from using fossil fuels, poses serious threats to ecosystems and societies, necessitating urgent efforts to reduce carbon emissions (Calvin et al., 2023). At the same time, increasing world populations and resource consumption levels put intense pressure on limited natural resources. This causes resource depletion, environmental damage, and concerns about having enough resources for the future (UNEP, 2024; United Nations Environment Programme, 2020). Problems like widespread plastic pollution, loss of biodiversity, and soil damage further demonstrate the environmental problems brought forth by traditional economic models (Bongaarts, 2019; Geyer et al., 2017). Addressing these connected crises requires moving towards economic models that operate within the earth's environmental limits and support global goals like the Sustainable Development Goals (United Nations, 2015)

To pursue a more sustainable future, the bioeconomy and circular economy offer vital approaches. The bioeconomy utilizes renewable biological resources to produce items like food, bio-based materials, and energy, replacing fossil-based inputs (European Commission, Directorate General for Research and Innovation, 2018). The circular economy complements this by seeking to decouple economic activity from resource use through smarter design and by keeping products and materials in use longer through reuse, repair, and recycling, thus minimizing waste (A New Circular Economy Action Plan, 2020; Kirchherr et al., 2017)

Recognizing this potential, the European Union (EU) has strategically included the bioeconomy and circular economy in its main long-term policies. These concepts are key parts of the European Green Deal, the EU's plan to reach climate neutrality by 2050 and address other environmental issues (Donnelly, 2024). The updated EU Bioeconomy Strategy clearly aims to link the economy, society, and the environment more closely, focusing on developing local bioeconomies, recognizing environmental limits, and ensuring sustainability (A Sustainable Bioeconomy for Europe, 2018). Similarly, the Circular Economy Action Plan describes specific actions to speed up the move to a circular system across different sectors (A New Circular Economy Action Plan, 2020).

Given this strong strategic focus and the complex nature of this change, closely tracking the progress, results, and effects of the bioeconomy is essential for making policies based on reliable data, taking specific actions, and making sure the change achieves its sustainability goals. This requires strong monitoring systems that can measure the many different aspects – economic, environmental, and social – of this changing area, leading to initiatives such as the EU Bioeconomy Monitoring System (BMS) (EU Bioeconomy Monitoring System, n.d.).

This system was developed and is mainly managed by the European Commission's Joint Research Centre (JRC), working together with other commission departments. The BMS serves as the EU's primary official tool for observing how the bioeconomy is developing across its Member States (MS) and provides measurable information to policymakers and other interested parties. (EU Bioeconomy Monitoring System, n.d.).

However, navigating the vast array of available indicators presents a significant challenge for strategic planning by companies and regions. Each indicator is grouped in a specific category, yet its multi-dimensional aspect is not considered. Furthermore, it provides limited practical insights for companies to find the most important indicators related to their sector or field of activity.

To address these gaps, as part of the EU-funded CALIMERO project, we aim to develop a harmonized methodology specifically designed for assessing and classifying the sustainability indicators of bio-based products and processes in the five sectors of Textile, Pulp & Paper, Woodworking, Construction, and Biochemicals.

This methodology complements the BMS by developing additional indicators grounded in a life cycle thinking approach, encompassing social, environmental, criticality, circularity, and other aspects. Relevant indicators and criteria are validated through a collaborative approach involving industrial and academic partners within each sector. Subsequently, a multi-criteria analysis (MCA) of these indicators will be performed to provide actionable insights supporting decision-making at both industry and policy levels within the targeted sectors. The primary outputs will include a specific set of indicators analyzed according to various criteria covering industrial and policy levels metrics, alongside guidelines on implementing them.

Ultimately, this methodology offers a crucial tool for policy makers and companies alike, providing a pathway to integrate validated, sector-specific indicators, thereby enabling alignment with regional/EU sustainability goals and supporting the transition towards a more sustainable and competitive European bioeconomy.

2. State-of-the-art

2.1. An Introduction to the EU Bioeconomy Monitoring System

The transition to a sustainable and circular bioeconomy represents a key strategic objective under the European Green Deal (Robert et al., 2020). To guide this transition effectively, the updated EU Bioeconomy Strategy (2018) emphasizes the importance of developing a comprehensive monitoring system capable of tracking economic, environmental, and social dimensions across EU Member States (Robert et al., 2020).

Operating within a complex policy landscape, the Bioeconomy Strategy interacts closely with various sectoral and cross-sectoral policies, including the Common Agricultural Policy, Common Fisheries Policy, the New Industrial Strategy for Europe, the EU Biodiversity Strategy, the Circular Economy Action Plan, and the 2030 Climate and Energy Framework (Robert et al., 2020). The Bioeconomy Strategy, encompassing five strategic objectives, **Table *1*** ,serves as a pivotal mechanism for enhancing coherence among these diverse policy initiatives (Robert et al., 2020).

A robust monitoring system is essential to measure the progress of the EU bioeconomy. Policymakers have emphasized the necessity for transparent, comprehensive assessments to support informed decision-making (Robert et al., 2020). Therefore, an internationally coherent monitoring system Led by the JRC in collaboration with multiple commission services and stakeholders was built and called Bioeconomy Monitoring System (BMS) (Robert et al., 2020). This monitoring system is envisioned as a vital tool for reflexive governance, facilitating evaluation and identifying policy interventions (Robert et al., 2020).

2.1.1. Implementation Framework

The implementation of the EU-BMS begins by translating the five strategic objectives of the 2018 Bioeconomy Strategy into clear normative criteria. These criteria are derived from established sustainability frameworks, such as the FAO's principles for sustainable bioeconomy (**Figure *2***) and the United Nations Sustainable Development Goals (SDGs) (Robert et al., 2020).

Table 1 2018 EU Bioeconomy Strategy: Objectives, Effectiveness Criteria, and Alignment with SDGs (Robert et al., 2020).

EU Strategy Objective	Normative content	Related SDGs

Ensuring food and nutrition security	• Food security and nutrition are supported • Sustainable trade of biomass for food uses is promoted	
Managing natural resources sustainably	• Ecosystem condition and biodiversity are maintained or enhanced • Primary production sectors are managed sustainably • Ecosystem services contribution to human wellbeing is maintained or enhanced without deteriorating ecosystem condition and/or biodiversity	
Reducing dependence on nonrenewable, unsustainable resources, whether sourced domestically or from abroad	• Resource efficiency, waste prevention and waste reuse along the whole bioeconomy value chain are improved • Food loss and waste are prevented or minimized and, when unavoidable, its biomass is reused or recycled • Sustainable production and consumption of biomass and biobased products (within the EU) are promoted • Consumption patterns of bioeconomy goods match sustainable supply levels of biomass • Bioeconomy should promote sustainable trade of biomass for nonfood uses • Sustainability of urban centers is enhanced	

Mitigating and adapting to climate change	• Climate change mitigation and adaptation are pursued • The sustainability of urban centers is enhanced	
Strengthening European competitiveness and creating jobs	• Economic development is fostered • Inclusive economic growth is strengthened • Resilience of the rural, coastal and urban economy is enhanced • Existing knowledge is adequately valued, and proven sound technologies are fostered • Knowledge generation and innovation are promoted • Demand and supply side market mechanisms of food and nonfood goods are enhanced	

2.1.2. Data and measurement limitations

Despite its comprehensive approach, the EU-BMS encounters several challenges, including (Robert et al., 2020):

- Data gaps, particularly in emerging biobased sectors (e.g., algae, bioplastics) and social sustainability indicators (e.g., equity, labor rights).
- Limitations in statistical classifications that complicate distinguishing biobased from fossil-based products.
- Attribution issues when assessing the impacts of EU bioeconomy activities on non-EU regions, particularly concerning international trade (e.g., palm oil, ethanol).

To mitigate these challenges, the JRC utilizes placeholder indicators and advocates for improved data classification and coding practices in official statistical systems (Robert et al., 2020).

2.1.3. Other Limitations of the current system

While the EU Bioeconomy Monitoring System provides a broad and structured overview of the bioeconomy's performance, it does not offer a customizable selection process tailored to the specific needs of industrial actors. Moreover, its current scope focuses primarily on a few bioeconomy sectors by only considering a few specific indicators for them, which is addressed by the inclusion of additional indicators in our assessment to ensure broader sectoral representation. Notably, the social and governance dimensions remain underrepresented compared to economic and environmental aspects. To address these gaps, supplementary indicators from other frameworks are required, thereby enhancing the inclusiveness and robustness of the monitoring system. This expanded approach allows for a more comprehensive and balanced evaluation, aligning more closely with the multidimensional nature of sustainability.

Additionally, the BMS struggles to fully capture crucial aspects of resource management relevant to modern sustainability goals, particularly concerning circularity and material criticality. While the EU strongly promotes the circular economy (European Commission, Directorate-General for Environment, 2020), the BMS's indicators related to circularity are often limited, potentially focusing only on recycling rates for specific, high-volume material streams rather than encompassing broader strategies like reuse, remanufacturing, or tracking circular business model adoption across diverse biobased value chains. Moreover, the assessment of material criticality is largely absent from the BMS framework. Bioeconomy processes, despite using renewable biomass, can still depend on non-renewable inputs, including critical minerals, catalysts or specific elements defined by the EU as Critical Raw Materials (CRMs) due to economic importance and supply risk (Critical Raw Materials Act).

Collectively, the identified gaps demonstrate a clear need for a more targeted approach. A method is required that may bridge the gap between high-level EU monitoring and the practical informational demands of individual biobased industries and the enterprises working within them. This method demands leveraging the contributions of industry and academic specialists in the relevant fields. Furthermore, a sophisticated analytical approach is necessary to convert massive volumes of qualitative and quantitative data into coherent and actionable information to help decision-making.

To address these methodological requirements, particularly the challenge of evaluating options against multiple and often conflicting criteria, the application of Multi-Criteria Analysis (MCA) is explored in this thesis. The subsequent section will present a review of existing literature on MCA. This review will cover its fundamental principles, common methods, and its applications in sustainability and bioeconomy contexts, thus providing the basis for selecting MCA as an appropriate framework for the methodology developed in this research.

2.2. Multi-Criteria Analysis in Environmental and Sustainability Decision-Making: A Literature Review

2.2.1 Introduction to Multi-Criteria Analysis (MCA/MCDM)

Multi-Criteria Analysis (MCA), often used interchangeably with Multi-Criteria Decision-Making (MCDM), constitutes a significant branch of decision theory and operations research. Its fundamental aim is to facilitate the selection of the most suitable alternative from a set of options by systematically evaluating them against multiple, often conflicting, criteria (Taherdoost & Madanchian, 2023). MCA is not a single method but rather an umbrella term encompassing a diverse array of tools and methodologies designed to address complex decision problems (Poulsen, 2022). It provides a structured, transparent, and systematic framework for comparing alternatives, proving particularly valuable when decisions involve significant non-monetary aspects, such as social or environmental impacts (Chief Minister, 2022). This structured approach to navigating complexity is central to addressing contemporary sustainability challenges.

A new sustainability paradigm, emphasizing environmental multi-functionality and robust social participation, highlights the need for analytical tools like MCA to manage complex demands (Diaz-Balteiro et al., 2020). The application of MCA methods have increased in environmental and sustainability contexts, including fields like sustainable engineering, sustainable forest management, and waste management (Kpadé et al., 2024) due to the consideration of environmental, social, and economic dimensions which often contradict each other (Malefaki et al., 2025).

However, the very diversity of MCA presents its own challenge. The existence of numerous methods, each with distinct strengths, weaknesses, and underlying assumptions (Taherdoost & Madanchian, 2023), means that the selection of an appropriate method can itself become a multi-criteria problem (Poulsen, 2022). This "meta-problem" underscores the importance of clear guidance for method selection (Ziemba, 2022) and a thorough understanding of the chosen method's implications. This has also encouraged the creation of frameworks to handle the conflicting results from various MCDM methods for better decision-making support (Pagone & Salonitis, 2023).

2.2.2 Common MCA/MCDM Methods in Environmental and Sustainability Contexts

A variety of MCA/MCDM methods are employed in environmental and sustainability decision-making, each with unique characteristics and suitability for different problem types. Among the most frequently cited and applied are the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Kpadé et al., 2024).

AHP is widely utilized for decomposing complex decision problems into a hierarchical structure of goals, criteria, sub-criteria, and alternatives. It employs pairwise comparisons to establish the relative importance of criteria and the preference for alternatives (Taherdoost & Madanchian, 2023). On the one hand, AHP is valued for its simple way of structuring problems and collecting expert judgments. On the other hand, it faces challenges because it assumes the criteria are independent, and it has the potential for "rank reversal," which means the final ranking can flip when alternatives are changed (Taherdoost & Madanchian, 2023).

TOPSIS ranks alternatives based on their simultaneous proximity to an ideal solution (the best hypothetical alternative) and distance from a negative ideal solution (the worst hypothetical alternative) (Behzadian et al., 2012) its conceptual simplicity is an advantage, though it requires careful normalization of data and can be sensitive to the definition of the ideal and anti-ideal points.

Outranking methods, such as the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) and Elimination and Choice Translating Reality (ELECTRE), form another significant group (Behzadian et al., 2012). These methods compare alternatives in pairs for each criterion, building an "outranking relation" that indicates the degree to which one alternative is at least as good as another. PROMETHEE, for instance, uses preference functions to express the intensity of preference for one alternative over another for each criterion (Ziemba, 2022). Outranking approaches are particularly useful when a full compensation between good performance on one criterion and poor performance on another is not considered appropriate (Ziemba, 2022).

Simpler aggregation methods like the Weighted Sum Model (WSM), also known as Simple Additive Weighting (SAW), are based on the arithmetic aggregation of weighted criteria scores (Hansen & Devlin, 2019). Their transparency and ease of use make them popular, although they assume full compensability among criteria.

The Analytic Network Process (ANP) extends AHP by allowing for interdependence and feedback relationships among criteria and alternatives, offering a more systemic view of the decision problem (Kpadé et al., 2024).

Given the inherent uncertainties and imprecision often encountered in environmental data and expert judgments, Fuzzy Set Theory (FST) and its extensions, such as Fuzzy AHP and Fuzzy TOPSIS, have gained attention (Taherdoost & Madanchian, 2023). These methods allow you to work with unclear or language-based information, making them useful for sustainability assessments, an area that often lacks precise numerical data.

Other notable methods include VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), which focuses on finding a compromise solution that is closest to the ideal (Štilić & Puška, 2023), and various hybrid approaches that combine the strengths of different techniques to address specific problem characteristics.

MCA methods can be broadly categorized based on several factors, including the type of aggregation procedure used (e.g., outranking relations, utility functions), whether they allow for compensation between criteria (compensatory, non-compensatory, or partial compensatory), the number of decision-makers involved (individual or group), or the nature of the problem (Taherdoost & Madanchian, 2023). Understanding these classifications is crucial for selecting a method that aligns with the specific structure of the decision problem, the nature of the available data, and the preferences of the decision-makers.

To provide a clearer overview, **Table *2*** summarizes common MCA/MCDM methods used in sustainability contexts.

Table 2 Overview of Common MCA/MCDM Methods in Sustainability Contexts

Method Name	**Principle**	**Common Applications in Sustainability**	**Key Strengths**	**Key Weaknesses**
AHP (Analytic Hierarchy Process)	Decomposes problem into hierarchy; uses pairwise comparisons to derive weights for	Forest management, energy planning,	Structures complex problems, systematic	Assumes criteria independence, potential for rank reversal, can be

	criteria and scores for alternatives (Taherdoost & Madanchian, 2023)	waste management, sustainable material selection (Kpadé et al., 2024)	elicitation of judgments, handles qualitative & quantitative data (Taherdoost & Madanchian, 2023)	laborious for many criteria/alternatives (Taherdoost & Madanchian, 2023).
TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	Ranks alternatives based on shortest distance to ideal solution and farthest distance from negative-ideal solution. (Kpadé et al., 2024)	Sustainable energy, waste management, supplier selection, environmental assessment. (Kpadé et al., 2024)	Conceptually simple, computationally efficient, considers both ideal and anti-ideal solutions. (Štilić & Puška, 2023)	Requires normalization, definition of ideal/anti-ideal can be subjective, does not show strength of preference. (Štilić & Puška, 2023)
PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation)	Outranking method; compares alternatives pairwise based on preference functions for each criterion. (Kpadé et al., 2024)	Environmental management, water resources, energy planning, landscape management. (Kpadé et al., 2024)	Handles qualitative data well, transparent preference functions, provides partial or complete ranking. (Ziemba, 2022)	Choice of preference function and parameters can be subjective, may lead to incomparability of some alternatives. (Ziemba, 2022)
ELECTRE (Elimination and Choice Translating Reality)	Family of outranking methods; uses concordance/discordance concepts to compare alternatives. [2]	Waste management, energy policy, environmental impact	Handles imprecise data, robust to small data changes, identifies non-dominated	Can be complex to apply, results may be difficult to interpret for non-experts, may not provide a complete

		assessment. [2]	alternatives. (Taherdoost & Madanchian, 2023)	ranking. (Taherdoost & Madanchian, 2023)
WSM/SAW (Weighted Sum Model / Simple Additive Weighting)	Aggregates performance scores by multiplying each criterion score by its weight and summing up. [2]	General sustainability assessment, project selection, resource allocation. (Malefaki et al., 2025)	Simple to understand and implement, transparent calculation.	Assumes full compensability between criteria, sensitive to criteria scaling and weighting (Ziemba, 2022)
ANP (Analytic Network Process)	Generalization of AHP; allows for interdependencies and feedback loops between criteria and alternatives. (Kpadé et al., 2024)	Complex system modeling in sustainability, supply chain management, policy analysis (Kpadé et al., 2024).	Models complex relationships and dependencies, provides a more systemic view (Štilić & Puška, 2023)	More complex than AHP, requires more data and effort for pairwise comparisons. (Ziemba, 2022)
Fuzzy AHP/TOPSIS etc.	Incorporates fuzzy set theory to handle imprecise, vague, or linguistic data in AHP, TOPSIS, etc (Štilić & Puška, 2023).	Sustainability assessment with uncertain data, risk assessment, environmental decision-making (Štilić & Puška, 2023).	Manages uncertainty and subjectivity effectively, allows for linguistic assessments (Taherdoost & Madanchian, 2023)	Can be computationally more intensive, development of fuzzy membership functions can be challenging.

VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje)	Ranks alternatives by focusing on closeness to the ideal solution, providing a compromise solution. (Štilić & Puška, 2023).	Environmental management, water resource planning, risk management. (Štilić & Puška, 2023)	Provides a compromise solution considering group utility and individual regret, useful for conflicting criteria. (Štilić & Puška, 2023)	Requires definition of weights and a strategy parameter, can be sensitive to these inputs (Ziemba, 2022)

2.2.3 Key Applications of MCA/MCDM in bioeconomy

2.2.3.1 In biobased sectors

The applications of MCA in bioeconomy span various bio-based sectors:

- **Sustainable Forest Management:** AHP and TOPSIS are commonly employed to address economic, social, and environmental aspects of forest management, including the valuation of ecosystem services and strategies for climate change adaptation (Kpadé et al., 2024). Hybrid methods like AHP-PROMETHEE have been used for landscape management decisions. (Lakicevic et al., 2021).
- **Bioenergy Systems:** This sector sees extensive use of MCDM, with AHP, GIS-based MCDM, TOPSIS, PROMETHEE, and ELECTRE being applied to decisions regarding site selection for bioenergy plants, choice of conversion technology, biomass resource assessment, and policy formulation (Güldeş & Gürcan, 2022). Criteria typically cover techno-economic feasibility (e.g., costs, efficiency), environmental impacts, and social considerations (e.g., job creation, community acceptance). Notably, social criteria have been identified as decisive factors for the viability of bioelectricity projects in some contexts (Buchholz et al., 2009).
- **Biomaterials and Green Material Selection:** Hybrid MCDM approaches, such as combining DEMATEL-based ANP (DANP) with Grey-TOPSIS (G-TOPSIS), are used for selecting green materials. These assessments consider economic properties (initial, maintenance, disposal costs), environmental attributes (energy saving, recyclability, CO2 emissions, water usage), and physical properties (density, strength) (Zhang et al., 2017). Other studies have applied AHP, TOPSIS, and GRA

for selecting sustainable materials in sectors like aviation and general engineering (Malefaki et al., 2025).

- **Circular Bioeconomy (CBE):** MCA methodologies contribute to CBE strategy formulation, technology impact assessment, and sustainability risk evaluation (Venkatesh, 2022). A multi-criteria approach has been proposed for effectively matching CBE technologies with specific regional contexts by evaluating a comprehensive set of success criteria (including biomass resources, technological capacity, social acceptance, environmental impact, economic viability, and political/legislative frameworks) and their region-specific and technology-specific characteristics through detailed evaluation matrices (Güldemund & Zeller, 2024).
- **Biorefinery Pathways and Siting:** Techno-economic and environmental assessments of different biorefinery pathways (e.g., for producing biobased adipic acid) compare alternatives based on key metrics such as minimum selling price (MSP) and GHG emissions (Sikazwe et al., 2024). For biorefinery sitting, multi-criteria decision support tools (DST) are developed that integrate economic, environmental (e.g., Global Warming Potential), and social (e.g., job creation, local social assets) metrics. The application of user-defined weights to these metrics can significantly alter the ranking of potential sites, reflecting different stakeholder priorities (Martinkus et al., 2019).
- **Food Systems:** MCA is utilized to compare the sustainability of different farming systems (e.g., conventional vs. organic), to develop consumer guidance tools, and to inform policy aimed at achieving sustainability goals. These assessments typically involve a range of economic, social, and environmental indicators (Poulsen, 2022).

Furthermore, across various bio-based projects, social acceptability often emerges as a crucial non-technical factor that can determine project success or failure. Studies on bioelectricity projects in Uganda (Buchholz et al., 2009), biorefinery siting considering social assets (Martinkus et al., 2019), and the identification of social acceptance as a key success cluster for the Circular Bioeconomy (Güldemund & Zeller, 2024) all highlight this point. Even if a bio-based project is technically sound and economically viable, a lack of community support or negative social impacts can create insurmountable barriers. MCA provides an invaluable framework for systematically integrating these often qualitative and context-dependent social criteria into the decision-making process, thereby fostering more holistic and socially sustainable outcomes.

2.2.3.2 Development of Frameworks

MCA's role extends beyond evaluation using pre-defined indicators; it is instrumental in the development of indicator frameworks themselves. This comprehensive involvement spans the entire lifecycle of indicator framework creation, including the identification of relevant criteria or indicators, their structural organization (often hierarchical), the process of scoring (which involves normalization to ensure comparability), and the crucial step of weighting to reflect relative importance (Poulsen, 2022).

The development of indicator frameworks using MCA is not a strictly linear progression but rather an iterative and co-evolutionary process. Initial application of an MCA might reveal deficiencies or gaps in an existing indicator set, prompting its revision and refinement. Feedback obtained from stakeholders during a participatory MCA process can lead to a re-evaluation and adjustment of both the indicators themselves and their assigned weights (Gudlaugsson et al., n.d.). This dynamic interplay suggests that building robust and relevant sustainability indicator frameworks with MCA is an ongoing learning process. In many cases, the dialogue and learning that occur during the participatory process can be as valuable, if not more so, than the final ranking or decision itself.

However, the quality of outcomes from a participatory MCA is intrinsically linked to the quality of the participation itself. While MCA provides the framework, its effectiveness hinges on *how* stakeholders are engaged: which groups are included or potentially excluded, how their inputs are elicited, synthesized, and aggregated, and how power imbalances among stakeholders are managed or mitigated (Participatory Multi-Criteria Decision Aid, n.d.). A poorly designed or executed participatory process can lead to results that are biased, unrepresentative, or fail to achieve genuine buy-in. Therefore, meticulous design of the engagement strategy, ensuring inclusivity, fairness, and transparency, is crucial for realizing the full potential of participatory MCA in achieving robust, equitable, and widely accepted sustainability decisions.

2.2.4 Rationale, Strengths, and Weaknesses of MCA/MCDM

Table *3* provides a summary of the key strengths and weaknesses associated with MCA/MCDM.

Table 3 Summary of Strengths and Weaknesses of MCA/MCDM

Strengths	Weaknesses
Structures Complexity: Breaks down complex problems into manageable components (*PDF*, n.d.).	**Subjectivity:** Relies on judgments in criteria selection, weighting, and scoring (Poulsen, 2022)
Handles Diverse Data Types: Accommodates quantitative, qualitative, monetary, and non-monetary data (Taherdoost & Madanchian, 2023)	**Complexity of Some Methods:** Can be difficult to understand and apply, requiring expertise (Poulsen, 2022).
Incorporates Different Perspectives: Facilitates stakeholder participation and integration of varied values (Štilić & Puška, 2023).	**Potential for Bias:** Unconscious or advocacy bias can influence the process (*PDF*, n.d.)
Transparency: Makes the decision process explicit and understandable if well-documented (Chief Minister, 2022)	**Data Availability and Quality:** Reliable and consistent data can be difficult to obtain (Štilić & Puška, 2023).
Flexibility and Adaptability: Can be tailored to specific problems and contexts (Poulsen, 2022).	**Model Uncertainty:** Mathematical models may not perfectly reflect real-world complexities (Štilić & Puška, 2023).
Efficiency (Relative to CBA): Can be less data and effort-intensive, useful for filtering options (*PDF*, n.d.).	**Assessing Absolute Viability:** Difficult to adequately consider the scale of benefits relative to costs (Chief Minister, 2022).
Consistency: Promotes consistent decision-making over time with a standardized framework (*PDF*, n.d.).	**Double Counting:** Risk of evaluating the same impact under multiple non-exclusive criteria (Chief Minister, 2022).
Provides Overall Evaluation: Many methods yield a final score or ranking for alternatives (Poulsen, 2022).	**Methodological Variance / Conflicting Rankings:** Different methods can yield different results (Poulsen, 2022).

	Perceived Arbitrariness: Especially with weighting, though exclusion of weights is also arbitrary (Poulsen, 2022).
	Reliance on Inputs: Quality of output depends heavily on the quality of expert/stakeholder input (Poulsen, 2022).

It is important to recognize the dual nature of some MCA characteristics. Subjectivity, for instance, while a primary criticism (Poulsen, 2022), is also intrinsically linked to MCA's strength in incorporating diverse human values and perspectives (Štilić & Puška, 2023). The challenge, therefore, is not to eliminate subjectivity entirely, which would negate a key benefit, but to manage it through transparent, structured, and participatory processes that legitimize the value judgments embedded in the model. The critical weighting step, often seen as a vulnerability (Poulsen, 2022), becomes an opportunity for explicit value articulation when handled openly.

Many of MCA's perceived strengths and weaknesses are, in effect, two sides of the same coin. The ability of many methods to produce a single summary score for easy comparison (Poulsen, 2022) can, if not complemented by an examination of disaggregated results, lead to a misleading sense of precision or mask important trade-offs between criteria. Effective application thus requires an awareness of these dualities - such as robust documentation, thorough sensitivity analysis, and stakeholder validation - to leverage the strengths while mitigating the associated weaknesses.

The definition of «strength" or "weakness" is also highly context dependent. The "complexity of some methods" (Poulsen, 2022) might be a significant drawback in situations requiring rapid, simple decisions with limited analytical capacity. However, in other contexts, this same complexity might be a strength if it allows for a more accurate modeling of an intricate socio-ecological system. Likewise, the "reliance on stakeholder input" (Poulsen, 2022) is a weakness if that input is poorly informed or biased, but a considerable strength if it leads to more legitimate, equitable, and widely accepted decisions.

2.2.5 Conclusion and Outlook

Multi-Criteria Analysis has established itself as a powerful and versatile set of methodologies for addressing the complex decision-making challenges inherent in environmental management and sustainability science. Its ability to systematically structure problems, integrate a wide array of quantitative and qualitative criteria, incorporate diverse stakeholder perspectives, and enhance the transparency of the decision-making process makes it an invaluable tool.

However, while MCA offers significant advantages, it is not a panacea. The limitations associated with its application, primarily concerning subjectivity in criteria selection and weighting, the complexity of certain methods, and the potential for bias, necessitate careful and critical management. Robust methodological choices, transparent documentation, rigorous sensitivity analysis, and meaningful participatory processes are essential to mitigate these limitations and ensure the credibility and legitimacy of MCA-derived outcomes.

Finally, the application of MCA is increasingly shifting towards more proactive and strategic uses in sustainability planning. Beyond problem-solving, such as selecting the best available technology for waste treatment, MCA is becoming an essential tool for foresight, scenario analysis, and the strategic design of sustainable pathways, for instance, in developing long-term forest management strategies responsive to climate change (Kpadé et al., 2024), planning smart and resilient local energy systems (Gudlaugsson et al., n.d.), or charting sustainable development trajectories for the bioeconomy (Güldemund & Zeller, 2024). This positions MCA as a critical instrument for navigating the complex and uncertain future of sustainability.

3 Research Methodology:

3.1 A Harmonized Methodology within the CALIMERO Project

Addressing the identified gaps, this research, conducted within the scope of the EU Horizon funded CALIMERO project, proposes a harmonized methodology for classifying and assessing the sustainability indicators. This methodology directly confronts the limitations discussed previously (Section 2.1.3).

This methodology complements the BMS by developing additional indicators grounded in a life cycle thinking approach, encompassing social, environmental, criticality, circularity, and other aspects. Relevant indicators and criteria are validated through a collaborative approach involving industrial and academic partners within each sector. Subsequently, a multi-criteria analysis (MCA) of these indicators will be performed to provide actionable insights supporting decision-making at both industry and policy levels within the targeted sectors. The primary outputs will include a specific set of indicators analyzed according to various criteria covering industrial and policy levels metrics, alongside guidelines on implementing them.

Ultimately, this methodology offers a crucial tool for policy makers and companies alike, providing a pathway to integrate validated, sector-specific indicators, thereby enabling alignment with regional/EU sustainability goals and supporting the transition towards a more sustainable and competitive European bioeconomy.

This chapter focuses on the developed methodology, which is based on a participatory approach with expert stakeholders and integrates MCA concepts. This interactive method was inspired by the EU Bioeconomy Monitoring System (BMS). This approach drew on the diverse expertise and technical knowledge of the project partners to assure the framework's practical applicability and strength. Figure 1 shows an overview of the recommended steps to be taken for this method.

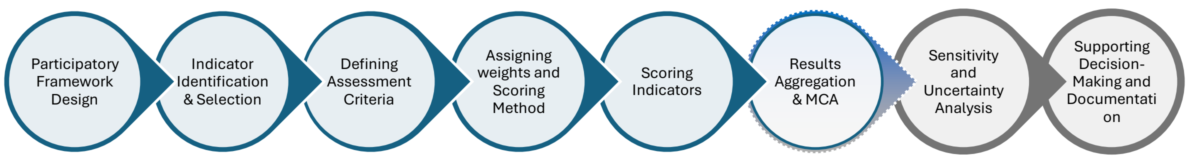

Figure 1 The recommended methodological approach, the blue sections represent the steps taken in this report at the day of submission.

3.1.1 Participatory Framework Design

This approach places a strong emphasis on transparency, consensus-building, and participatory decision-making throughout its creation and application. A shared online platform (an Excel file provided in Annex) was used to support this participatory process, enabling project partners to work together and offer feedback. Experts from European academia and industry comprised the partner consortium, which made it possible to combine theoretical knowledge with real-world industry experience. Throughout the methodology's development, a range of channels, including email and virtual meetings, were used to ensure continuous participation, monitor progress, and take partner feedback into account.

3.1.2 Indicator Identification and Selection

The first action in developing the bioeconomy indicator framework was to compile a comprehensive initial pool of potential indicators. This process began by including indicators from the existing bioeconomy monitoring system, the BMS. The list was then complemented by additional indicators developed within the CALIMERO project.

From Task 1.2 (Josefin Neuwirth et al., 2022) within the CALIMERO project, the environmental and social hotspots of the each sector was identified. For the environmental impact, Ecoinvent 3.1 (*Ecoinvent Version 3.1*, n.d.) database was used and the impact assessment of all the datasets related to the products of the sectors was performed. The impact categories which contributed to the top 80% single score impacts were considered as the hotspots.

For social hotspots, the two major social databases, Social Hotspot DataBase (SHDB) (*Social Hotspot Database*, n.d.) and Product Social Impact Life Cycle Assessment (PSILCA) (*Psilca*, n.d.), were used to identify the important social hotspots of the sectors. A selection of sectorial products was analyzed from these databases. Considering that the hotspots identified with PSILCA and SHDB were not consistent, the data gaps, and nuance of this methodology, it was concluded that these hotspots do not reflect reality. Therefore, a third complementary method was included. For this, relevant social themes based on the UNEP Guidelines for Social LCA (UNEP, 2020a) was also included into the framework.

Other indicators from the developed methodologies by the partners from of CALIMERO project were also included in the framework. Below is a list of the indicators:

Table 4 Methods contributing to development of additional Indicators included in the framework

Method/Framework developed	Brief description of the framework/ method
Biodiversity impacts	A novel LCIA method, using circuit theory-based modelling, quantifies forestry land use impacts on ecological connectivity; Characterization Factors (CFs) are provided per m^2/county.
Ecosystem services impacts	Land use CFs assess differences in vegetation's particulate matter removal for biomass production versus a reference system; this indicator is currently under development.
Circularity Indicators	Combined circularity indicators from methods such as the Material Circularity Indicator, Critical Transition indicators, and ISO 59020/2024 are utilized, based on analysis in T3.2
Criticality indicators	An Excel tool evaluates bio-based material criticality using combined indicators from the IRTC tool (metals/minerals) and the BIRD framework (bioeconomy).
Dynamic carbon footprint	Time-dependent global warming indicators (generated via DyPLCA & CCI tools) are integrated over time for a single value, following RE2020 rules for Global Warming Potential (GWP) over 100 years post-product use.
Human Toxicity Novel CFs	A new machine learning method (developed by LIST) generates novel CFs for chemical substances for midpoint ecotoxicity and human toxicity assessments; these are to be added to the Environmental Footprint (EF) method's existing CFs.
Ecotoxicity Novel CFs	Similarly, a machine learning method generates novel CFs for chemicals for midpoint ecotoxicity and human toxicity assessments, supplementing existing EF method CFs.
Occupational Exposure Limits indicator	The qualitative Occupational Exposure Limits (OEL) indicator is suggested for site-specific Social Life Cycle Assessment (S-LCA) studies, usable independently or within a health and safety reference scale.
Process Variables to optimize in the Multi-Objective Optimization framework for all the sectors	Mostly process-based parameters
Job creation Potential	Job Creation Potential (JCP), an S-LCA social indicator, quantifies the total jobs (internal and supplier-based) that can be created by a product system.
Life Cycle Costing indicators	The sum of discounted future cash flows, potentially considering the time value of money.
	Average cost per product unit, indicating the minimum selling price for break-even (Net Present Value = 0).
	Internal Rate of Return (IRR), representing investment return.
	Payback period, the time to recover investment costs.
	Pricing GHG emissions via the EU Emissions Trading System (ETS) at €75 per ton of CO_2 equivalent.

A process was then defined for selecting the most relevant indicators from the initial pool. By focusing on indicators that demonstrate a discernible link to or influence on the selected sectors and the wider regional bioeconomy. The subsequent assessment and selection process prioritizes those indicators with the highest potential utility for strategic decision-making. This step involved a practical assessment by project partners to filter this pool and identify a preliminary set of relevant indicators based on their expert judgment regarding the relevancy of each indicator.

They assigned a score to each indicator reflecting its perceived level of importance or relevance, as shown in Table 5. Based on the project's requirements for clear differentiation, a scoring approach without a middle option was adopted, encouraging partners to make more decisive choices regarding indicator importance. **Table *5***

Table 5 Relevancy scoring description

Score	Relevancy	
1	Very Low Relevance	The indicator is hardly related to the sector
2	Low Relevance	The indicator is somewhat related, but not very important.
3	Moderate Relevance	The indicator is fairly relevant to the sector
4	High Relevance	The indicator is strongly related to the sector

A key aspect of this participatory assessment was the occurrence of differing opinions on the relevancy level of an indicator between partners for the regional level. Disagreements were particularly noted when partners' relevance scores for a single indicator showed significant disparity (e.g., one partner scoring it as low/very low importance (1-2) while another scored it high/very high importance (3-4)). While some participatory methods employ explicit consensus-building workshops or Delphi techniques to resolve disputes, this methodology opted for a quantitative aggregation approach followed by a feedback loop: those scoring higher than 3 were included and then a summary of the results was sent to the partners for their confirmation. This method was chosen given the large number of disputed indicators, which complicates discussing indicators separately due to time constraints.

The characteristics of the collected data are presented in Table 6. As it is not possible to include all the indicators in this report, an informational table is included only.

Table 6 Summary of the evaluated and short-listed indicators

No. of total indicators evaluated	Shortlisted Indicators			
	Regional	Construction	Textile	Woodworking
409	44	93	88	81

To process the scores and derive a collective assessment, a simple arithmetic average of indicator scores was calculated. Indicators with an average score above a predefined threshold (60% for construction and woodworking, 62% for textile and 50% for regional) were provisionally included in a shortlisted set. Indicators falling below this threshold were provisionally excluded (due to lack of receiving feedback and data from certain partners, the biochemical and pulp & paper sector were excluded). Higher thresholds were chosen for some sectors to make the number of indicators manageable for the partners to evaluate in the subsequent steps.

To maintain transparency and leverage the consortium's collective expertise, the resulting list of provisionally included and excluded indicators was shared with all partners via the collaborative platform. Partners were given the opportunity to review this preliminary selection and voice objections to any specific indicators that they felt were misclassified, initiating a final review loop to ensure critical insights were not overlooked in the initial statistical aggregation. This feedback mechanism is vital in participatory processes to ensure stakeholders feel heard and to refine results based on practical knowledge (Rowe & Frewer, 2000).

This initial selection process, combining expert judgment, a defined scoring system, simple quantitative aggregation, and a final review loop, resulted in a refined shortlist of indicators deemed most relevant for deeper assessment based on further criteria in the subsequent methodological steps.

3.1.3 Criteria Definition and Selection

Following the initial selection of relevant indicators, the subsequent phase involved a detailed assessment based on specific, predefined criteria and sub-criteria.

The criteria used for this assessment were developed in collaboration with the project partners. Through multiple interactive meeting sessions and feedback loops, partners contributed to identifying the most critical aspects by which indicators should be judged for their potential utility to policymakers and industry. This ensures the assessment criteria are grounded in the practical realities and information needs of the intended users.

Ultimately, the developed criteria were structured around two main, inter-related categories:

1. **Incentives and Decision-Making Support (IDMS):** This category focuses on the potential of an indicator to provide meaningful insights that can directly inform strategic decisions, motivate action, track progress towards goals, or reveal opportunities and challenges for policymakers and private sector actors within the bioeconomy.
2. **Data Quality and Availability (DQA):** This category addresses the practical feasibility of implementing an indicator, considering the reliability, accuracy, timeliness, accessibility, and overall ease of obtaining the necessary underlying data.

For each of these criteria, sub-criteria were developed as thoroughly explained hereafter.

3.1.3.1 IDMS – Company point-of-view:

To assess how indicators provide incentives from an industrial private sector viewpoint, the following set of sub-criteria was established. These sub-criteria were designed to capture specific drivers relevant to companies, such as considering regulatory landscapes, reputation and brand, and enhancing market position, which can differ significantly from regional or public sector objectives.

- **Innovation & Technological Advancement:** This criterion evaluates whether an indicator relates to or stimulates activities that increase the likelihood of innovation and technological upgrades within the company or sector. For businesses, innovation is critical for making new bio-based products, making processes better, gaining competitive advantage, and adjusting to changing market needs and resource availability. (Fernando et al., 2019). Companies can find out how their investments in R&D can lead to real competitive advantages and keep track of where innovation has a big impact.

- **Legal and Regulatory Risk Management:** This criterion assesses if an indicator can reveal existing or emerging regulatory requirements relevant to the company's bioeconomy activities. Identification of such indicators is important for proactive risk management, helping companies ensure compliance, avoid penalties, other reputational losses associated with non-compliance (Whalley & Guzelian, 2017). In this context, the research by (Ares-Sainz et al., 2025) offers critical insights by systematically identifying key sustainability and governance indicators derived from certification schemes and relevant policy frameworks. Their work highlights how indicators within such systems are vital for industries to demonstrate adherence to regulatory requirements, proactively manage inherent risks in bio-based value chains, and support strategic decision-making in the bioeconomy.

- **Supply Chain Risk Identification:** This criterion considers the indicator's usefulness in identifying potential risks within the company's supply chain that could disrupt operations. For businesses reliant on biological resources and complex bio-based value chains, understanding vulnerabilities related to feedstock availability, logistics, or processing is essential (Stampe & Hellingrath, 2021). The escalating frequency and severity of disruptive events, encompassing economic crises, natural disasters, and pandemics, have emphasized the inherent vulnerabilities within supply chains and the importance of risk management.

  A study by Al-Sharrah et al. integrated environmental and risk indicators into supply chain optimization models for process industries, proposing a simplified risk index for sustainability assessment (Ghanima Al-Sharrah et al., 2016). Concurrently, another study, Tseng et al. identified and validate data-driven sustainable supply chain management (SSCM) indicators for the textile industry, categorizing them into aspects like "SC risk assessment" and "SC resilience" using a hybrid methodology (Tseng et al., 2022).

- **Market Demand:** This criterion evaluates the extent to which an indicator can reveal new or current market demands that may influence a company's competitive positioning. Indicators reflecting consumer preferences for sustainable or bio-based products, market size, growth trends, or shifts in value chains are critical for companies to identify opportunities, tailor product offerings, and maintain market relevance.
  Tracking market demand indicators is of paramount importance for navigating today's dynamic and often volatile market landscapes. These indicators, which can range from broad macroeconomic figures like GDP growth and inflation rates that signal the overall health and direction of an economy (Meixell & Wu, 2001) to more specific product-level "leading indicators" that predict demand trends for particular technology clusters (Gafurdjan Zakhidov, n.d.), provide invaluable insights for forecasting and strategic decision-making.

- **Social Impact:** This criterion assesses how an indicator impacts the local community or society in a way that could either strengthen or weaken the company's social license to operate. While broad social sustainability is important, companies specifically focus on aspects of social impact that affect their community relations, workforce stability, and ultimately, the acceptance of their operations by stakeholders.

- **Operational Efficiency and Productivity:** This criterion considers whether an indicator can be leveraged to enhance process efficiency or overall operational productivity within the company. Sustainability indicators, such as those related to resource use efficiency, waste reduction, or energy consumption, can often highlight areas for operational improvements, leading to cost savings and increased productivity.

- **Brand & Reputation Impact:** This criterion evaluates whether an indicator affects the company's brand value, investor confidence, or overall market reputation. A company's performance on sustainability and bioeconomy-related issues increasingly influences how it is perceived by customers, investors (ESG considerations), and the public, impacting brand loyalty, access to capital, and overall reputation.

3.1.3.2 IDMS- Policymakers Point-of-view:

Developing sub-criteria under regional policymakers' point of view required a holistic view on bioeconomy development. The Food and Agriculture Organization of the United Nations (FAO) report, "Aspirational Principles and Criteria for a Sustainable Bioeconomy" (FAO, 2021), outlines ten aspirational principles developed to guide the transition towards a sustainable and circular bioeconomy globally. These principles were collaboratively developed by the International Sustainable Bioeconomy Working Group (ISBWG), a multi-stakeholder group established in 2016, following a recommendation from 62 ministers of agriculture at the Global Forum for Food and Agriculture in 2015. The development process involved international experts and aimed to create a common ground for discussions on sustainability and circularity, encompassing environmental, social, economic, and governance dimensions. The complete list of the principles is illustrated in **Figure *2***. This comprehensive set of principles, while non-binding, is designed to be applied by policymakers and other stakeholders in developing and monitoring bioeconomy strategies at various scales, ensuring that sustainability and circularity are embedded from the outset to avoid future risks and trade-offs.

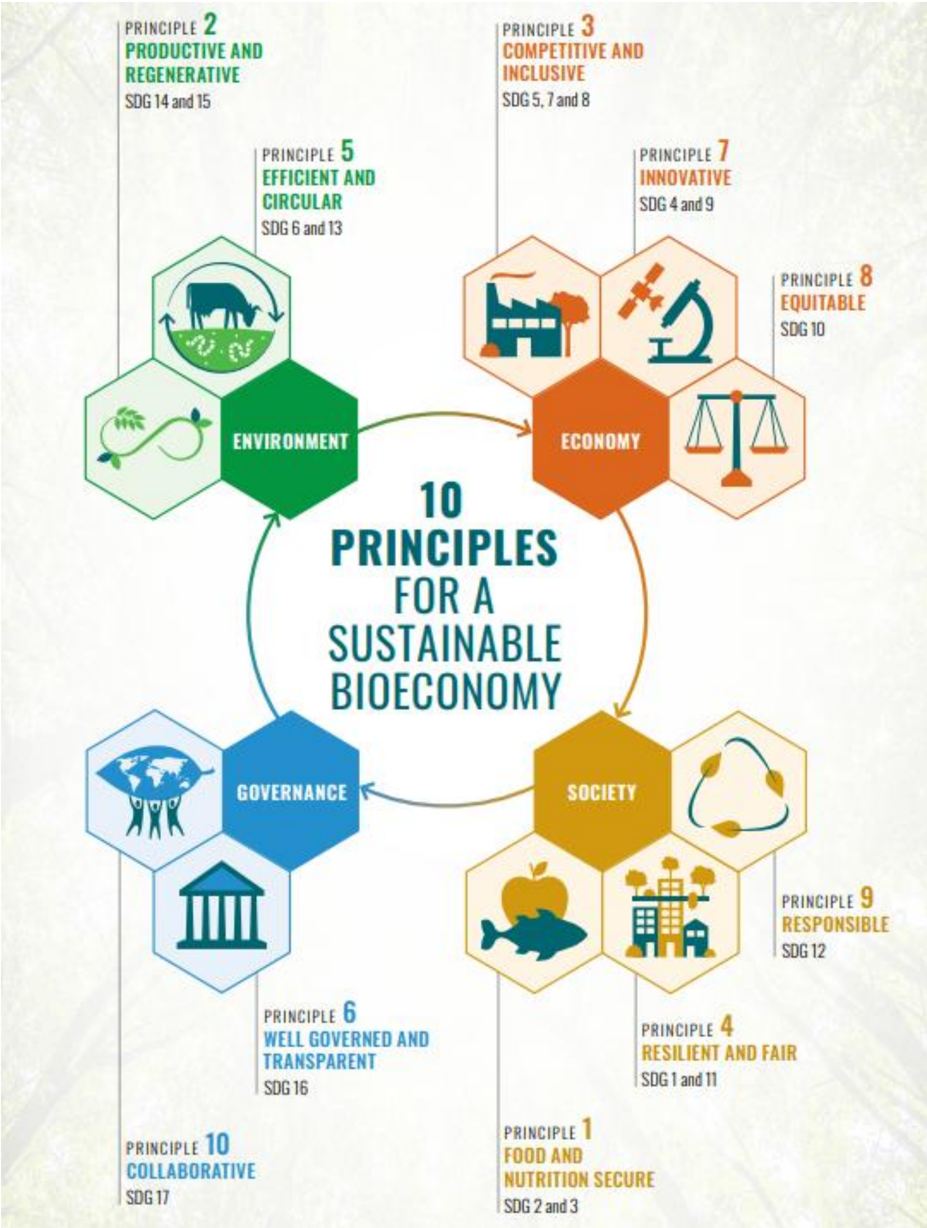

Figure 2 – 10 aspirational principles for a sustainable bioeconomy (FAO, 2021)

This is of the most important source to base the development of criteria on. Inspired by these principles, the following criteria were developed.

- **Innovation & Technological Advancement** (Principles 3 & 7)
- **Legal and Regulatory Alignment** (Principles 6 & 10)
- **Bioeconomy Value Creation** (Principle 3)
- **Food and Nutrition Security** (Principles 1 & 4)
- **Sustainable Natural Resource Management** (Principles 2, 5 & 9)
- **Climate Change Mitigation & Adaptation** (Principles 2 & 5)
- **Employment & Economic Fairness** (Principles 4 & 8)

3.1.3.3 Data Quality & Availability

For the assessment of indicator data quality and availability, a comprehensive approach was adopted, integrating established methodologies from both statistical reporting frameworks and life cycle assessment (LCA) principles. For instance, Eurostat has proposed a scoreboard for the selection of indicators within the SDG framework with parameters focusing mostly on the statistical quality of the indicators, e.g., timeliness, data availability, frequency of dissemination, and geographical coverage (European Commission, n.d.-b). The Bioeconomy Monitoring System (BMS) framework's data quality assessment was also built on Eurostat data quality evaluation criteria (Robert et al., 2020). Complementing these statistical considerations, principles from the pedigree matrix of LCA were utilized for determining the level of uncertainty. Depending on this level of uncertainty, a coefficient of variation (CV) is generated which implies the amount of variation as a percentage. The criteria are Technological representativeness, Geographical representativeness, Time-related representativeness, Completeness, Precision/uncertainty, Methodological appropriateness and consistency/accuracy (Weidema & Wesnæs, 1996). Considering that our indicator set comprises a mix of BMS indicators and LCA-based indicators, a combination of these two frameworks was built to be comprehensive.

The following criteria are considered:

- **Data accessibility:** If the data is already available, or if it needs simple/complex calculations to generate
- **Transparency and documentation:** Is the data open-source, request-based, and properly documented?
- **Frequency of dissemination (Updates):** Are data updated yearly, every 2 years, every 3 years, etc.?

- **Comparability over time:** Is the methodology for calculating the indicator stable over time?
- **Timeliness:** How many years does it take for the data of a specific year to be disseminated?
- **Geographical coverage:** If the data is reported for all regions or countries.
- **Technology representativeness (relatable):** If the technology or process used in your study matches the real-life technology it represents or not.
- **Completeness:** Are all necessary data points available without significant gaps?

It is important to note that inclusion of *Accuracy and Precision* as a criterion is also important but the difficulty and impracticality of assessing such criteria for every indicator led to its exclusion from the list.

3.1.4 Designing the Criteria Scoring Methodology

With the assessment criteria categories defined, the next step involved designing the specific methodology for scoring each shortlisted indicator against these criteria. Developing a clear and consistent scoring system is essential for translating qualitative judgments or semi-quantitative information into a format suitable for comparative analysis and aggregation (Singh et al., 2012). Given the distinct nature of the two criterion categories, tailored scoring approaches were developed.

For the DQA criteria, a semi-quantitative to qualitative scoring system was designed. Scoring scales were developed for specific data quality aspects, such as temporal correlation, geographical correlation, technological correlation, reliability, completeness, and accessibility. Partners evaluated each indicator against these aspects, providing ratings or qualitative descriptions based on their knowledge of existing data sources (e.g., the BMS or other relevant datasets) and the practical feasibility of data collection for the target sectors and regions. **Table *7*** demonstrates the scoring criterion.

Table 7 Data Quality and Availability scoring matrix

Criteria	Scoring system			
	D	C	B	A
Data accessibility	Not available or requires complex calculations	Some data is available, but indicators need to be estimated by combining datasets or doing basic calculations	All required data is available and easy to access, but indicator must be calculated (e.g., sum, ratio, %)	Directly available and ready-to-use from a single source
Transparency and documentation	Data is not public, or comes with no explanation	You must request the data, and even then, it has limited explanation	Data is open-source or requestable, and has some documentation	Data is open-source and well-documented
Frequency of dissemination (Updates)	Updated every 4+ years	Updated every 3 years	Updated every 2 years	Updated annually or more frequently
Comparability over time	No data points without methodological break	At least 2 data points without methodological break	At least 3 data points without methodological break	At least 5 data points without methodological break
Timeliness	Released with 4+ years of delay	Released with 3 years of delay	Released with 2 years of delay	Released within 1 year of reference year
Geographical coverage	MS* data represents <50% of EU total or no EU aggregate available	MS data represents 50-75% of EU total and EU aggregate available	MS data represents at least 75-99% of EU total and EU aggregate available	Data for all MS and EU aggregate available
Technology representativeness (relatable)	Data with unknown technology / sector or from distinctly different sector	Data comes from a different sector or technology, but with partial relevance or overlapping features	Data from similar sector or average of sectors with similar technology	Data is from the exact sector, material, or process being studied
Completeness	There are 5+ data points missing	There are 3-4 data points missing	There are 1-2 data points missing	All data points are available
Accuracy & Precision	Data is based on assumptions, expert judgment, or unclear origin and varies significantly across sources or time	Estimated data from grey literature or weak databases; moderate inconsistencies or unexplained variation	Data from reliable sources like recognized databases, but modelled or with some variation across sources or time	Directly measured or peer-reviewed data from trusted sources; stable across years and between sources

For the IDMS criteria, a more holistic scoring approach was adopted to capture the potential utility of each indicator from the perspective of policymakers and industry users. Instead of quantitative metrics, this method relies on expert judgment guided by a set of key principles and guiding questions. These guiding questions prompt scorers to consider various facets, such as the indicator's ability to inform strategic planning, highlight trade-offs, track policy effectiveness, reveal business opportunities, or function as a performance benchmark. They are neither exhaustive nor limiting but serve to stimulate comprehensive reflection on the indicator's potential value for decision support and creating incentives within the bioeconomy sectors. Utilizing guiding questions in expert assessments is a recognized method to structure subjective evaluations while allowing for the incorporation of expert knowledge and contextual understanding (Pradhan et al., 2017; Rowe & Frewer, 2000).

The detailed scoring methodologies, including the specific scales or guiding questions for each criterion, were documented and provided to all project partners to ensure a common understanding and approach during the scoring process conducted in the subsequent step. Table 8 and 9 showcase the guiding questions.

It is important to note that the questions are provided only to guide the assessment, but the list is not meant to be complete. The partners were instructed that when evaluating, the goal is not to assess whether each indicator answers all the questions, but to assess how well each indicator addresses the questions that are applicable to it.

The criteria are scored from A to D, where A indicates the highest relation and connection between the indicator and the criterion concepts, and D the lowest.

Table 8 IDMS criteria for company perspective

IDMS Company Perspective	To score this criterion, ask yourself:
Innovation & Technological Advancement	■ Does the indicator **involve or reflect the use of new technologies, materials, or systems**? ■ Does it **reflect an environment that supports innovation** (e.g., policy incentives, infrastructure, market readiness, investments, etc.)? ■ Does it **track innovation outcomes, such as adoption, performance improvements, or R&D outputs**?
Legal and Regulatory Risk Management	■ Does this indicator reflect a value that is directly **limited or regulated by existing law or regulation**? ■ Is the indicator **monitored by authorities for compliance with existing legislation**? ■ Is it **linked to eligibility for public subsidies, permits, or environmental licenses**? ■ Is the **indicator covered by mandatory reporting frameworks or compliance audits**?
Supply Chain Risk Identification	■ Does the indicator highlight **dependency on specific inputs, or regions**? ■ Does it reflect **disruption factors** that could affect the operation (e.g., political instability, climate risks, price volatility)? ■ Does it help assess the **resilience or fragility of the upstream or downstream supply chain**?
Market Demand	■ Does it link to a **consumption of a specific product/service** of interest? ■ Does the indicator **reflect customer or societal preferences** that is linked to your category of products/services? ■ Does it capture **movement toward niche or premium markets** that offer strategic positioning potential?
Operational Efficiency and Productivity	■ Is it related to the **technical performance** of your production process?
Social Impact	■ Would this indicator be linked to **publicly sensitive issues** with growing societal pressure? (e.g. related to animal welfare, climate justice, biodiversity loss, etc.) ■ Does the indicator reflect an **impact on people's health, safety, living conditions, or human rights**? ■ Could poor performance on this indicator lead to **social tension, protests, or reputational pressure from the public or NGOs**? ■ Is it **tied to vulnerable or marginalized groups** (e.g., farmers, indigenous communities, low-income households)?
Brand & Reputation Impact	■ Does this indicator relate to **socially or environmentally sensitive topics with strong public visibility**? (for e.g. related to animal welfare, pollution, labor rights, deforestation)

	■ Could poor performance on this indicator **damage trust with investors, consumers, or business partners**? ■ Would this indicator be used in **marketing, CSR reporting, or product certifications**?

Table 9 IDMS for Regional Perspectives

IDMS Regional Perspective	To score this criterion, ask yourself:
Innovation & Technological Advancement	■ Does this indicator track concrete results of innovation within our region? ■ Does it show that existing knowledge is used or innovation is promoted? ■ Does it involve or reflect the use of new technologies, materials, or systems? ■ Does it track innovation outcomes, such as adoption, performance improvements, or R&D outputs?
Legal and Regulatory Alignment	■ Is this indicator directly linked to existing regulations or policy objectives? ■ Does it highlight areas where new regional legal frameworks might be needed?
Supply Chain Resilience	■ Does it show the security or stability of regional bio-based sourcing? ■ Does it identify vulnerabilities in regional bioeconomy value chains? ■ Does it show external factors affecting supply chain stability (e.g., disasters)? ■ Does it show regional import reliance for key bio-based materials or products? ■ Does it show regional biomass supply (quantity, origin, security)? ■ Does it highlight causes of regional supply chain risk (e.g., external reliance, internal issues)?
Social Impact and Public Concern	■ Does it show impacts of the regional bioeconomy on the health, safety, or quality of life of regional communities or workers? ■ Does it help to measure public or consumer attitudes, acceptance, or concerns regarding bioeconomy? ■ Can this indicator show equity or fairness aspects of the bioeconomy, such as income distribution, access to opportunities, or treatment of specific social groups (e.g., gender, age, smallholders)?
Bioeconomy Value Creation	■ Does this indicator measure economic size or value generated by bioeconomy sectors? ■ Can this indicator show the creation or growth of new bio-based products, markets, or value chains within the region? ■ Does the indicator track financial investment or economic efficiency within the regional bioeconomy (e.g., capital flows, productivity, profitability)? ■ Does this indicator help assess the economic competitiveness or market performance of regional bio-based products or sectors?
Food and Nutrition Security	■ Does this indicator relate to regional food security, addressing aspects like competition for resources, food availability, accessibility, or quality?
Sustainable Natural Resource Management	■ Does this indicator track the state or health of key regional biological resources (e.g., forests, fish stocks, agricultural biomass potential)? ■ Does it show regional bioeconomy resource efficiency or sustainable practices? ■ Does it monitor sustainable regional resource use or extraction rates?
Climate Change Mitigation & Adaptation	■ Does it show regional efforts, policies, or investments aimed at climate change mitigation or adaptation? ■ Does this indicator measure regional GHG emissions, removals (sequestration), or the carbon footprint?

	■ Can this indicator show the contribution of the regional bioeconomy to climate change mitigation?
Employment & Economic Fairness	■ Does it measure regional bioeconomy jobs (creation, levels, types)? ■ Does it help assess aspects of economic fairness or equity related to the regional bioeconomy? ■ Does it show the quality of employment or working conditions within the regional bioeconomy?

3.1.5 Scoring the Indicators

Following the design of the criteria scoring methodologies, the project partners proceeded to conduct a detailed assessment of the shortlisted indicators. Within the two main categories: IDMS and DQA.

The basis for the scoring differed depending on the nature of the criterion being assessed. For the Data Quality and Availability criteria, partners used available documentation related to the indicators and relevant data sources. For the IDMS criteria, scoring was primarily based on the partners' expert judgment and experience within academic research and industry practice.

Considering the long list of shortlisted indicators, the indicators were split among the partners according to their expertise and available resources. The scores assigned by each partner for every criterion of every indicator were systematically recorded on the shared online platform.

Figure A snippet of the framework filled by the partners is presented in **Figure 5 i**n the Annex. The full table of results is also available through a shared excel file provided in the Annex.

3.1.6 Aggregation and Multi-Criteria Assessment

The final stage of the methodological process involved aggregating the individual partner scores.

3.1.6.1 Criteria Weighting:

one approach to assessing the indicators is the weighted sum model or the simple additive model, where each criterion is given a weight according to its importance. The weighting of criteria differed between the two main assessment categories.

For the DQA, not all criteria were considered equally important. A double weight (x2) was assigned to the criteria of “Data Accessibility” and “Transparency and Documentation”.

This decision was based on the principle that data can only be practically utilized if it is available and accompanied by sufficient documentation to validate its credibility. All other DQA criteria received a standard weight (x1), as they could be partially compromised depending on specific project needs.

For the IDMS criteria, equal weighting was applied. This approach ensures that all criteria are given the same level of importance in the baseline assessment. It is acknowledged, however, that for specific applications, weights would need to be assigned based on the unique context of the study, such as the market, country, or policy scenario.

3.1.6.2 Quantitative Scoring Transformation

As the initial scores were qualitative (A to D), a transformation to a quantitative scale was required for the analysis.

For the DQA criteria, a linear scoring system was adopted as shown in **Table *10***.

Table 10 Qualitative to Quantitative scoring for DQA criteria

Qualitative score	A	B	C	D	No information
Quantitative representation (C_n)	4	3	2	1	0

The overall score of each indicator was the sum of the score of each criteria considering their weight:

$$Data\ Q\&A = \sum_{n=1}^{m}(C_n \times W_n) \quad \text{(Eq. 1)}$$

For the IDMS criteria, a non-linear scoring approach was chosen, as detailed in **Table 11**.

Table 11 Qualitative to Quantitative scoring for ICDM criteria

Qualitative score	A	B	C	D	Not relevant
Quantitative representation (C_n)	20	7	3	1	0

This non-linear scale was selected to assign significantly greater value to indicators that achieved the highest score (A) for any given criterion, thereby promoting the selection of indicators that demonstrate excellence in specific areas. The total IDMS score was then calculated as the sum of these converted scores:

$$IDMS = \sum_{n=1}^{m} C_n \quad \text{(Eq. 2)}$$

3.1.6.3 Mono-Dimensionality

Beyond the composite scores, two additional metrics were developed to visualize the characteristics of each indicator.

- **Mono-Dimensionality (Specificness):** In contrast, this metric measures an indicator's performance on its two strongest criteria, highlighting specialized excellence. It was calculated by averaging the three highest scores an indicator received for the IDMS criteria.

$$\text{Mono} - \text{Dimensionality (Specificness)} = \frac{Max\ (n_1+n_2)}{2} \qquad \text{(Eq. 3)}$$

A high score for both "IDMS" and "Specificness" suggests a highly versatile and useful indicator. Conversely, a low score for both implies limited utility. Importantly, a high "Specificness" score can identify a valuable, specialized indicator even if its overall IDMS score is modest, preventing potentially useful indicators from being overlooked.

The next step was to average the scores provided by all project partners for each criterion, resulting in a single aggregated score for each indicator within the two main categories. This produces a multi-dimensional performance profile for each indicator based on the collective expert judgment of the consortium.

Following the aggregation process, the results are intended for an analysis in which the contrasts and similarities among the various indicators are systematically compared. However, as the complete dataset of partner responses had not yet been acquired by the projected deadline of late May, only partial data is available at this time. Performing a conclusive analysis on this incomplete dataset would be premature and could yield misleading results.

Therefore, the subsequent chapter does not present the final analysis. Instead, it provides an illustrative example of the analytical approach that will be applied, offering a preview of the insights and comparisons that are expected to be achieved once the full dataset is compiled.

4 Analysis

Disclaimer: Please note that the following analysis is preliminary and illustrative. It is based on a fraction of expected data. Therefore, the results presented here are not conclusive but serve to demonstrate the analytical framework that will be applied once the complete dataset is acquired. The complete analysis will be presented in the defense and more graphs will be presented.

Figure 3, shows the results for the shortlisted regional indicators, plotted according to their scores for DQA and IDMS. The ICDM scores have been normalized according to the minimum and maximum score for better visibility in the table. The graph is divided into four quadrants, each representing a different performance profile:

1. **High DQA and High IDMS**: Indicators in this quadrant are considered ideal. They are recognized as having high value for decision-making and are supported by high-quality data and robust methodologies.
2. **High DQA and Low IDMS:** These indicators have high data quality but scored lower on direct decision-making value in this assessment. They could, however, be valuable for specific applications, particularly if they exhibit a high "Mono-Dimensionality" score, indicating specialized excellence.
3. **Low DQA and Low IDMS:** This quadrant contains indicators that scored lower on both DQA and IDMS criteria relative to other shortlisted indicators. While they have passed an initial relevance screening, this scoring identifies them as less critical or impactful within this comparative framework.
4. **High IDMS and Low DQA:** These indicators are considered highly important for decision-making but currently suffer from poor data quality or availability. They represent key areas where future efforts should be focused on improving data collection and methodology, thereby enhancing their overall usability.

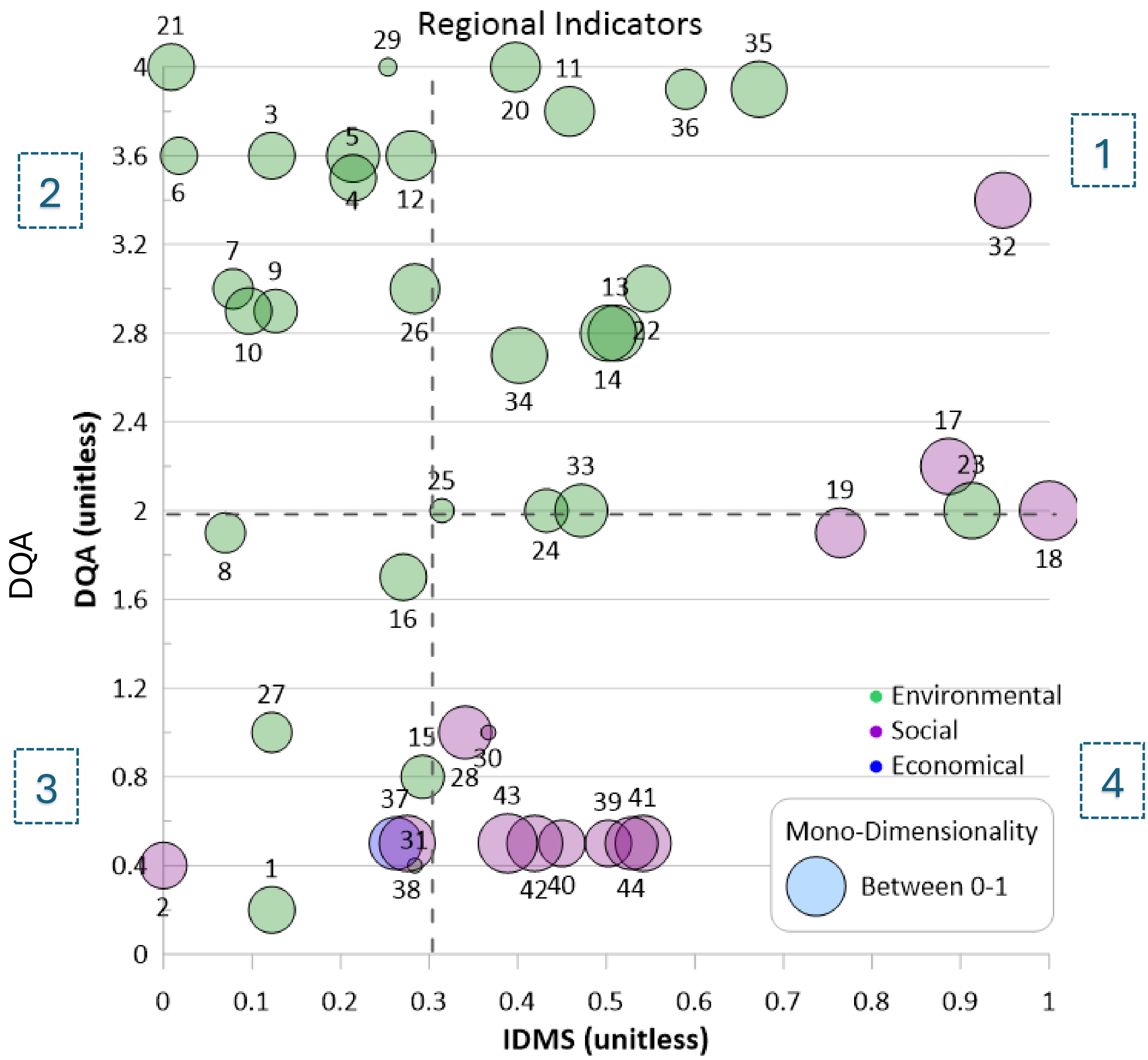

Figure 3 MCA of regional indicators

Table 12 Regional indicators corresponding number and their aspect

Section 1		Section 2		Section 3		Section 4	
11	Forest growing stock	3	Biochemical oxygen demand in rivers	1	Environmental impacts based on product-based LCA and basket of representative products of the bioeconomy	15	Flood regulation (flood control, flow, demand, potential, unmet demand, monetary values)
13	Conservation Status of European Habitats	4	Phosphate in rivers	2	Market or consumers acceptance	19	Occupational toxics and hazards
14	Conservation status of grassland	5	Nitrate in groundwater	8	Landscape fragmentation Index	28	EF3.1 Human toxicity, cancer
17	Legal system	6	Exceedance of air quality standards in urban areas	16	Air quality	30	Safe & healthy living conditions
18	Occupational injuries and deaths	7	Percentage area of urban green space (or percentage of natural area within the city boundaries)	27	EF3.1 Human toxicity, non-cancer	39	Corruption (SHDB)
20	EF3.1 Climate Change	9	Forest fragmentation and connectivity index	31	Environmental footprints in exporting countries (to EU)	40	Corruption (UNEP Guidelines)
22	EF3.1 Acidification	10	Share of forest area	37	Contribution to economic development	41	Child Labor
23	EF3.1 Resource use, fossils	12	Bird and butterfly indices EU aggregate (common farmland bird Index, common forest bird index, grassland butterfly index)	38	Health & safety	42	Fair Salary
24	EF3.1 Land use	21	EF3.1 Particulate matter			43	Freedom of Association & Collective Bargaining
25	EF3.1 Water use	26	EF3.1 Photochemical ozone formation			44	Health and Safety
32	Social condition in exporting countries (to EU)	29	Climate change, short term, fossil				
33	Certified forests						
34	Land use / land cover type taken over by agricultural land						
35	Share of renewable energy in gross final energy consumption						
36	Circular material rate						

- Environmental
- Social
- Economical

** The reference point of each indicator can be found in the complementary shared excel file in the annex*

The application of this methodology to a comprehensive suite of bioeconomy-related datasets represents a novel approach. It is important to note that this analysis is not exhaustive and may contain errors, a consideration inherent to the scale of the data being examined. It is important to note that a preliminary selection process was already conducted to isolate these most relevant indicators for analysis. Therefore, the most of the indicators presented here already have demonstrated significance regardless of how we classify them. This graph further highlights a subset of these indicators that are paramount for strategic decision-making, alongside a set of crucial indicators that necessitate enhanced data quality to improve their practical application. A further analysis and example of interpretating will be provided on the defense on the specific indicators from each sector and each quadrant of the figure.

While the total IDMS score provides an overall evaluation, it aggregates the score across all sub-criteria, which can mask an indicator's specific strengths. To offer a more granular analysis, the Table 13 disaggregates these results, presenting the top-performing indicators for each individual criterion.

It is noteworthy that certain indicators, such as 'EF3.1 Climate Change' and 'Health & Safety', appear repeatedly across multiple criteria. This recurrence suggests their multifaceted relevance and underscores the high level of importance assigned to them by the stakeholders in this study.

Table 13 Top 10 indicators of each criterion under regional perspective

Innovation & Technological Advancement	Legal and Regulatory Alignment	Supply Chain Resilience	Social Impact and Public Concern	Bioeconomy Value Creation	Food and Nutrition Security	Sustainable Natural Resource Management	Climate Change Mitigation & Adaptation	Employment & Economic Fairness
EF3.1 Climate Change	Climate change, short term, fossil	Circular material rate	Safe & healthy living conditions	Contribution to economic development	Land use / land cover type taken over by agricultural land	Circular material rate	Share of renewable energy in gross final energy consumption	Fair Salary
Circular material rate	EF3.1 Climate Change	Share of renewable energy in gross final energy consumption	Health & safety	Market or consumers acceptance	EF3.1 Water use	Land use / land cover type taken over by agricultural land	EF3.1 Climate Change	Contribution to economic development
Climate change, short term, fossil	Certified forests	Climate change, short term, fossil	Child Labour	Circular material rate	EF3.1 Climate Change	Certified forests	Climate change, short term, fossil	Corruption
Share of renewable energy in gross final energy consumption	Fair Salary	Forest growing stock	Market or consumers acceptance	Share of renewable energy in gross final energy consumption	Climate change, short term, fossil	Environmental impacts based on product-based LCA and basket of representative products of the bioeconomy	Circular material rate	Child Labour
Market or consumers acceptance	Health and Safety	Child Labour	Fair Salary	Land use / land cover type taken over by agricultural land	Market or consumers acceptance	Biochemical oxygen demand in rivers	Environmental impacts based on product-based LCA and basket of representative products of the bioeconomy	Corruption
Health & safety	Occupational injuries and deaths	Contribution to economic development	Corruption	Certified forests	Conservation Status of European Habitats	Phosphate in rivers	Forest growing stock	Legal system
Contribution to economic development	Conservation status of grassland	Corruption	Health and Safety	EF3.1 Water use	EF3.1 Land use	Nitrate in groundwater	Flood regulation (flood control, flow, demand, potential, unmet demand, monetary values)	Freedom of Association & Collective Bargaining
EF3.1 Water use	Conservation Status of European Habitats	Legal system	Occupational injuries and deaths	EF3.1 Climate Change	Nitrate in groundwater	Share of renewable energy in gross final energy consumption	Share of forest area	Safe & healthy living conditions
EF3.1 Resource use, fossils	Exceedance of air quality standards in urban areas	Land use / land cover type taken over by agricultural land	Contribution to economic development	Fair Salary	Flood regulation (flood control, flow, demand, potential, unmet demand, monetary values)	Forest fragmentation and connectivity index	Conservation status of grassland	Health and Safety
Environmental impacts based on product-based LCA and basket of representative products of the bioeconomy	Health & safety	Market or consumers acceptance	Certified forests	Environmental impacts based on product-based LCA and basket of representative products of the bioeconomy	Fair Salary	Environmental footprints in exporting countries (to EU)	Percentage area of urban green space (or percentage of natural area within the city boundaries)	Occupational injuries and deaths

Conclusion

The transition to a sustainable European bioeconomy is a strategic priority, yet it presents significant monitoring challenges. High-level frameworks like the EU's Bioeconomy Monitoring System (BMS) are essential for tracking progress at a national scale but often fail to provide the granular, sector-specific, and practical guidance required by industrial actors and regional policymakers. This thesis addressed this critical gap by developing and presenting a novel methodology for assessing and classifying sustainability indicators tailored to the specific needs of the bioeconomy.

Developed within the EU-funded CALIMERO project, this research established a harmonized, participatory methodology centered on Multi-Criteria Analysis (MCA). By engaging a consortium of academic and industrial experts, a comprehensive pool of indicators was compiled and systematically evaluated. The core of this work was the assessment of these indicators against two purpose-built dimensions: their utility for Incentives and Decision-Making Support (IDMS) and their practical Data Quality and Availability (DQA). This dual-lens approach allows for a nuanced classification that moves beyond simple relevance, identifying indicators that are not only important but also robust and usable.

The primary output of this research is a transparent and replicable framework that categorizes indicators, offering clear insights into strategic action. It distinguishes between ideal, ready-to-use indicators (High IDMS, High DQA) and those of high strategic importance that require concerted efforts to improve their data quality (High IDMS, Low DQA). It is important to recognize that this framework is dynamic. The classifications it generates are not static; they will evolve as new indicators are introduced, others are excluded, or as DQA scores are updated over time. Consequently, an indicator deemed suitable in one assessment may be superseded in a future analysis under different conditions. This methodology provides a crucial tool that complements the existing BMS, enabling companies and policymakers to select indicators that are truly relevant to their specific context, thereby fostering better alignment between industrial practices and EU sustainability goals.

The main limitation of this study at the point of submission is the incomplete collection of expert responses, which prevented a full-scale application of the methodology. Consequently, the analysis presented in this report is illustrative rather than conclusive. Furthermore, the exclusion of the biochemical and pulp & paper sectors from the preliminary analysis due to a lack of data highlights a dependency on active stakeholder participation.

Future work should prioritize the completion of data collection to perform the full analysis and deliver definitive, prioritized indicator sets for each sector. The immediate next step is to present the complete analysis as planned. Looking further ahead, this methodology could be used in specific case studies and scenarios in the bioeconomy sectors and could form the basis of an interactive digital tool to further enhance its usability. Research efforts could also be directed at the indicators identified as highly important but with low data quality, focusing on developing strategies to overcome these data gaps.

In conclusion, the methodology developed in this thesis provides collaborative pathway for navigating the complexity of sustainability assessment in the bioeconomy. By systematically integrating expert knowledge with multi-criteria analysis, it offers a practical approach to transform data into actionable intelligence, supporting the critical transition towards a more sustainable and competitive European bioeconomy.

Annex

Other sectors

Other Indicators

Indicator Category	Indicator name	Unit	Construction sector				Woodworking sector				...
			Academic Partner		Industrial Partner		Academic Partner		Industrial Partner		...
			Relevant for industrial actors in the construction sector	Relevant for policymakers at a regional level	Relevant for industrial actors in the construction sector	Relevant for policymakers at a regional level	Relevant for industrial actors in the woodworking sector	Relevant for policymakers at a regional level	Relevant for industrial actors in the woodworking sector	Relevant for policymakers at a regional level	...
Food security and nutrition are supported (BMS)	Agricultural factor income per annual work unit (AWU)	index (2010=100)	1	3	1	3	1	1	1	1	...
	New food products (by sector)	kg	1	1	1	1	1	1	1	1	...
	New food value chains (by sector)		1	1	1	1	1	1	1	1	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	...
Local Community (Social stakeholder theme)	Access to Material Resources	Risk Level (Very high to Very Low)	2	2	2	2	2	2	2	2	...
	Environmental Footprints	Risk Level (Very high to Very Low)	1	1	1	1	2	2	2	2	...
	GHG Footprints	Risk Level (Very high to Very Low)	1	1	1	1	2	2	2	2	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	...
Calimero Indicators (Circularity)	End-of-life energy recovery rate		2	3	4		3	3	3	2	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Figure 4 A snippet of the framework for indicators selection

Shared Online Platform: [T5.4 Bioeconomy Indicators]

Indicator Category	Indicators List	Innovation & Technological Advancement	Legal and Regulatory Alignment	Supply Chain Resilience	Social Impact and Public Concern	Bioeconomy Value Creation
		■ Does this indicator track concrete results of innovation within our region? ■ Does it show that existing knowledge is used or innovation is promoted? ■ Does it involve or reflect the use of new technologies, materials, or systems? ■ Does it track innovation outcomes, such as adoption, performance improvements, or R&D outputs?	■ Is this indicator directly linked to existing regulations or policy objectives? ■ Does it highlight areas where new regional legal frameworks might be needed?	■ Does it show the security or stability of regional bio-based sourcing? ■ Does it identify vulnerabilities in regional bioeconomy value chains? ■ Does it show external factors affecting supply chain stability (e.g., disasters)? ■ Does it show regional import reliance for key bio-based materials or products? ■ Does it show regional biomass supply (quantity, origin, security)? ■ Does it highlight causes of regional supply chain risk (e.g., external reliance, internal issues)?	■ Does it show impacts of the regional bioeconomy on the health, safety, or quality of life of regional communities or workers? ■ Does it help to measure public or consumer attitudes, acceptance, or concerns regarding bioeconomy? ■ Can this indicator show equity or fairness aspects of the bioeconomy, such as income distribution, access to opportunities, or treatment of specific social groups (e.g., gender, age, smallholders)?	■ Does this indicator measure economic size or value generated by bioeconomy sectors? ■ Can this indicator show the creation or growth of new bio-based products, markets, or value chains within the region? ■ Does the indicator track financial investment or economic efficiency within the regional bioeconomy (e.g., capital flows, productivity, profitability)? ■ Does this indicator help assess the economic competitiveness or market performance of regional bio-based products or sectors?
Local economies of countries exporting	Social condition in exporting countries (to	D: Very weak connection	A: Strongly related	B: Moderately related	B: Moderately related	D: Very weak connection
Demand and supply-side market mecha	Market or consumers acceptance	A: Strongly related	D: Very weak connection	A: Strongly related	A: Strongly related	A: Strongly related
Hotspots T1.2	EF3.1 Climate Change	A: Strongly related	A: Strongly related	A: Strongly related	A: Strongly related	B: Moderately related
Hotspots T1.2	EF3.1 Particulate matter	B: Moderately related	A: Strongly related	C: Weak connection	A: Strongly related	C: Weak connection
Hotspots T1.2	EF3.1 Acidification	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection
Hotspots T1.2	EF3.1 Resource use, fossils	B: Moderately related	C: Weak connection	B: Moderately related	B: Moderately related	C: Weak connection
Hotspots T1.2	EF3.1 Land use	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection
Hotspots T1.2	EF3.1 Water use	A: Strongly related	B: Moderately related	B: Moderately related	B: Moderately related	B: Moderately related
Hotspots T1.2	EF3.1 Photochemical ozone formation	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection
Hotspots T1.2	EF3.1 Human toxicity, non-cancer	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection
Hotspots T1.2	EF3.1 Human toxicity, cancer	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection	C: Weak connection
IMPACT WORLD+ V2.1 (Mid-Point Level i	Climate change, short term, fossil	A: Strongly related	A: Strongly related	A: Strongly related	A: Strongly related	B: Moderately related
VALUE CHAIN ACTORS	Corruption	No apparent link. The indicator has	B: Moderately related	C: Weak connection	B: Moderately related	D: Very weak connection
WORKERS	Child Labour	No apparent link. The indicator has	B: Moderately related	C: Weak connection	A: Strongly related	D: Very weak connection
WORKERS	Fair Salary	No apparent link. The indicator has	B: Moderately related	C: Weak connection	B: Moderately related	B: Moderately related
WORKERS	Freedom of Association & Collective Barg	No apparent link. The indicator has	No apparent link. The indicatc	No apparent link. The indicator has no n	C: Weak connection	No apparent link. The indicator has no
Health and Safety	Occupational toxics and hazards	B: Moderately related	A: Strongly related	No apparent link. The indicator has no n	B: Moderately related	No apparent link. The indicator has no
Health and Safety	Occupational injuries and deaths	B: Moderately related	A: Strongly related	No apparent link. The indicator has no n	A: Strongly related	No apparent link. The indicator has no
Governance	Legal system	No apparent link. The indicator has	B: Moderately related	C: Weak connection	B: Moderately related	D: Very weak connection

Figure 5 A snippet of the scoring the indicators based on the criteria

References

Ares-Sainz, J. L., Arias, A., Matovic, N., Ladu, L., Feijoo, G., & Moreira, M. T. (2025). Key governance and sustainability indicators for certification systems: Bridging certification and policy frameworks in the bioeconomy. *Sustainable Production and Consumption*, *56*, 156–181. https://doi.org/10.1016/j.spc.2025.03.017

Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., & Ignatius, J. (2012). A state-of the-art survey of TOPSIS applications. *Expert Systems with Applications*, *39*(17), 13051–13069. https://doi.org/10.1016/j.eswa.2012.05.056

Bongaarts, J. (2019). IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. *Population and Development Review*, *45*(3), 680–681. https://doi.org/10.1111/padr.12283

Buchholz, T., Rametsteiner, E., Volk, T. A., & Luzadis, V. A. (2009). Multi Criteria Analysis for bioenergy systems assessments. *Energy Policy*, *37*(2), 484–495. https://doi.org/10.1016/j.enpol.2008.09.054

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Péan, C. (2023). *CLIMATE CHANGE 2023* (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Chief Minister, T. and E. D. (2022, September 7). *Multi-Criteria Analysis*. Chief Minister, Treasury and Economic Development. https://www.treasury.act.gov.au/capital-framework/prove/detailed-technical-guidance/multi-criteria-analysis

Diaz-Balteiro, L., González-Pachón, J., & Romero, C. (2020). Sustainability as a Multi-Criteria Concept: New Developments and Applications. *Sustainability*, *12*(18), Article 18. https://doi.org/10.3390/su12187527

Donnelly, A. (2024). Priority 1: The European Green Deal. In H. Suder & L. Wittenberg (Eds.), *The von der Leyen Commission* (pp. 35–58). Nomos Verlagsgesellschaft mbH & Co. KG. https://doi.org/10.5771/9783748918882-35

Ecoinvent Version 3.1. (n.d.). [Database]. Ecoinvent. Retrieved May 26, 2025, from https://support.ecoinvent.org/ecoinvent-version-3.1

Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (Eu) (2024). http://data.europa.eu/eli/reg/2024/1252/2024-05-03/eng

European Commission. (n.d.-a). *EU Bioeconomy Monitoring System* [Dashboard]. Retrieved May 24, 2025, from https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en

European Commission. (n.d.-b). *Eurostat* [Database]. Retrieved June 3, 2025, from https://ec.europa.eu/eurostat

European Commission. Directorate General for Research and Innovation. (2018). *A Sustainable Bioeconomy for Europe* (No. 10.2777/792130). European Comission. https://data.europa.eu/doi/10.2777/792130

European Commission, Directorate-General for Environment. (2020). *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe* (No. 52020DC0098). European Comission.

FAO. (2021). *Aspirational principles and criteria for a sustainable bioeconomy*. FAO ; https://openknowledge.fao.org/handle/20.500.14283/cb3706en

Fernando, Y., Chiappetta Jabbour, C. J., & Wah, W.-X. (2019). Pursuing green growth in technology firms through the connections between environmental innovation and sustainable business performance: Does service capability matter? *Resources, Conservation and Recycling*, *141*, 8–20. https://doi.org/10.1016/j.resconrec.2018.09.031

Gafurdjan Zakhidov. (n.d.). *Economic Indicators: Tools for Analyzing Market Trends and Predicting Future Performance* [3030-3184]. Kokand University. Retrieved May 30, 2025, from https://www.researchgate.net/publication/380519295_ECONOMIC_INDICATORS_TOOLS_FOR_ANALYZING_MARKET_TRENDS_AND_PREDICTING_FUTURE_PERFORMANCE

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782

Ghanima Al-Sharrah, Lababidi, H. M., & Ali, Y. I. (2016). *Planning A Supply Chain With Risk And Environmental Objectives*. https://doi.org/10.5281/ZENODO.1125883

Gudlaugsson, B., Francis, C., Thomson, C., & Ingram, D. (n.d.). *Refining the multi-criteria assessment for smart local energy systems*.

Güldemund, A., & Zeller, V. (2024). Reflecting Regional Conditions in Circular Bioeconomy Scenarios: A Multi-Criteria Approach for Matching Technologies and Regions. *Sustainability*, *16*(7), 2935. https://doi.org/10.3390/su16072935

Güldeş, M., & Gürcan, Ö. F. (2022). Multi-Criteria Decision-Making Methods for Biomass Energy Systems: A Review. In F. Balo, A. Topal, E. Demir, & A. Ulutaş (Eds.), *Advances in Environmental Engineering and Green Technologies* (pp. 182–214). IGI Global. https://doi.org/10.4018/978-1-6684-2472-8.ch008

Hansen, P., & Devlin, N. (2019). Multi-Criteria Decision Analysis (MCDA) in Healthcare Decision-Making. In P. Hansen & N. Devlin, *Oxford Research Encyclopedia of Economics and Finance*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190625979.013.98

Josefin Neuwirth, Klara Midlander, Maria Lidberg, Nilay Elginoz Kanat, Sahar Safarianbana, Matilda Lidfeldt, Alexandre Charpentier Poncelet, & Margarida Vidinha. (2022). *Hotspot analysis of most impactful industrial processes* (No. D1.2). https://calimeroproject.eu/wp-content/uploads/2024/06/CALIMERO_WP1_-D1.2_fin.pdf

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kpadé, C. P., Tamini, L. D., Pepin, S., Khasa, D. P., Abbas, Y., & Lamhamedi, M. S. (2024). Evaluating Multi-Criteria Decision-Making Methods for Sustainable Management of Forest Ecosystems: A Systematic Review. *Forests*, *15*(10), Article 10. https://doi.org/10.3390/f15101728

Lakicevic, M. D., Reynolds, K. M., & Gawryszewska, B. J. (2021). An integrated application of AHP and PROMETHEE in decision making for landscape management. *AUSTRIAN JOURNAL OF FOREST SCIENCE*. https://enauka.gov.rs/handle/123456789/800817

Malefaki, S., Markatos, D., Filippatos, A., & Pantelakis, S. (2025). A Comparative Analysis of Multi-Criteria Decision-Making Methods and Normalization Techniques in Holistic Sustainability Assessment for Engineering Applications. *Aerospace*, *12*(2), Article 2. https://doi.org/10.3390/aerospace12020100

Martinkus, N., Latta, G., Rijkhoff, S. A. M., Mueller, D., Hoard, S., Sasatani, D., Pierobon, F., & Wolcott, M. (2019). A Multi-Criteria Decision Support Tool for Biorefinery Siting: Using Economic, Environmental, and Social Metrics for a Refined Siting Analysis. *Biomass and Bioenergy*, *128*, 105330. https://doi.org/10.1016/j.biombioe.2019.105330

Meixell, M. J., & Wu, S. D. (2001). Scenario analysis of demand in a technology market using leading indicators. *IEEE Transactions on Semiconductor Manufacturing*, *14*(1), 65–75. https://doi.org/10.1109/66.909656

Pagone, E., & Salonitis, K. (2023). Comparative Study of Multi-criteria Decision Analysis Methods in Environmental Sustainability. In S. G. Scholz, R. J. Howlett, & R. Setchi (Eds.), *Sustainable Design and Manufacturing* (Vol. 338, pp. 223–231). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9205-6_21

Participatory Multi-Criteria Decision Aid. (n.d.). Barcelona Lab for Urban Environmental Justice and Sustainability. Retrieved May 26, 2025, from https://www.bcnuej.org/participatory-multi-criteria-decision-aid/

Poulsen, L. K. (2022). *Multi Criteria Assessment, Food, Sustainability*.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., & Kropp, J. P. (2017). A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earth's Future*, *5*(11), 1169–1179. https://doi.org/10.1002/2017EF000632

Psilca. (n.d.). [Database]. Retrieved May 26, 2025, from https://psilca.net/

Robert, N., Giuntoli, J., Araujo, R., Avraamides, M., Balzi, E., Barredo, J. I., Baruth, B., Becker, W., Borzacchiello, M. T., Bulgheroni, C., Camia, A., Fiore, G., Follador, M., Gurria, P., la Notte, A., Lusser, M., Marelli, L., M'Barek, R., Parisi, C., … Mubareka, S. (2020). Development of a bioeconomy monitoring framework for the European Union: An integrative and collaborative approach. *New Biotechnology*, *59*, 10–19. https://doi.org/10.1016/j.nbt.2020.06.001

Rowe, G., & Frewer, L. J. (2000). Public Participation Methods: A Framework for Evaluation. *Science, Technology, & Human Values*, *25*(1), 3–29. https://doi.org/10.1177/016224390002500101

Sikazwe, M. K., Louw, J., & Görgens, J. F. (2024). Techno-economic and environmental assessment of a sugarcane biorefinery: Direct and indirect production pathways of biobased adipic acid. *Biofuel Research Journal*, *11*(04), 2225–2242. https://doi.org/10.18331/BRJ2024.11.4.3

Singh, R. K., Murty, H. R., Gupta, S. K., & Dikshit, A. K. (2012). An overview of sustainability assessment methodologies. *Ecological Indicators*, *15*(1), 281–299. https://doi.org/10.1016/j.ecolind.2011.01.007

Social Hotspot Database. (n.d.). [Database]. SHDB. Retrieved May 26, 2025, from http://www.socialhotspot.org/

Stampe, L., & Hellingrath, B. (2021). Risk Indicators and Data Analytics in Supply Chain Risk Monitoring. In U. Buscher, R. Lasch, & J. Schönberger (Eds.), *Logistics Management* (pp. 246–263). Springer International Publishing. https://doi.org/10.1007/978-3-030-85843-8_16

Štilić, A., & Puška, A. (2023). Integrating Multi-Criteria Decision-Making Methods with Sustainable Engineering: A Comprehensive Review of Current Practices. *Eng*, *4*(2), Article 2. https://doi.org/10.3390/eng4020088

Taherdoost, H., & Madanchian, M. (2023). Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia*, *3*(1), Article 1. https://doi.org/10.3390/encyclopedia3010006

Tseng, M.-L., Bui, T.-D., Lim, M. K., Fujii, M., & Mishra, U. (2022). Assessing data-driven sustainable supply chain management indicators for the textile industry under industrial disruption and ambidexterity. *International Journal of Production Economics*, *245*, 108401. https://doi.org/10.1016/j.ijpe.2021.108401

UNEP (Ed.). (2024). *Bend the trend: Pathways to a liveable planet as resource use spikes*. International Resource Panel.

United Nations. (2015). *World Public Sector Report 2015: Responsive and Accountable Governance*. United Nations.

United Nations Environment Programme. (2020). *Global Resources Outlook 2019: Natural Resources for the Future We Want*. UN. https://doi.org/10.18356/689a1a17-en

Venkatesh, G. (2022). Circular Bio-economy—Paradigm for the Future: Systematic Review of Scientific Journal Publications from 2015 to 2021. *Circular Economy and Sustainability*, *2*(1), 231–279. https://doi.org/10.1007/s43615-021-00084-3

Weidema, B. P., & Wesnæs, M. S. (1996). Data quality management for life cycle inventories—An example of using data quality indicators. *Journal of Cleaner Production*, *4*(3), 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1

Whalley, M., & Guzelian, C. (2017). *The legal risk management handbook: An international guide to protect your business from legal loss*. Kogan Page Limited.

Zhang, H., Peng, Y., Tian, G., Wang, D., & Xie, P. (2017). Green material selection for sustainability: A hybrid MCDM approach. *PLOS ONE*, *12*(5), e0177578. https://doi.org/10.1371/journal.pone.0177578

Ziemba, P. (2022). Application Framework of Multi-Criteria Methods in Sustainability Assessment. *Energies*, *15*(23), Article 23. https://doi.org/10.3390/en15239201