BIOTRANSFORM

TRANSITION PATHWAYS TO CIRCULAR BIO-ECONOMY

Circular BIOeconomy TRANSFORMation for regions by enabling resource and governance networks

D1.4 Literature review comparing impact assessment methodologies for linear fossil and circular bio-based economies

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List of Terms and Definitions

Abbreviation	Definition
CE	Circular economy
DOI	Digital Object Identifier
GUI	Graphical user interface
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCDM	Multi-criteria approaches
CBA	Cost-Benefit analysis

Table 1: Terms and Definitions

Executive Summary

The overall objective of BIOTRANSFORM is to support policymakers in enabling the transition from linear fossil-based value chains to circular bio-based systems across the EU, and the main objective of this review is to identify knowledge gaps and possible obstacles in evaluation methods; this information will provide an initial framework to consider and include when developing BIOTRANSFORM´s assessment package. Consequently, together with the information gathered in Tasks 1.1, 1.2 and 1.3, this will help the BIOTRANSFORM partners to improve the user manual of the assessment package developed as part of WP2.

In this document, a bibliographic review of the methodologies and indicators that already exist to assess the environmental, social and economic impacts of fossil/bio-based, and linear/circular economies has been carried out, as well as their transitions at the macro level, that is, at the national or regional level. A total of 11543 publications have been reviewed (without duplicates), of which 122 have finally been selected. Also, the selected publications have been classified according to a colour coded multicriteria that makes easy for the target user to determine and select the methodologies that are more interesting for them, which will be detailed throughout this deliverable. A critical analysis of the existing options in the different sectors, and the most used methodologies, has been carried out. As shown below, the sectors with the most information are Waste Management and Industry, and the most used methodologies are the Life Cycle Assessment/Life Cycle Inventory/Life Cycle Impact Assessment, and the Multi Criteria Approaches.

1. Introduction

The circular economy and the bioeconomy are popular narratives in sustainability debates in politics, scientific research, and business. These terms offer different ways of addressing economic, social, and ecological goals, thus promoting different pathways for sustainability transformations. In contrast to the traditional linear economic model, which follows the “extract, produce, use and dispose” pattern, the circular economy promotes the reuse, repair, recycling and regeneration of existing products and materials.

As discussed in the publication (Ahmed et al., 2022), the Circular Economy (CE) model is being incorporated into diverse business models in a wide variety of industries and across different levels, representing a direct approach to overcoming global challenges. Indeed, it is defined as an industrial system that is restorative or regenerative, which aims to protect the environment and, at the same time, achieve prosperous economic development that takes into account social aspects. It also enables the different objectives of sustainable development to be achieved by focusing mainly on recycling, reuse, repair, and remanufacturing, by developing new systems and business models and by changing consumption patterns. This paradigm shift is due to the fact that the 17 Sustainable Development Goals established by the United Nations in 2015 as part of the 2030 Agenda, a global action plan to promote sustainable development worldwide, and covering a wide range of interconnected themes addressing the economic, social and environmental challenges facing the planet, have renewed the global vision of sustainability and highlighted the urgency of concerted efforts by multiple stakeholders, including economic actors and society as a whole.

The bioeconomy is the third term that has gained popularity in the last decade. The term bioeconomy, at times also called ‘bio-based economy’ or ‘knowledge-based bioeconomy’, leverages the potential of biological resources from land and sea for the development and commercialization of goods and services; it thus proposes the substitution of fossil-based activities with those based on living biomass, with biotechnology and knowledge-based innovations driving this process (D’Amato & Korhonen, 2021). This covers, for example, technologies for converting biomass into a variety of goods. The term bioeconomy is frequently associated with the principles of sustainability and CE in policies and publications. The EC claims that bioeconomy will strongly support industrial innovation, and that the success of bioeconomy development and implementation relies strongly on the systemic integration of sustainability and circularity, putting the protection of the environment and the enhancement of biodiversity at its heart (European Commission 2018, Robert et al. 2020).

Indeed, circular bioeconomy processes are often defined as those that offer sustainable and scalable opportunities, capable of integrating a high degree of specialization, to deliver applicable, productive, and cost-effective solutions. However, high failure rates in the translation from good science to high impact scaled solutions must be overcome (Hankamer et al., 2023).

Quantifying the circularity and sustainability of products and services is essential for designing business policies and strategies and prioritizing evidence-based sustainable solutions during the transition to the Circular Economy. For this quantification, there are what are known as key performance indicators or KPIs and, recognizing the need for a circular economy that decouples economic progress from resource depletion, these indicators have been established based on aspects such as quantity and quality of material use, energy use required, and other aspects which are detailed in *Annex 2 – BIOTRANSFORM Repository*, an in-depth analysis of each of the selected publications. As the article (Kusumo et al., 2022) indicates, Circularity indicators can be used to evaluate the circularity of a product or system, which refers to the capacity to preserve both the quantity and quality of a material, as well as the efficiency with which a company can transition from linear to circular business models. Circularity indicators can also be used to evaluate the effectiveness of a company's transition from linear to circular business models and to assess how successfully a company is able to preserve both the quantity and the quality of a material. In terms of sustainability, Padi & Chimphango developed in 2021 the percentage sustainability index, an estimation tool that includes the assessment of life cycle sustainability. Sustainability has three pillars: environmental, economic and social, in 2018 Petit et al. defined eco-social and environmental indicators to assess the performance of value chains.

Enormous quantities of fossil fuels are turned into material and energy commodities in the existing economic system to meet society's consumption requirements, including basic needs while also sustaining its health and quality of life levels. Current consumption levels, however, cause resource stock depletion and the emission of carbon dioxide and other greenhouse gases, so this model is not sustainable. As a result, people in all societies must take their responsibilities and actions seriously in order to accelerate the transition to sustainable, post-fossil-carbon economies through the sustainable use of renewable biomasses - rather than fossil resources - for the production of biomaterials and bioenergy. This will necessitate a significant shift in socioeconomic, political, business, industrial, agricultural, energy, and technical systems. The CE literature is deficient in terms of theory and technique for implementing the Circular Economy, for this reason studies that focus on the development of evaluation methods or frameworks are necessary. Assessment methods or frameworks are methodologies that provide guidance on the dimensions and variables that need to be taken into account to measure the circularity, such as the use of indicators or models.

The purpose of this document is to give an overview of the current state of play in terms of methodologies and indicators measuring the transition towards the circular bioeconomy.

The Circular Economy can be analyzed at different levels, and each level focuses on different aspects and actors. In the following, each level is briefly explained:

- Macro level (countries, cities, regions, and nations): Focuses on policies and strategies at national, regional, and global levels, developing legal frameworks, regulations, and policy programs. The main actors are governments and international institutions.

- Meso level (inter-industrial and symbiotic partnerships): Focuses on the sectorial or regional level. The main actors are companies, sectoral associations, local authorities, and business networking in Circular Economy.

- Micro (business and consumers): Focuses on the company level. Cleaner and more sustainable consumption, production and purchasing. Specifically, recycled materials are incorporated into production processes, waste management strategies and new business models are adopted.

- Nano (products, materials, and components): The main actors are consumers and citizens. At this level, responsible consumption and product repair are promoted and education and awareness raising is very important to encourage change. Sustainable extraction of resources and extension of the life cycle of products.

Within these levels, the present study is based on methods aimed at the macro levels, as the end users targeted by the BIOTRANSFORM assessment package are policymakers.

2. Methodology

The methodology that has been followed in the literature review is based on the PRISMA statement, a road map to help authors best describe what was done, what was found, and in the case of a review protocol, what they are planning to do. Articles and reports have been selected according to the eligibility inclusion and exclusion criteria. The inclusion criteria of the study were: documents written in English, documents focused on analysis at the macro level, documents up to the present (in those searches in which the result has been very high, the most recent results have been prioritized for the analysis), and finally, documents corresponding to the keywords selected. On the other hand, the exclusion criteria have been: all results that did not correspond to the inclusion criteria, all the results with insufficient or irrelevant data, and duplicates (the procedure carried out to eliminate duplicates is discussed later).

The steps that have been followed are:

1. First, a keyword search has been carried out, both on the Scopus platform and on the ScienceDirect platform.
2. Secondly, among all the results obtained, each one of them identified by its DOI (Digital Object Identifier), the duplicates that existed have been eliminated.
3. Once the duplicates have been eliminated, the analysis of each one of the publications has been carried out, obtaining the relevant information, and classifying them according to the criteria explained in detail below.

The steps followed are shown in Figure 1.

The following figure of *Annex 1 - String Words table* shows the different search criteria, depending on the selected keywords, some of them joined by “AND” and others by “OR”, to avoid loss of information. The searches have been carried out both on the Scopus platform and on the ScienceDirect platform, as mentioned in step 1.

A total of 11,543 publications have been reviewed, it must be taken into account that duplicates are included in this number. Once the duplicates were eliminated, the number of publications to analyse was reduced to 7,848, among 122 with relevant information were selected. All selected publications are open access articles, as not everyone who reads the deliverable will necessarily have access to the scientific literature. Those numbers that are marked in orange, indicate that the results obtained have been very high, in these cases, it has been necessary to filter the results giving preference to the most recent publications. Finally, once the information has been obtained from each of the publications, they have been classified according to a multi-criteria colour coded, which is explained below.

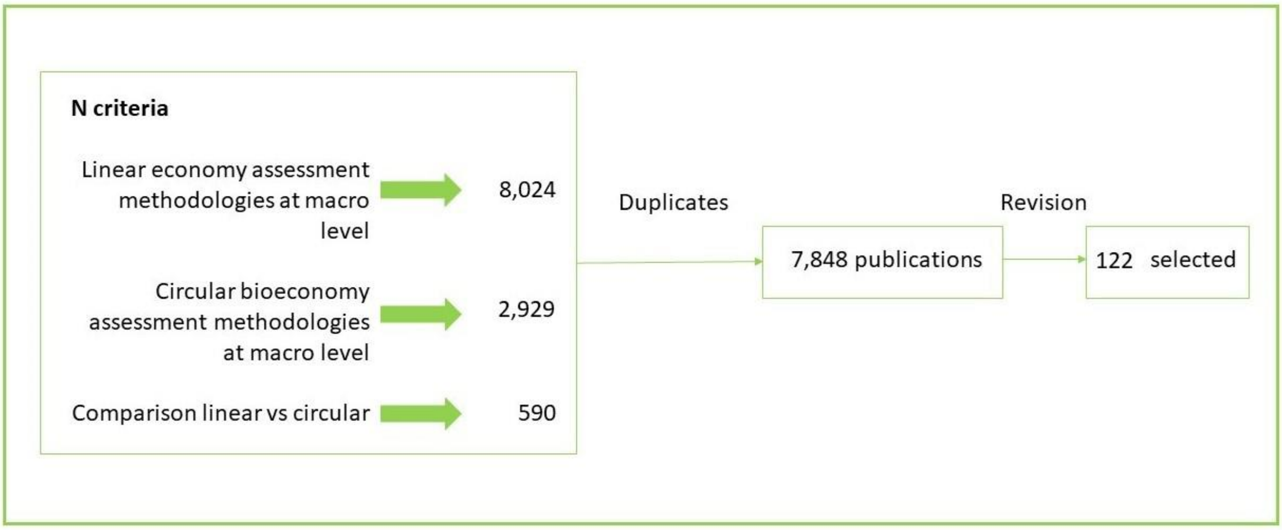

Figure 1: Methodology

STRING WORDS

				TOTAL		
			PARTNER	Science Direct	Scopus	
Scope	N.	Search		Revised	Revised	Included
Linear economy assessment methodologies at macro level	1	"economy" AND "performance assessment" AND "methodology" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"	ALCN	2034	908	3
	2	"economy assessment" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		87	540	6
	3	"economy performance" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		442	392	0
	4	"economy" AND "indicator" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		6	6	19
	5	"economy" AND "linear" AND "performance assessment" AND "methodology" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		522	689	0
	6	"economy assessment" AND "linear" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		49	45	1
	7	"economy performance" AND "linear" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		357	99	2
	8	"economy assessment" AND "linear"AND "indicator" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		21	24	0
	9	"economy" AND "linear" AND "Sustainability" AND "performance assessment" AND "methodology" AND "macro" OR "country" OR "region" OR "local" AND NOT "circ		483	365	0
	10	"economy assessment" AND "Sustainability" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		84	225	2
	11	"economy performance" AND "Sustainability" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular"		391	255	2
Circular bioeconomy assessment methodologies at macro level	12	"circular bioeconomy" AND "performance assessment" AND "methodology" AND "macro" OR "country" OR "region" OR "local"	CTA	18	77	1
	13	"circular bioeconomy assessment" AND "macro" OR "country" OR "region" OR "local"		1	0	0
	14	"circular bioeconomy performance" AND "macro" OR "country" OR "region" OR "local"		1	0	0
	15	"circular bioeconomy" AND "Sustainability" AND "performance assessment" AND "methodology" AND "macro" OR "country" OR "region" OR "local"		7	75	4
	16	"end of life" AND "performance assessment" AND "methodology" AND "bio" AND "macro" OR "country" OR "region" OR "local"		74	112	6
	17	"end of life assessment" AND "bio" AND "macro" OR "country" OR "region" OR "local"		3	11	0
	18	"end of life performance" AND "bio" AND "macro" OR "country" OR "region" OR "local"		10	13	0
	19	"circular bioeconomy" AND "performances" AND "indicator" AND "macro" OR "country" OR "region" OR "local"		460	774	16
	20	"end of life" AND "bio" AND "indicator AND "macro" OR "country" OR "region" OR "local"		612	681	11
Comparison linear vs circular	21	"linear economy" AND "circular bioeconomy" AND "assessment" OR "performance" AND "methodology"	LIST	127	36	0
	22	"linear economy" AND "circular bioeconomy" AND "assessment" OR "performance" AND "indicator"		87	47	0
	23	"linear economy" AND "circular bioeconomy" AND "Sustainability" AND "assessment" OR "performance" AND "methodology"		126	34	14
	24	"linear economy" AND "circular bioeconomy" AND "Sustainability" AND "assessment" OR "performance" AND "indicator"		87	46	35
-	25	Serendipity (those found randomly or sugested by explicitely by peers)		0	0	0
		TOTAL (total after selection based on the agreed criteria)	All	6089	5454	122
				TOTAL revised	11543	
				TOTAL included	122	

Figure 2: Annex 1 - String Words

Among the selected publications, it has been necessary to define criteria to assess the different identified circular bioeconomy methodologies. The aim was do it through a colour coded system that makes easy for the target user to determine and select the methodologies that are more interesting for him.

Saidani et al. (2017) synthetised and classified the required, desired, and ideal features of a circularity assessment methodology within a proposed hierarchy inspired by Maslow´s pyramid of needs.

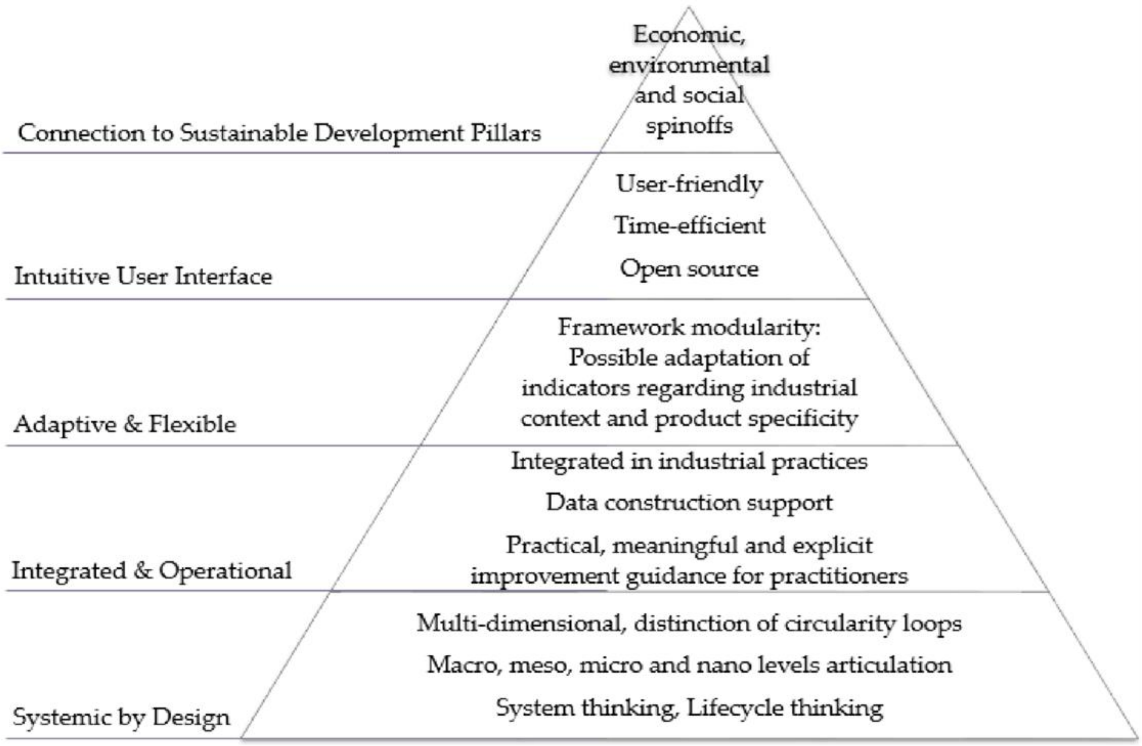

Figure 3:Proposed hierarchy of desired features to design frameworks, methods, tools, and indicators aiming at measuring product circularity performance. (Saidani et al. 2017)

Although this figure is for product circularity assessment it could easily be used for macro level circularity assessment as well. Therefore, the following five cornerstones have been used for the colour coded multicriteria assessment:

- Systemic by design
- Integrated and operational
- Adaptive and flexible
- Intuitive user interface
- Connection with sustainable development skills

Details about each feature can be found in *Figure 2*. First, the two requirements positioned at the base of the pyramid: “systemic by design” and “integrated and operational”, are considered as mandatory and required features, respectively, to ensure a holistic approach, i.e., to consider the whole complexity of circular economy paradigm during product circularity measurement, and to be fit with industrial practices during design and development phases. Then, the two following requirements, “adaptive and flexible” and “intuitive user interface”, are seen as additional and desired features, respectively, to have the ability to consider different products from diverse industrial sectors, and to be effectively and efficiently used by practitioners. Finally, the requirement placed at the top of the pyramid “connection to sustainable development pillars”, is deemed as an ultimate and ideal feature, reminding us that circular economy targets and measures should not be a goal in itself but rather a means to an end in order to achieve a more sustainable development and society.

First, the “systemic by design” cornerstone highlights that the measurement tool should encompass a wide spectrum of the circular economy paradigm—including its complexity and principles. Such as lifecycle thinking, consideration of systemic levels and interplay between implementation levels (macro, meso, micro, and nano) are essential for an effective measure of product performance in the light of circular economy.

Second, the ‘integrated and operational” cornerstone emphasizes that the framework needs to be fit with industrial practices. Integrated design is a practice to combine different values (e.g., functions, aesthetics, manufacturability, assimilability, recyclability) of the product lifecycle in the early phases of the design process. As such, developed framework should be compatible and complementary with other tools and software used during product design and development phases, to help for instance decision-making. In addition, to be operational, as one of the main challenges to evaluate properly product circularity lies on the ability to gather adequate date, the framework should support data construction. In this light, a standardized input datasheet could be developed to facilitate the data collection, for instance divided in several sections such as technical data (e.g., bill of materials) and market or organizational data (e.g., supply chain, end-of-life pathways).

Third, the “adaptive and flexible” cornerstone underlines that the framework should be designed with a modular and non-frozen approach to be continuously improved through time and feedback.

Fourth, the “intuitive user interface” cornerstone highlights the importance of designing a proper graphical user interface (GUI) for non-expert actors in circular economy. In order to be time-efficient and user-friendly, the GUI should ease the acquisition of data, as well as enable a comfortable visualization of the results.

Fifth, the “connection to sustainable development pillars” cornerstone stresses that the actual impact of circularity should be analysed against the sustainability performance of given a product entering in a circular economy loop. It becomes therefore relevant to check if the potential circularity will lead to effective benefits regarding sustainability, or under which conditions and trade-offs between the three pillars.

	Main features	Green	Yellow	Red
Systemic by design	• Multi-dimensional, distinction of circularity loops • Macro, meso, micro and nano levels articulation • System thinking, lifecycle thinking	It has the 3 features	It has 2 features	It has only 1 or none feature
Integrated and operational	• Integrated in industrial practices.	It has the 3 features	It has 2 features	It has only 1 or none feature

	• Data construction support • Practical, meaningful, and explicit improvement guidance for practitioners			
Adaptive and flexible	• Framework modularity: possible adaptation of indicators regarding industrial context and region specificity	It has the feature	Not so flexible, only for other sectors (but not other regions) or only for other regions (but not other sectors)	It doesn´t have the feature
Intuitive user interface	• User-friendly • Time-efficient • Open source	It has the feature	It has 2 features	It has only 1 or none feature
Connection with sustainable development skills	• Economic, environmental, and social aspects	It addresses the 3 aspects of sustainability	It addresses 2 of the 3 aspects of sustainability	It addresses only 1 of 3 sustainability or none of them

Table 2: Terms and Definitions

Below is the list of methodologies that include those listed in Sassanelli et al. (2019) and other categories were added according to the new approaches identified:

- Life cycle assessment / Life cycle inventory / Life cycle impact assessment (LCA, LCI, LCIA).
- Multi-criteria approaches and fuzzy logic (MCDM & fuzzy).
- Design for X and guidelines (DfX & guidelines).
- Data Envelopment Analysis and Input-Output models (DEA & I/O).
- Material Flow Analysis (MFA).
- Emergy and exergy based approaches (Emergy & exergy).
- Discrete event simulation / Simulation (DES & Simulation).
- Ecological footprint (Eco footprint).
- Cost-Benefit analysis (CBA).
- Other methodologies (Other).
- Mixed: this option is used when the approach uses a combination of at least two of the aforementioned methodologies.

To analyse the trends in current research activities, the approaches have been classified according to following the sectors of application:

- Agri-food
- Building
- Forest
- Industry
- Marine
- Metallurgy
- Services

- Waste management
- Water
- Energy
- Biotechnology

3. Results

An interesting study by (Sinkko et al., 2023) presenting the Bioeconomy Footprint sets out a process based LCA approach to measure the environmental impacts of the EU bioeconomy. The Bioeconomy Footprint Trend Assessment highlights the important role of the food sector, which, on the one hand, is entirely bio-based and, on the other hand, is associated with the basic needs of consumers. It states that the Bioeconomy Footprint can support the objectives of potential users of the EU BMS to prioritise actions through its granularity and inform stakeholders. It also raises the need to establish proposed alternatives ranging from basic indicators based on trend assessment to more elaborate metrics; reflecting decoupling of resources and resource efficiency assessments, to an assessment against the PB framework to provide an absolute sustainability perspective.

In the classified results, a more in-depth analysis (*Annex 2*) has been carried out, indicating among other things: name, scope, type (methodology or indicator), methodology, a brief description, sustainable development approach, platform, input, output, advantages, disadvantages, environmental protection indicator/area, graphic representation of results, sector, and it has been classified according to a colour coded multicriteria, which will be discussed later. For the included information, an analysis of the year and the sector has been conducted in order to identify trends concerning CE assessment.

In this analysis, the Circular Economy has been studied at the macro level, i.e., countries, cities, regions, and nations are involved. The macro level has been selected because the objective of BIOTRANSFORM is to support policy makers in enabling the transition from linear fossil fuel-based value chains to bio-based circular systems across the EU. Thus, the end-users of the BIOTRANSFORM assessment package are the policymakers. Furthermore, in some studies, the term meso level conflicts with macro level, for example, Chinese CE law considers regions as macro scale, while Smol et al. (2017) propose regions as meso level, as the connection between macro and micro levels. For these actors, the largest number of included articles found in the consulted platforms (Science Direct and Scopus) include in their search the following terms:

Scope "macro-level linear economy assessment methodologies": "economy assessment" AND "macro" OR "country" OR "region" OR "local" AND NOT "circular". Varying between the terms "economy" "performance" and "sustainability".

For this domain, the differentiating element that limits the results lies in combining economy with terms such as development or assessment. Moreover, those where "indicator" appears are the least abundant. This is the opposite situation for the other areas: “Evaluation methodologies for the linear economy at the macro level”, "Evaluation methodologies for the circular bioeconomy at the macro level" and "Linear vs. circular comparison" where the results related to this term are the most included (29%), (31%), and (40%) respectively, among those chosen in each area. As already discussed, (Kusumo et al., 2022) circularity indicators are essential to assess the circularity of a product or service.

The following table shows a summary of the results of the analysis that have finally been included, indicating the number of publications included according to methodology. A complete list of the publications included in this review, including an analysis of each of them, can be found in *Annex 2 - BIOTRANSFORM Repository*. As can be seen, the most commonly used methodologies are Life Cycle Analysis and the Multi-criteria approach.

Method	Publications
Life Cycle Assessment / Life Cycle Inventory / Life Cycle Impact Assessment	31
Multi-criteria approaches and fuzzy logic	16
Design for X and guidelines	0
Data Envelopment Analysis and Input-Output models	2
Material Flow Analysis	2
Emergy – and exergy – based approaches	5
Discrete Event Simulation / Simulation	0
Ecological footprint	0
Cost-Benefit analysis	1
Other methodologies	54
Mixed	11

Table 3: Summary of results - methodology

4. Discussion

According to Sassanelli et al., the most widely used methods for CE assessment are LCA-based approaches, along with MCDM. In a review by Moraga et al. (2019), CE indicators available up to now were studied, but there was no comprehensive positioning framework for all the indicators and aspects included in the CE, only output and result indicators were analysed, and a great deal of knowledge was required about key aspect of CE, to use the indicators, which made it difficult to use for non-experts.

The main sectors that have been found in the bibliographical review have been Waste Management, and secondly, Industry. On the other hand, the sectors with the least results have been Metallurgy, and the Marine sector. Regarding the temporal analysis, in the following graphic shows the upward evolution in recent years, with respect to the results of research related to the circular bioeconomy. This graphic reflects the growing macro-level interest in the circular bioeconomy to address the economic, environmental, and social challenges we face. This interest is driven by the need to find more sustainable and environmentally friendly approaches.

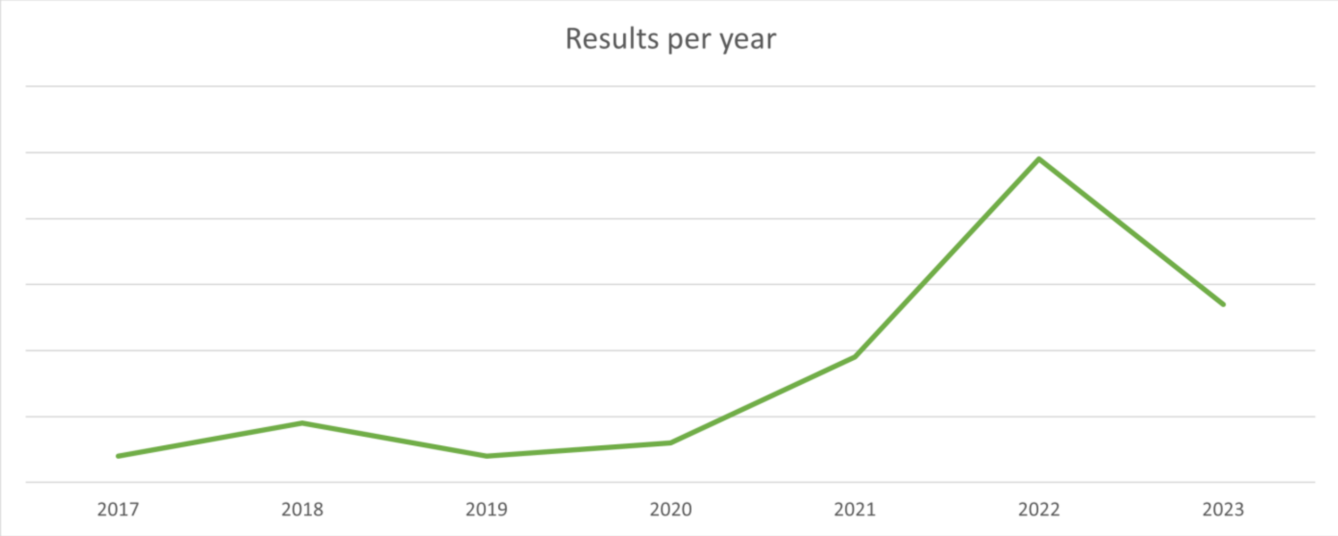

Figure 4: Results per year

The most used method is the LCA, LCI, LCIA, it is important to note that this methodology is very well known in the technical areas and circular bioeconomy. The second most used methodology is the MCDM, possibly because it is not necessary to use a specific software, it is very easy to use, it can be applied in an excel document, and it is a very versatile method. Finally, in the cases in which the methodology has been considered mixed, in most cases, it has been between LCA/LCI/LCIA and MCDM methods. Some of the indicators are based on the EC 4R framework.

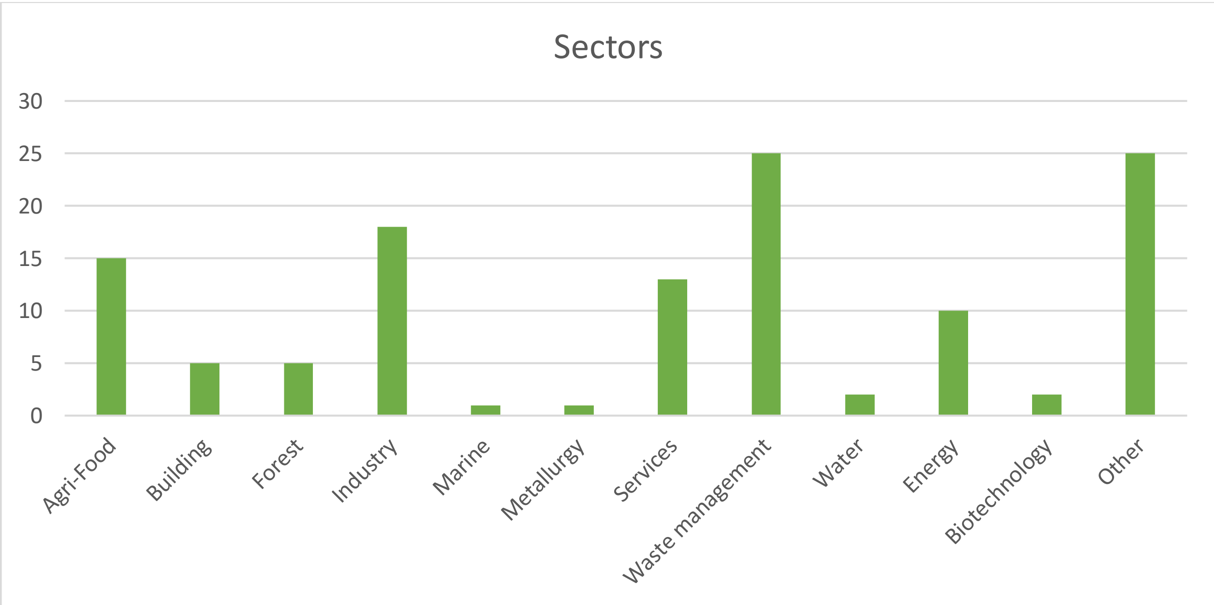

Figure 5: Results per sector

The graph above shows the grouping of the selected results grouped according to the different sectors. As mentioned above, the sectors with the most information are Industrial and Waste Management, and the sectors with the least information are Marine and Metallurgy. It is important to note that there are a large number of publications that are a mix of several sectors, or otherwise undefined and general/transversal, in this case, these publications are included in the category “other”.

5. Conclusions

The analysis of the bioeconomy in the different regions shows that meeting the objectives of the European Green Pact is a major challenge and that the sustainable transition can be achieved by developing national circular bioeconomy strategies. This study demonstrates that the role of the bioeconomy can be investigated by analysing different methodologies and indicators, which is a necessity as the bioeconomy and the biocycle is seen as a growing trend, with an increasing number of new organisations, services, materials, and products debuting on the market, creating new value chains. There is a need to assess the circularity of bio-based systems at the macro level for practitioners in the sector.

So far, 11,543 sources of information have been identified through a bibliographic review. Of these, 122 were selected for further study and classified in a new positioning framework. Of these 122 references: 35 are on macroeconomics, its evaluation processes and methodologies and indicators for the scope "Evaluation methodologies of the linear economy at macro level". 38 on circular bioeconomy and end-of-life corresponding to “Circular bioeconomy assessment methodologies at macro level” and 49 on linear economy and circular bioeconomy framed in the scope "Linear vs. circular comparison". All the information obtained from each of the publications can be found in *Annex 2*.

It is important to highlight that the evolution of new studies, methodologies and indicators in the circular bioeconomy sector has been growing very rapidly in recent years, so it is necessary to continually update new studies.

This information and that of the rest of WP1 is the basis for the development of the tools, since as far as possible, the tools developed will be based on existing assessment methods.

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7. Annex I

Annex 1 in separate excel file.

8. Annex II

Annex 2 in separate excel file.