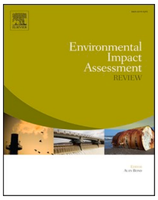
Environmental Impact Assessment Review 106 (2024) 107493

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar



How to select the best approach for circular economy assessment? 3D positioning framework, decision support tool and critical analysis for bio-based systems

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ARTICLE INFO

Keywords:
Circular economy
Circular bioeconomy
Assessment
Sustainability
Decision support tool

ABSTRACT

Although the transition from linear to circular economy is being carried out by many different actors, there is still not a well-established methodology for its assessment. In this paper, a review of available approaches for evaluating circular economy (technical and biological cycles) has been conducted. In total, 2.113 information sources have been revised and 105 of them were included in the review. They have been categorised per level (macro, *meso*, micro and nano), cycle (technical, biological or both) and methodology used, together with the sector according to NACE codes. Using this information, a positioning framework for classifying the different appraisal options has been developed and depicted in a 3D cube where each category is represented in one of the axes (level, cycle, and methodology). Moreover, a decision support tool has been created to help triple helix stakeholders selecting the most suitable approach according to the information they are looking for, i.e. the initial question they pose regarding how to assess circular economy. Since the main gap concerning available approaches has been identified for the biological cycle at micro and nano levels, a critical analysis of existing choices has been conducted. Finally, open areas for future work towards promoting circular bioeconomy assessment are identified.

1. Introduction

Circular economy (CE) and sustainable development are two concepts that have arisen during the last decades, concerning not only academia or policy makers, but also for other stakeholders such as private companies that try to make their processes and products more sustainable. Schöggl et al. (2020) investigated about how both terms are related and how they have been addressed in literature over the last two decades. Sustainable development can be considered compatible and consistent with the CE as it is linked to social, environmental, and economic aspects. In fact, it actively pursues both monetary returns (such as value creation and cost savings from using less basic raw materials) and environmental and social positive effects (such as impact reduction and new jobs) (Saidani et al., 2017). Another term that has gained momentum during the last decade is bioeconomy, usually appearing next to sustainability and CE concepts in policies and publications (European Commission, Directorate General for Research and Innovation, 2018). This has led to the term circular bioeconomy (CBE), which arises from the bioeconomy and CE concepts being entwined around 2015 and being progressively used since 2016 (Hetemäki et al., 2017). Before 2015, only some references to the CBE idea were made by the Ellen MacArthur Foundation, affirming that bioeconomy could be considered an inherent part of CE by incorporating the biological cycle into their CE infographic (Pauli, 2010). Later, and regarding biological cycles, Navare et al. (2021) studied how CE could be monitored for them, concluding that the complete evaluation of biological cycle qualities by the CE monitoring standards is lacking.

As pointed out by Lindberg et al. (2015), industrial systems

Abbreviations: (CE), Circular Economy; (CBE), Circular Bioeconomy; (KPI), Key Performance Indicator; (B2B), Business-to-business; (LCA), Life Cycle Assessment; (LCI), Life cycle Inventory; (LCIA), Life Cycle Impact Assessment; (MCDM), Multi-criteria Decision Methodology; (DfX), Design for X; (DEA), Data Envelopment Analysis; (I/O), Input-Output models; (MFA), Material Flow Analysis; (DES), Discrete Event Simulation; (GDP), Gross Domestic Product.

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https://doi.org/10.1016/j.eiar.2024.107493
Received 21 March 2023; Received in revised form 24 February 2024; Accepted 19 March 2024

nowadays use widely Key Performance Indicators (KPIs) for improving industrial performance. It is clear that when it comes to circularity, it is important to define the corresponding indicators and methodologies that can allow evaluating the progress of the circular transition. More specifically and on circularity indicators, an extensive review was provided by Saidani et al. (2019) and a lot of discussions that can be found in literature about how these indicators actually capture the different facets of the CE. Sassanelli et al. (2019) pointed out that there is a dearth of literature on CE performance evaluation and a lack of approaches capable of simultaneously measuring and gauging all the variables present in a circular system. So far, measuring circularity is usually conducted by external consulting companies, as the role of in-house circularity and/or sustainability expert/manager is still emerging. These companies depend on their appropriate commercial and marketing experience. Sometimes, even though these methodologies and instruments provide a first evaluation of product circularity performance, the complexity of the CE paradigm as a whole is seldom taken into account (Saidani et al., 2017). Also, evaluation of CE at value chain, company, or product level is barely considered in indicators reviewed, e.g. Ghisellini et al. (2016) only focussed on country level and technology or industrial parks level where several firms are interconnected.

Furthermore, Saidani et al. (2017) conclude that, at the micro level, the CE is only partially examined in terms of ecologically friendly consumption and greener manufacturing. Micro level measures for the CE do not consider all its complexity or all practical end-of-life options to stop the loop. Thus, although some recent reviews focus on the biological cycle (e.g. Zhang et al. (2022)), there is still a lack of a comprehensive revision of CBE assessment approaches for the micro level.

Finally, there is a quick growth of papers about CE and CBE implementation and assessment (the use of the topics “circular economy”, “circular bioeconomy”, “assessment” and “evaluation” in title, abstract or key words over time is explained in Fig. S1, included in the Supplementary materials). For example, 126 and 159 new papers were produced only during 2021 and 2022, respectively, for CE assessment. This would make making necessary to update the past reviews on this topic, including now the CBE dimension. As for positioning frameworks built on top of reviews, Moraga et al. (2019) concluded that there was not one positioning framework comprehensive for all the indicators and aspects included in the CE. As stated by the authors, the review and framework provided only analysed output and result indicators. Also, this positioning framework requires extensive knowledge about CE key aspects, making difficult for newcomers and/or industry practitioners to use it.

Within this context, industry practitioners often ask themselves how the circularity potential can be evaluated during the product development phase and across its lifetime, and at the value chain level, especially for bio-based processes. Through this journey, private companies experience challenges and barriers when implementing and appraising CE as summarised by Rincón-Moreno et al. (2021). These authors concluded that companies face hard and human-based barriers and that hard barriers may be remedied by financial stimulus and technical modernisation since they are related to a lack of financial resources, technology, poor information systems, etc. Bressanelli et al. (2018) conducted a systematic review of supply chain redesign for CE, identifying “measures, metrics, indicators” as one of the standards and regulation challenges when it comes to CE implementation. Moreover, Garcés-Ayerbe et al. (2019) explored the challenges and opportunities for European Small and Medium-Sized Enterprise companies, pointing out that: (1) those that have not transitioned to CE would be probably due to lack of expertise to carry out such activity; and (2) companies already implementing some CE practices found difficult to find the expertise needed to measure CE. Thus, it can be drafted that private companies might need support when it comes to CE in terms of assessing its progress and identifying best technologies and spots to be implemented. To overcome this, there have been efforts from regional actors that have performed a survey of CE tools and platforms that support CE application on a business-to-business (B2B) level, e.g. the one from Circular Flanders (Vlaanderen Circulair, 2024). However, to the best of this research authors knowledge, there is no decision support tool that can guide the private stakeholders in selecting an approach for CE appraisal according to information needed, their commercial sector and the measurement scope.

This way, the following specific research questions arise:

- Which approaches are available for CE assessment (both technical and biological cycles) and how could they be classified in a proper positioning framework?
- How to develop a decision support tool that could help and guide stakeholders, from different knowledge levels and linked to different systems, on their evaluation of CE?
- Which appraisal approaches can be found for CBE, specially at micro and nano level as this are the most relevant for companies?
- Which are the open areas that can be identified for future research?

The research work carried out is presented herein as follows. Section 2 summarises the methodology that has been used for the conducted literature review and for the development of the positioning framework and the decision support tool. Section 3 presents main results and introduces the new positioning framework and decision support tool. Discussions about the relevance of the findings presented are gathered in Section 4. Finally, Section 5 goes over the main points and conclusions drafted, together with details of current limitations of the study and suggestions for future research.

2. Material and methods

The methodology followed for the literature review is based in the PRISMA statement (Page et al., 2021). Main steps have been deciding on the target journals and information sources, establishing the exclusion and inclusion criteria, doing the review (identification and selection of relevant publications according to the defined criteria), systematisation of the main findings and drafting the discussions and conclusions. Due to the novelty of the topics, not only scientific peer reviewed journals have been considered, but also non-peer-reviewed publications, following the recommendations from Geissdoerfer et al. (2017). They delved into the relationship between CE and sustainability and concluded that the primary constraints of their study stem from conducting a bibliometric analysis that relied on the assumption that researchers disseminate their most significant findings in journals and build upon previously published articles. Hence, they stated that it is essential to acknowledge that valuable contributions may come from unpublished documents, reports, and other non-academic sources not featured in scholarly journals. Accordingly, sources of grey literature from business organisations, project reports, etc. as well as peer reviewed publications included in Science Direct, Web of Science, SAGE, Springer, Taylor & Francis and Google Scholar, together with European Commission documents have all been looked at as potential data sources. Concerning the strings of words used, the ones from Sassanelli et al. (2019) were used as starting point. Since they did not put special focus on the biological cycle, the term “bio” has been added to the key words used to capture the biological cycle dimension. It is important to note as well that, when looked for CBE, its synonyms were also looked in titles, abstracts, and keywords (string: “circular bioeconomy” OR “circular bio-based economy” OR “circular bio-economy”). Strings used are depicted in Table 1 next to the results of the review work that has been carried out for database sources.

Regarding the classification strategy, the inclusion criteria were defined by the authors at the beginning of the investigation, these have been: (i) information published up to 2022; (ii) peer reviewed publications as well as grey literature; (iii) content actually dealing with CE (technical or biological cycle); (iv) when quite similar papers from the same research group were identified, only the most recent one (as it has been considered as the most complete and updated) has been included. Regarding the third criteria, it is important to notice that several articles

Table 1
String words used in the databases review exercise and results for revised and included information sources.

		Science Direct		Scopus	
N.	Search	Revised	Included	Revised	Included
1	“circular economy” AND “performance assessment” AND “methodology”	310	17	75	6
2	“circular economy assessment”	35	14	35	8
3	“circular economy performance”	78	12	61	3
4	“end of life” AND “performance assessment” AND “methodology”	667	14	190	2
5	“end of life assessment”	63	1	94	0
6	“end of life performance”	98	6	134	5
7	“circular bioeconomy” AND “performance assessment” AND “methodology”	13	1	4	2
8	“circular bioeconomy assessment”	2	0	0	0
9	“circular bioeconomy performance”	2	0	0	0
10	“end of life” AND “performance assessment” AND “methodology” AND “bio”	157	3	0	0
11	“end of life assessment” AND “bio”	9	1	2	0
12	“end of life performance” AND “bio”	12	0	0	0
13	Random	20	0	41	10
	TOTAL	**1466**	**66**	**636**	**33**

included CE in the title, key words or abstract but the topic was not found in the research work (being sometimes related to e.g. environmental impact assessment, ecology, sustainability, etc.).

After the revision and selection made following these criteria, a final categorisation step was conducted. To do so, the following categories were identified for each selected piece of information: level, cycle, methodology, sector, subsector, year, and country. As for the level, these are related to the scope of the analysis exercise, I.e., system boundaries. These are nano, micro, *meso*, macro or a combination of them as in some cases, the studied publication authors state that their method can be applied to several levels. One example is the publication from Ahmed et al. (2022) that developed a multilevel approach for CE assessment, addressing macro, meso, micro and nano levels. Concerning the cycle, this is related to the type of material (technical or biological) as defined by Braungart et al. (2006) and the Ellen Macarthur (2015), and later discussed by Navare et al. (2021). It is worth mentioning that when the paper did not mention explicitly the biological cycle but tackled bio-based materials such as food, organic waste, etc. the category tech-bio has been allocated. Such category has also been allocated when the information source explicitly mentioned that both technical and biological cycles would be applicable. Pertaining to the methodology, this is about the theoretical approach used for the analysis, including those listed by Sassanelli et al. (2019) and other categories added to better accommodate the new identified approaches:

- 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)
- Other methodologies (Other)
- Mixed (this option is used when the approach uses a combination of at least two methodologies)

The sector (and subsector) have been identified following the classification from the NACE codes (List of NACE Codes, 2024). It is worth mentioning that some approaches are devoted to the manufacturing sector from a general point of view, i.e. they do not specify the subsector of application. For those cases, the whole set of manufacturing subsectors from the NACE code list has been considered (noted as C10-C33). Finally, the year is linked to the time of the publication and the country to the geographical location of the main author.

For a careful analysis of the systematized information, dynamic charts were used in order to better represent and examine the main data and findings. Website links to the dynamic charts and the decision support tool have been produced and can be found in the Supplementary materials section.

So far, a total of 2113 papers, documents and reports have been revised with a total of 105 selected for inclusion in the review. A dynamic representation of this table can be found in the Supplementary materials (DC1). Finally, a summary of the process that has been implemented in presented in Fig. 1.

3. Results

For the included information, an analysis of the year and corresponding author location has been conducted. Main results are presented in the Fig. 2. When the included information was related to a webpage for a circularity assessment approach from a private company, the term “N/A" has been stated.

3.1. Positioning and classification frameworks review and critical analysis

CE and CBE can be modelled, implemented, and measured for a system with boundaries. A taxonomy for the systems that can be considered in CE has been discussed in literature, and although most of the authors point out macro, *meso* and micro levels as the main taxonomies (Moraga et al., 2019), the definition of these terms is not used on a consistent manner and might differ slightly between the different authors. Moreover, Saidani et al. (2017) go beyond and propose a fourth term, the nano level, specifically addressing “an operational and product-level including components and materials” that belongs to value chains and could be considered throughout their entire lifecycle. A summary of the different interpretations of the taxonomies is provided in Table 2.

It is interesting to pay attention to the *meso* level, which has been mostly covered in Chinese publications as stated by Geng and Doberstein (2010) and Geng et al. (2012). In fact, all those that fall under the category of *meso* level have the corresponding author based in China (Han et al., 2017; Li, 2011; Pan et al., 2016). Only when references address mixed levels such as macro-*meso* or meso-micro, information from other countries can be found. The development of industrial parks is being fostered and supported by the Chinese government with a wide approach since they include not only industrial facilities, but also business and research facilities, residential buildings, and service areas. Another definition for meso scale is provided by Geng et al. (2012) as they consider the natural environment and corresponding regional networks as well. Furthermore, in some studies, the term meso level conflicts with macro scale. For example, Chinese CE law considers regions (area between larger than a city but smaller than a country) as macro scale, while Smol et al. (2017) propose considering regions as the connection between macro and micro levels when measuring CE eco-innovation, i.e., consider regions at meso level. As a potential solution to this controversy, Moraga et al. (2019) suggested that when a taxonomy is used, it could be helpful to state as well the scope.

There have been several attempts to identify, categorise and review

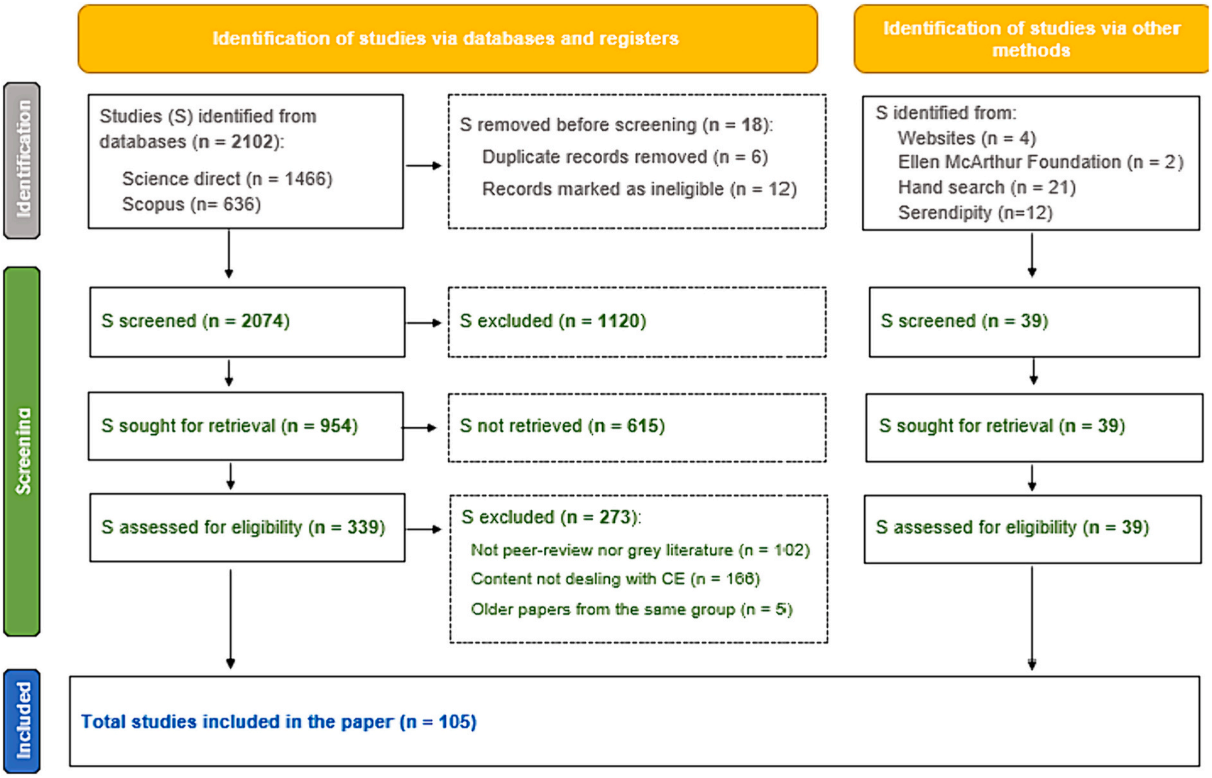

Fig. 1. PRISMA Flow Diagram for the conducted literature search.

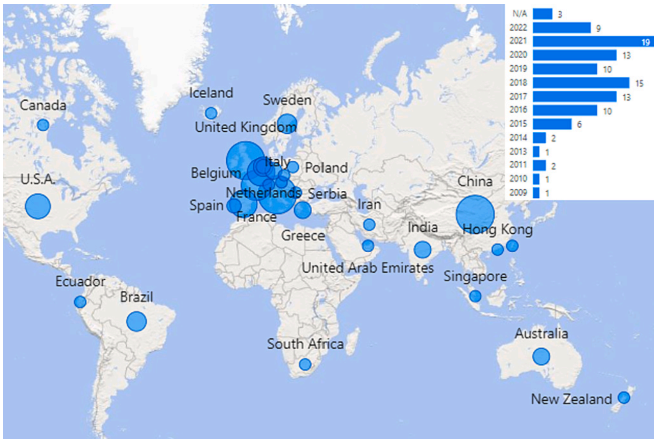

Fig. 2. Included circular economy assessment approaches per location of corresponding author and publication date.

Table 2
Levels for modelling, implementing, and measuring circular economy according to literature.

Level \Reference	Saidani et al., 2017	Balanay et al., 2016	Banaitė and Romeris, 2016	Moraga et al., 2019
Macro	City, province, region, nation	Society	City, province, region, country	National level, global scale as and additional scale
Meso	Eco-industrial parks	Inter-enterprise	Symbiosis association	Eco-industrial parks
Micro	Single company or consumer	Enterprise	Single company or Consumer	Single product, service, organisation
Nano	Products, components, and materials	–	–	–

CE assessment methods, producing positioning frameworks. Saidani et al. (2017) do not provide a positioning framework itself as they tested and validated three practices related to the assessment of product circularity at micro level and delved into the requirements that an ideal circularity measurement framework might have. Sassanelli et al. (2019) reviewed systematically and categorised different methods according to the approach used. For each of the assessment approaches, triple bottom line aspects were studied (economic, environmental, and/or social aspects), as well as adopted variables and lifecycle stage. In the relevant review from Moraga et al. (2019) a large pool of CE indicators were studied. A categorisation framework was proposed according to a set of CE strategies defined by the authors and to parameters established using the Life Cycle Thinking methodology. Finally, it is worth noticing that these reviews cover the technical cycle of the CE butterfly model from the Ellen MacArthur Foundation. In the case of Moraga et al. (2019) both cycles are used in the framework, but these are addressed equally. As for the biological cycle, it is worth mentioning the review and discussion from Navare et al. (2021) who studied the gaps in CE monitoring for the biological cycle.

3.2. *Proposal for a positioning framework for circular economy assessment approaches classification*

So far, the available positioning frameworks are not able to address all aspects from CE, nor CBE specificities. Therefore, as a result of the research work presented herein, a positioning framework is proposed with the aim of providing a classification able to cover new CBE assessment approaches to be further developed during the next years as well (i.e., not only CE systems linked to the technological cycle).

The proposed positioning framework consists of a triple-axis space where each axis corresponds to a characteristic of the CE assessment approach. The X-axis refers to the assessment level. The Y-axis refers to the methodology. Finally, the *Z*-axis refers to the CE cycle considered. This way the positioning framework can be imagined as a 3D cube where the different CE approaches can be positioned inside. The aim behind this design is that even stakeholders with bare knowledge about CE can select a method that is suitable for their needs just knowing the level of their system to evaluate, the cycle involved and the preferred methodology.

Approaches have been represented in the proposed positioning framework as depicted in Fig. 3 while in Table 3 detailed information is provided (ordered alphabetically according to CE cycle, level and methodology respectively). For the sake of simplicity, approaches with the same level, cycle and methodology have been grouped under the same dot. Extended information about each approach (brief description) as well as projections from the 3D cube (level vs cycle, cycle vs. methodology and methodology vs. level) can be found in the Supplementary materials (Table S1, Figs. S2, S3 and S4). Projections make easier getting insights about gaps and more studied approaches.

3.3. *Decision support tool for triple helix stakeholders on how to select the most suitable circular economy assessment approach*

Using the information gathered through the literature review, a decision support tool has been created with the aim to help the end-user in identifying the best approach to address its needs when it comes to CE evaluation. To do so, the tool workflow starts by asking the end-user about the information that it is being looked for. Then, the second step is to select the level, followed by the sector. Last step is to select the cycle. As a result, the publications meeting the selected inputs are shown to the end-user by providing the “Name”, “Aim” and “Reference” from Table 4 fields. The link to the decision support tool, which is available online for free, is provided in the Supplementary materials (DC3).

The following table summarises the different kinds of information that might be sought by the user and how this is linked to the different CE assessment methodologies that have been identified herein.

Also, it is important to consider what these methods do as their different characteristics can also explain why particular methods are employed at certain levels or within particular sectors. LCA, including LCI and LCIA, employs comprehensive data encompassing the entire life cycle of a product or process, from raw material extraction through production, use, and disposal. LCA, primarily focusing on environmental impacts, evaluates each life cycle stage. The overarching goal is to quantify and assess the environmental performance of a product or process, identifying areas for sustainability improvement (Curran, 2016). MCDM & fuzzy utilize multiple criteria, both qualitative and quantitative, relevant to decision-making. MCDM assesses alternatives based on various criteria, while fuzzy logic addresses uncertainties and imprecise information. The primary objective is to facilitate decision-making by considering and balancing multiple criteria, particularly in complex and uncertain situations (Stewart and Durbach, 2016). DfX relies on design specifications, constraints, and requirements and aims to optimize a product or process for specific factors such as reliability, sustainability, and manufacturability. The goal is to enhance overall performance by focusing on specific aspects during the design phase (Jari et al., 2011)(Jari et al., 2011). DEA & I/O use input and output data to analyse the efficiency of decision-making units. DEA measures the relative efficiency of multiple units, while Input-Output models analyse interdependencies between economic sectors. The objective is to assess efficiency and resource allocation in various processes or economic sectors (Cooper et al., 2011). MFA relies on quantitative data regarding material inputs, outputs, and stocks within a defined system, i.e. MFA tracks material flow through a system to understand resource consumption and waste generation. The goal is to assess the sustainability and efficiency of material use within a specific context (Graedel and Allenby, 2009). Emergy- and exergy-based approaches involve the use of emergy, which considers various types of energy, and exergy, which assesses energy quality in a system. Emergy evaluates the energy hierarchy, while exergy evaluates energy efficiency and quality, both aiming to provide insights into the use of energy resources and their efficiency within a given system (Sciubba, 2009). Finally, DES relies on input parameters and conditions for simulation models aiming to simulate and analyse system performance under different conditions, facilitating process optimization and informed decision-making (Collins et al., 2023).

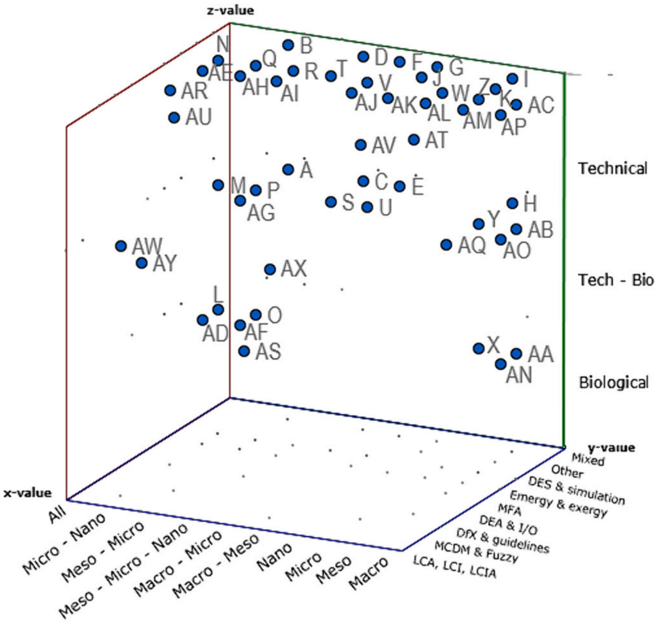

Fig. 3. Proposed positioning framework and analysed circular economy assessment approaches.

As a practical example, a medium size company devoted to waste management would like to compare several CBE approaches that they could implement at process level. Accordingly, they launch the tool and select “Appraisal of options from many viewpoints using numerous competing criteria" when asked about the type of information they are looking for. Internally, the tool filters all MCDM & fuzzy logic methodologies. Then, they select the nano level, the waste management sector (E according to NACE) and the bio cycle. As a result, three approaches are shown, together with the main aim and rerence (Briassoulis et al., 2021; D’Adamo et al., 2020; Padi and Chimphango, 2021). This way they can have a look at those publications and get some inspiration, contact the researchers or, if they have the proper staff, develop its own assessment based in the information provided. Fig. 4 presents a snapshot of the developed decision tool, showing the lay-out of the user interface, for the presented example.

Although the main end-user targeted for this tool is the private sector, there are other stakeholders than can also benefit from it. Policy makers interesting in appraising CE or CBE in their region could identify the most relevant approaches for macro level. Regional innovation agents or organisations managing technical/industrial parks could explore the options under *meso* level. Finally, academia could use it in a benchmarking exercise to explore state-of-the-art approaches.

3.4. *Circularity assessment approaches identified*

In order to get some insights from the analysed approaches, a dynamic chart representing the sectors, levels and cycles is provided in the Supplementary materials (dynamic charts DC4, DC5 and DC6). From the sector perspective, a first insight is that the NACE codes covered are *A - Agriculture, forestry and fishing, B - Mining and quarrying, C –*

Table 3
Approaches identified for circular economy assessment; (*): approaches provided by non-peer-reviewed sources.

ID	Dot ID	Name	Level	Method	Cycle	Sector & subsector	Reference
1	A	r.forcircular	Macro	MCDM & Fuzzy	Bio	A02	Sacchelli et al., 2022
2	AS	Forest-based CBE assessment	Macro - Micro	DfX & guidelines	Bio	A02	Paletto et al., 2021
3	L	Biochemicals production indicators	Micro	LCA, LCI, LCIA	Bio	C20	Ögmundarson et al., 2020
4	O	CBE value chain selection	Micro	MCDM & Fuzzy	Bio	E38	Lokesh et al., 2018
5	AA	Dairy supply chain CE assessment	Micro	Mixed	Bio	E38	Stanchev et al., 2020
6	X	Pig farming chain CE assessment	Micro	Other	Bio	C10	Secco et al., 2020
7	AD	CalcPEFDairy	Nano	LCA, LCI, LCIA	Bio	C10	Egas et al., 2020
8	AD	Hybridised sustainability metrics for bio-based products	Nano	LCA, LCI, LCIA	Bio	E38	Lokesh et al., 2020
9	AF	Recirculation potential assessment of bioplastics	Nano	MCDM & Fuzzy	Bio	E38	Briassoulis et al., 2021
10	AF	Socio-economic Indicator for EoL Strategies	Nano	MCDM & Fuzzy	Bio	E28	D'Adamo et al., 2020
11	AF	Percentage sustainability index (PSI)	Nano	MCDM & Fuzzy	Bio	E38	Padi and Chimphango, 2021
12	AN	Bioplastics CE performance indicator	Nano	Mixed	Bio	E38	Spierling et al., 2019
13	D	Municipal solid waste recycling efficiency	Macro	DEA & I/O	Tech	A31	Expósito and Velasco, 2018
14	D	Marine CE performance evaluation	Macro	DEA & I/O	Tech	A31	Ding et al., 2020a
15	D	Extended Malmquist index	Macro	DEA & I/O	Tech	D35	Ding et al., 2020b
16	D	CE efficiency at regional level evaluation	Macro	DEA & I/O	Tech	E38	Wu et al., 2014
17	G	CE efficiency of resource and products	Macro	Emergy, exergy	Tech	E38	Geng et al., 2013
18	B	Spatial assessment of CE indicators	Macro	MCDM & Fuzzy	Tech	E38	Stanković et al., 2021
19	B	Urban CE performance evaluation	Macro	MCDM & Fuzzy	Tech	E38	Wang et al., 2021
20	F	Ecological network for cities	Macro	MFA	Tech	E28	Gao et al., 2021
21	F	Monitoring framework on CE	Macro	MFA	Tech	E38	Mayer et al., 2019
22	I	Key indicators for monitoring the CE - French methodology	Macro	Other	Tech	B07	Magnier et al., 2017
23	I	OECD Inventory of CE indicators*	Macro	Other	Tech	E38	OECD, 2020
24	I	CE progress monitoring	Macro	Other	Tech	E38	Potting et al., 2018
25	I	Hierarchical structure model and evaluation index system	Macro	Other	Tech	E38	Yang et al., 2011
26	I	Displaced production from recycling or reuse quantification	Macro	Other	Tech	E38	Zink et al., 2016
27	AR	EVR (Eco-cost value ratio)	Macro - Micro	LCA, LCI, LCIA	Tech	F41	Scheepens et al., 2016
28	J	Emergy analysis	Meso	Emergy, exergy	Tech	C24	Pan et al., 2016
29	K	CE evolution assessment in aluminium industrial parks	Meso	Other	Tech	B07	Han et al., 2017
30	K	CE performance of eco-industrial parks	Meso	Other	Tech	C20	Li, 2011
31	AV	CE evaluation in local productive arrangements	Meso - Micro	DES, simulation	Tech	C31	Oliveira et al., 2018
32	AU	Performance evaluation of recoverable End-of-Life products	Meso - Micro	MCDM & Fuzzy	Tech	E38	Wibowo and Grandhi, 2017
33	AT	CE performance measurement model (CEPMM)	Meso - Micro - Nano	Other	Tech	E38	Nandi et al., 2021
34	T	SeCUWio model	Micro	DEA & I/O	Tech	B07	Liao et al., 2019
35	W	Product-related environmental performance indicators	Micro	DES, simulation	Tech	E38	Issa et al., 2015
36	W	Design based remanufacturability index	Micro	DES, simulation	Tech	C30	James et al., 2021
37	R	Design for Deconstruction (DfD)	Micro	DfX & guidelines	Tech	E28	Akinade et al., 2017
38	N	Methodological framework for the eco-efficiency assessment	Micro	LCA, LCI, LCIA	Tech	F41	Angelis-Dimakis et al., 2016
39	N	CE Indicators dashboard	Micro	LCA, LCI, LCIA	Tech	C10-C33	Pauliuk, 2018
40	N	Life cycle assessment-cradle-to-cradle-predictive building systemic circularity indicator (LCA-C2C–PBSCI)	Micro	LCA, LCI, LCIA	Tech	F41	Antwi-Afari et al., 2022
41	N	Sustainable CE framework	Micro	LCA, LCI, LCIA	Tech	C13	Thakker and Bakshi, 2021
42	Q	SCI (Sustainable Circular Index)	Micro	MCDM & Fuzzy	Tech	E38	Azevedo et al., 2017
43	Q	Green supply chain management performance assessment	Micro	MCDM & Fuzzy	Tech	F41	Kazancoglu et al., 2018
44	Q	Circularity and Maturity Firm-Level Assessment tool (CM-FLAT)	Micro	MCDM & Fuzzy	Tech	C28	Sacco et al., 2021

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Table 3 (*continued*)

ID	Dot ID	Name	Level	Method	Cycle	Sector & subsector	Reference
45	Q	CE measurement scale for building industry	Micro	MCDM & Fuzzy	Tech	F41	Nuñez-Cacho et al., 2018
46	Q	WEEE recycling evaluation	Micro	MCDM & Fuzzy	Tech	E38	Xu et al., 2018
47	V	Circular business model indicator	Micro	MFA	Tech	C10-C33	Rossi et al., 2020
48	AC	Performance evaluation in sustainable supply chain networks	Micro	Mixed	Tech	E38	Motevali Haghighi et al., 2016
49	Z	Circle Economy*	Micro	Other	Tech	C10-C33	Knowledge Hub | Circle Lab, 2024
50	Z	CE performance indicators	Micro	Other	Tech	F41	Rincón-Moreno et al., 2021
51	Z	Disassembly and deconstruction analytics system (D-DAS)	Micro	Other	Tech	E28	Akanbi et al., 2019
52	Z	GRI based CE assessment framework	Micro	Other	Tech	D35	Baratsas et al., 2022
53	AL	Design for EoL	Nano	DES, simulation	Tech	C35	Favi et al., 2016
54	AL	End-of-Life Index	Nano	DES, simulation	Tech	E38	Lee et al., 2014
55	AL	Eco-design potential assessment	Nano	DES, simulation	Tech	C30	Santini et al., 2010
56	AI	Design for disassembly tool	Nano	DfX & guidelines	Tech	E28	Favi et al., 2019
57	AK	Sustainability ratios and env. Performance assessment	Nano	Emergy, exergy	Tech	E38	Jamali-Zghal et al., 2015
58	AE	CE Life Cycle Assessment (CE-LCA) model	Nano	LCA, LCI, LCIA	Tech	C35	van Stijn et al., 2021
59	AE	GRI (Global Resource Indicator)	Nano	LCA, LCI, LCIA	Tech	D35	Adibi et al., 2017
60	AE	Unit process model-based method. - Design for manufacturing	Nano	LCA, LCI, LCIA	Tech	F41	Eastwood and Haapala, 2015
61	AE	Indicator for retained env. Value of circular solutions	Nano	LCA, LCI, LCIA	Tech	E28	Haupt and Hellweg, 2019
62	AH	Product Recovery Multi-Criteria Decision Tool (PR-MCDT)	Nano	MCDM & Fuzzy	Tech	E38	Alamerew and Brissaud, 2019
63	AH	Framework for End-of-Life mgmt. of electronic products	Nano	MCDM & Fuzzy	Tech	E28	Iakovou et al., 2009
64	AJ	CE assessment for building envelope systems	Nano	MFA	Tech	E38	Finch et al., 2021
65	AJ	Circularity calculator*	Nano	MFA	Tech	C10-C33	Circularity Calculator, 2024
66	AJ	Circularity indicators for electronic sector	Nano	MFA	Tech	F41	Pollard et al., 2022
67	AP	Resource longevity indicator	Nano	Mixed	Tech	F43	Franklin-Johnson et al., 2016
68	AP	Decision making support for building design	Nano	Mixed	Tech	C26	Fregonara et al., 2017
69	AP	Simulation-based analytical framework	Nano	Mixed	Tech	E38	Gbededo et al., 2018
70	AP	Decision support methodology based on ETV Standards	Nano	Mixed	Tech	E38	Grimaud et al., 2017
71	AP	CPI (CE Performance Indicator)	Nano	Mixed	Tech	E28	Huysman et al., 2017
72	AM	BIM-based Whole-life Performance Estimator (BWPE)	Nano	Other	Tech	C26	Akanbi et al., 2018
73	AM	Resource effectiveness evaluation of CE strategies	Nano	Other	Tech	C38	Parchomenko et al., 2020
74	AM	3R rate calculation - Vehicles	Nano	Other	Tech	C30	Delogu et al., 2017
75	AM	CEI - Circular Economy Index	Nano	Other	Tech	C10-C33	Di Maio and Rem, 2015
76	AM	Circular Economy Toolkit (CET)*	Nano	Other	Tech	C10-C33	Circular Economy Toolkit, 2024
77	AM	Circular Economy Indicator Prototype (CEIP)	Nano	Other	Tech	E28	Cayzer et al., 2017
78	AM	Life cycle sustainability performance	Nano	Other	Tech	E28	Kamali et al., 2018
79	AM	CN_Con - Metric for evaluating novelty and circularity	Nano	Other	Tech	F41	Ruiz-Pastor et al., 2022
80	AM	PLCM (Product-Level Circularity Metric)	Nano	Other	Tech	E38	Linder et al., 2017
81	AM	CE-conviviality design tool	Nano	Other	Tech	E38	Ralph, 2021
82	AM	eDiM (ease of Disassembly metric)	Nano	Other	Tech	F41	Vanegas et al., 2018
83	AM	Total EcoSite Integration for urban and industrial symbiosis	Nano	Other	Tech	E38	Van Fan et al., 2021
84	C	Resource efficiency and competitiveness potential analysis	Macro	DEA & I/O	Tech - bio	C10	Pagotto and Halog, 2016
85	C	Supply chain-linked ecologically based Life Cycle Assessment	Macro	DEA & I/O	Tech - bio	C10	Park et al., 2016
86	A	CE composite index	Macro	MCDM & Fuzzy	Tech - bio	E38	Garcia-Bernabeu et al., 2020
87	E	Water circularity in cities assessment	Macro	MFA	Tech - bio	E36	Arora et al., 2022
88	H	Performance of waste management systems	Macro	Other	Tech - bio	E28	Campitelli et al., 2022
89	H	Indicators for progress in CE at regional level	Macro	Other	Tech - bio	E38	Avdiushchenko and Zajaç, 2019
90	AQ	Circular City Analysis Framework (CCAF)	Macro - Meso	Other	Tech - bio	E38	de Ferreira and Fuso-Nerini, 2019
91	AY	Multi-level CE assessment framework	All	MCDM & Fuzzy	Tech - bio	C24	Ahmed et al., 2022

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Table 3 (*continued*)

ID	Dot ID	Name	Level	Method	Cycle	Sector & subsector	Reference
92	S	Green Performance Map (GPM)	Micro	DEA & I/O	Tech - bio	C30	Lindahl et al., 2022
93	M	Eco-efficiency methodology based on CE thinking	Micro	LCA, LCI, LCIA	Tech - bio	C10	Laso et al., 2018
94	M	Sustainability performance of food value chains	Micro	LCA, LCI, LCIA	Tech - bio	C10	Petit et al., 2018a
95	P	Circonomics index	Micro	MCDM & Fuzzy	Tech - bio	E36	Kayal et al., 2019
96	P	CE assessment framework for public sector organisations	Micro	MCDM & Fuzzy	Tech - bio	E38	Droege et al., 2021
97	P	Circulytics*	Micro	MCDM & Fuzzy	Tech - bio	E36	Ellen Macarthur, 2015
98	U	Water Circularity Indicator	Micro	MFA	Tech - bio	E36	Kakwani and Kalbar, 2022
99	Y	Assessment tool for the evaluation of CE implementation	Micro	Other	Tech - bio	E28	Diéguez-Santana et al., 2021
100	AW	CE Performance Assessment (CEPA)	Micro - Nano	LCA, LCI, LCIA	Tech - bio	C10-C33	Rocca et al., 2021
101	AX	Material Circular Indicator (MCI)*	Micro - Nano	MFA	Tech - bio	C10-C33	Ellen Macarthur, 2015
102	AG	Circularity across product-life cycle stages	Nano	MCDM & Fuzzy	Tech - bio	C13	Vimal et al., 2021
103	AO	3E assessment systematic framework	Nano	Mixed	Tech - bio	E35	Ng and Martinez Hernandez, 2016
104	AB	Triple-C indicator	Micro	Mixed	Tech - bio	O84	Wurster and Ladu, 2022
105	AX	VRE (Value-based Resource Efficiency)	Micro - Nano	MFA	Tech - bio	C10-C33	Di Maio et al., 2017

Table 4
Methodologies considered in the present study and information provided by them.

Methodology	Information provided by the selected methodology	Reference
LCA, LCI, LCIA	Environmental impact	European Environment Agency, 2024
MCDM & fuzzy	Appraisal of options from many viewpoints using numerous competing criteria	Kaya et al., 2019
DfX & guidelines	Rules, guidelines, and procedures used throughout the product life cycle	Mesa, 2023
DEA & I/O	Process efficiency and economic performance	Cooper et al., 2011
MFA	Resource streams data	Laner et al., 2014
Emergy & exergy	Resource and energy flows (origin, quality, utilization, losses)	Dewulf et al., 2008
DES & simulation	Process performance under different conditions	Charnley et al., 2019
Other	Other kind of information	–
Mixed	Combination of different insights	–

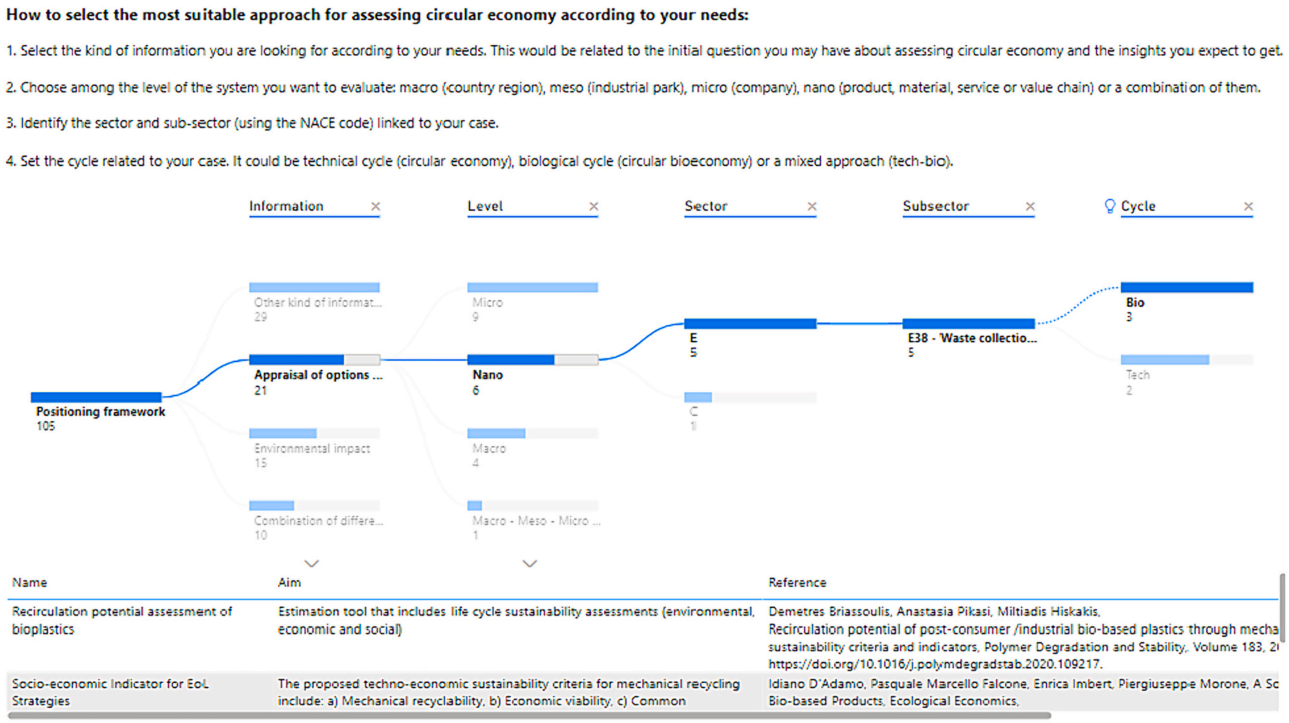
Manufacturing, D - Electricity, gas, steam and air conditioning supply, E - Water supply; sewerage; waste management and remediation activities, F – Construction and O - Public administration and defence; compulsory social security. Also, the two sectors that can be pointed out as trends are sector C and E. It is interesting to note that sector A has publications only since 2018, linked to the appearance of CBE devoted approaches, all at macro level. From the level perspective, until 2015, the number of papers per year was similar for macro, micro and nano levels, but from that year onwards, micro and nano levels have experienced a larger growth than macro, e.g. in 2022, there were 3 approaches for macro, 15 for micro and 8 for nano. It is also interesting to point out that mixed approaches concerning the level have emerged during the last years, probably as an effort to create flexible CE assessment methodologies. From the methodology perspective, MFA is the methodology that has increased the most the number of approaches identified.

Furthermore, when delving into the sector and the different methodologies that are used, sector A approaches linked to blue economy have used both DEA & I/O. Sector C usually uses LCA/LCI/LCIA (ca. 27%), followed at a distance by MFA and DES &simulation, while in the case of sector E, the most used one is MCDM & fuzzy (ca. 31%). For the rest of sectors (B, D, F and O) is not possible to identify a tendence.

As for the level and the methodologies used, at macro level, the two most used (ca.24% each) are MCDM & fuzzy and DEA &I/O. This could be explained by the need of policy makers of information related to insights about several options to be implemented at regional level and by the question that the implementation of CE poses in terms of economic impact. At *meso* level no conclusions can be drafted as no single methodology excels as the most used one. On the contrary, in the case of the micro level, ca. 30% of the identified approaches use MCDM & fuzzy, followed by LCA/LCI/LCIA. Aside from the need of the companies in investigating the impact of different CE related options, companies are usually interested as well in environmental impact related info due to regulation aspects and because nowadays claiming a lower environmental impact has become a marketing strategy. Finally, at nano level, ca. 20% of the approaches used mixed methodologies, probably to properly capture the CE dimension of products, materials and services. This is followed by LCA/LCI/LCIA and MCDM & fuzzy with 15% each.

Moreover, from the identified information sources, it is important to note that there are not many assessment methods specified for CBE. From a total of 2113 identified sources, only 234 included the “bio” prefix, accounting for a ca.11.5% of the total. An analysis of the number of approaches included in the review at a later stage per level and CE loop can be found in Table 5. From those selected (105 approaches) only 12 are specifically designed for CBE (roughly a 11.4%). If the scope is broadened to approaches that could be used for both technical and biological loops, several additional papers can be identified. Specifically, a total of 22 additional approaches can be pointed out, almost the double as for biological loop only.

Only 1 approach has been identified for CBE assessment at macro level. In this paper, Sacchelli et al. (2022) developed a decision support tool that uses geography features in order to measure CBE in the forest-based economy (called r.forcircular), together with financial



How to select the most suitable approach for assessing circular economy according to your needs:

1. Select the kind of information you are looking for according to your needs. This would be related to the initial question you may have about assessing circular economy and the insights you expect to get.

2. Choose among the level of the system you want to evaluate: macro (country region), meso (industrial park), micro (company), nano (product, material, service or value chain) or a combination of them.

3. Identify the sector and sub-sector (using the NACE code) linked to your case.

4. Set the cycle related to your case. It could be technical cycle (circular economy), biological cycle (circular bioeconomy) or a mixed approach (tech-bio).

Name	Aim	Reference
Recirculation potential assessment of bioplastics	Estimation tool that includes life cycle sustainability assessments (environmental, economic and social)	Demetres Briassoulis, Anastasia Pikasi, Miltiadis Hiskakis, Recirculation potential of post-consumer /industrial bio-based plastics through mecha sustainability criteria and indicators, Polymer Degradation and Stability, Volume 183, 2 https://doi.org/10.1016/j.polymdegradstab.2020.109217.
Socio-economic Indicator for EoL Strategies	The proposed techno-economic sustainability criteria for mechanical recycling include: a) Mechanical recyclability, b) Economic viability, c) Common	Idiano D'Adamo, Pasquale Marcello Falcone, Enrica Imbert, Piergiuseppe Morone, A Sc Bio-based Products, Ecological Economics,

Fig. 4. User Interface from the developed decision support tool for a given example (circular bioeconomy, nano level, sector E and MCDM & Fuzzy methodologies).

Table 5
Circular bioeconomy assessment methodologies identified (ID as depicted in Table 3).

Level	Circular economy loop					
	Biological		Technical		Technical - Biological	
	Number of publications	ID	Number of publications	ID	Number of publications	ID
Macro	1	*1*	14	*13–26*	6	*84–89*
Meso	0	–	3	*28–30*	0	
Micro	4	*3–6*	19	*34–52*	9	*92–99, 104*
Nano	6	*7–12*	31	*53–83*	2	*102, 103*
Macro - Meso	0	–	0	–	1	*90*
Macro - Micro	1	*2*	1	*27*	0	–
Meso - Micro - Nano	0	–	1	*33*	0	–
Meso - Micro	0	–	2	*31, 32*	0	–
Micro - Nano	0	–	0	–	3	*100, 101, 105*
Macro - Meso - Micro - Nano	0	–	0	–	1	*91*
Total	**12**		**71**		**22**	

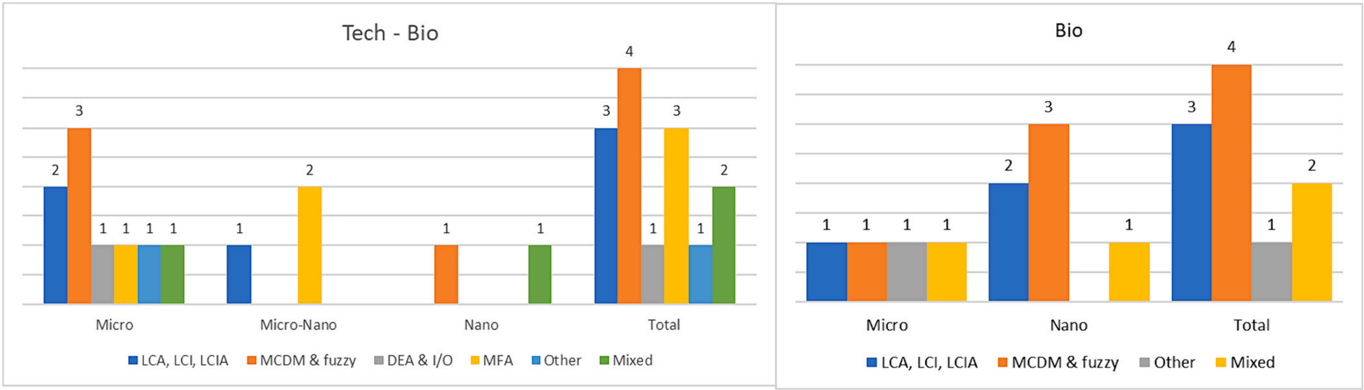


Fig. 5. Methodologies used for micro and nano levels for biological cycle (left) and technical-biological cycle (right). When no approach was available, the category is not shown, e.g. no approach for Micro – Nano and biological cycle.

performance. Additionally, only 6 approaches that could be considered for both technical and biological loops in CE have been identified at macro level. At meso level, no method has been identified either for CBE assessment (not for biological, neither for technical-biological loops).

Concerning the methodologies, a dynamic report can be found in the Supplementary materials (DC8), while Fig. 5 provides information about the methodologies used for biological and technical-biological cycles.

4. Discussion

As a novelty, the conducted review considers the sector and sub-sectors according to the NACE codes, which provides evidence of the private sector-driven dimension of this research as it permeates the two main outputs. These are a positioning framework and a decision support tool, produced as first-of-a-kind outputs available free for stakeholders. As for the framework, the 3D cube layout provides flexibility by classifying the different approaches according to three categories (level, cycle, methodology) instead of only two aspects as it usually happens in 2D representations, being possible to gain insights from a quick look to both the cube or the projections. The projections become useful as they allow the reader analysing the information according to its needs, e.g. if the reader is not interested in or is not familiar with the methodology as main aspect, it could just check the level vs. cycle projection to get the relevant insights, providing a flexible approximation to the use and interpretation of the review results. Also, to the best of the author's knowledge this is the first framework including the biological cycle category.

Regarding the decision support tool, main advantage is that it guides the end-user in finding the approach that better fits its needs according to the initial question that arises at the beginning of the CE assessment exercise. Other reviews, repositories or platforms that summarise approaches for CE assessment mostly present the different methodologies, without connecting this to the end-user question and information needs. This way, if the end-user is not fully familiar with a methodology and what that can do, the selection exercise could result in a wrong decision. This advantage is also important for end-users that are newcomers to CE and that are not very familiar with technical terms. Moreover, the use of the proposed tool could pave the way for further CE implementation, supporting different policies such as the European Green Deal. In fact, according to the findings from Boonman et al. (2023) the European Union's overall Gross Domestic Product (GDP) is projected to be 14.9 billion euros in 2030 under the status quo. When the recent circular economy policies targeting the industry are effectively carried out, it is anticipated that the GDP of the EU would be 3.9% higher, with Eastern Europe seeing the biggest gains.

Since the main gap has been identified for the biological cycle and for the company, product or materials in the value chain level, the following paragraphs will delve into the approaches falling under these categories, i.e. the following sub-sections delve into the approaches for the biological cycle at micro and nano levels.

4.1. Analysis of the sectors

As just a few approaches have been identified for the biological cycle, those approaches amenable to be used by both technical and biological cycles will be considered in the discussion as well. A dynamic report for this analysis can be found in the Supplementary materials (DC7). Concerning the main sectors covered by the biological and technical-biological approaches, the most addressed sector is *E - Water supply; sewerage; waste management and remediation activities*. However, it is interesting to note that for the technical-biological cycle, there is almost the same number of approaches devoted to sectors E and *C - Manufacturing*. Last relevant insight is that, at micro and nano levels, there are no approaches that have been identified for the sector *A – Agriculture, forestry and fishing*, as this sector is only addressed by two publications at macro level (dealing with forest). It is difficult to find a consensus among literature about CBE sectors, even for bioeconomy itself as Beluhova-Uzunova et al. (2019) point out. From the findings, it could be stated that circularity assessment for agriculture, forestry and fishing is done mostly by policy makers through their regional assessments while the management and treatment of waste from these sectors, together with the use of such biomass by the industry are more likely to be addressed by companies and industry practitioners.

Going into details about the sub-sectors as for the biological cycle (see Fig. S5 from Supplementary materials), within the *E*-sector, most approaches are devoted to *E38 - Waste collection, treatment and disposal activities; materials recovery*. From the identified approaches in this subsector, these cover wastes such as food and food industry waste, bioplastics, and organic fraction from urban solid waste. From the sector C, there are two publications for food manufacturing (C10) and one for biochemicals (C20).

As for the technical-biological cycle (see Fig. S6 from Supplementary materials) where both C and E sectors are equally addressed, most of the approaches for the manufacturing sector have a general scope, with only 2 papers devoted to food manufacturing and one to textile industry. From the sector E, there is the same number for both E38 and E36, the latter linked to waste management and treatment.

4.2. Analysis of the methodologies used

It can be pointed out that, for the biological cycle, MCDM in the most used methodology. This is due to its user-friendly characteristics, to the lack of need for a specific software as decision matrixes can be usually implemented in Excel file and to the versatility of the method. This finding is aligned with the work from dos Santos Gonçalves and Campos (2022) who conducted a review for measuring CE with multicriteria methods. They highlight how MCDM techniques can address CE challenges by integrating circularity indicators into methodologies. The results from their review emphasise the robustness of this approach for decision-makers across different scales of CE implementation. Furthermore, it notes a growing interest in combining MCDM methods with CE considerations over time, emphasising the need for continuous innovation in creating comprehensive models across economic, environmental, and societal dimensions.

Second place goes for LCA, LCI and LCIA method, as this is a well-known methodology in technical areas and the environmental perspective that permeates CBE concept. If considered both technical-biological and biological cycles together, MFA is the third methodology more used, because it is usually used for the technical cycle and therefore in some cases could be extrapolated to the biological cycle. In the case of mixed methodologies, MCDM and LCA, LCI and LCIA are in all cases one of the two or more methodologies used. It is interesting to note that for the biological cycle approaches the methodologies DEA & I/O and MFA have not been used by the identified papers. Briefly, the choice of methods varies due to the systemic nature of the CE. Transitioning to circularity involves profound changes in the economic system, encompassing all levels and sectors rather than simple adjustments in product design. Moreover, the notion that the biological cycle is inherently circular would lack empirical support, justifying the need for specialized evaluation methods for biological systems.

4.3. Analysis of the scope

The following paragraphs delve into micro and nano levels of the biological loop. At micro level, the most relevant one is the one from Lokesh et al. (2018). These authors propose a method based on MCDM to be utilized as a decision-making tool regarding the best biobased value chain since the method highlights the circularity characteristics of different biobased value chains/business. The criteria consider variables such feedstock variation, a multi-regional supply chain, a range of end-of-life possibilities, weaknesses in sustainability programs, EU feedstock preference, and multi-sector use. Stanchev et al. (2020) developed a multilevel environmental assessment for processes dealing with dairy effluents by developing material and environmental circularity performance indicators at the anaerobic digestion plant, the dairy processing facility, and the entire supply chain levels. Ögmundarson et al. (2020) defined a methodology for bioprocess optimisation, creating a single score that can be used at the beginning of the development of biochemical production, combining indicators from LCA and techno-economic evaluation. Finally, as for other methods, Secco et al. (2020) focused on pig farming chain circularity and developed a model built upon GRI's sustainability indicators statistical analysis.

At nano level, from those approaches based in LCA/LCI/LCIA, Lokesh et al. (2020) developed hybridised sustainability metrics for evaluating the circularity and resource efficiency of bioproducts. These authors defined a set of hybridised indicators (hazardous chemical use, waste generated, resource circularity and energy efficiency) that are used together with a selection of LCA based indicators. Briassoulis et al. (2021) worked on a mechanical recycling criteria that considers economic feasibility, common environmental and techno-economic aspects, and the possibility for material recirculation. (Egas et al., 2020) developed the CAlcPEFDairy methodology: a tool for evaluating product environmental footprint in the case of raw milk and dairy products. For MCDM methods, D'Adamo et al. (2020) focussed on bioproducts and defined a socio-economic Indicator for end-of-life strategies based in an integrated analytic hierarchy process–multicriteria decision analysis model. Also, Padi and Chimphango (2021) elaborated the Percentage sustainability index, a estimation tool that includes life cycle sustainability assessment. Mixed methodologies were used by Spierling et al. (2019), who developed performance indicators to pinpoint the best routes for bioplastics. They adapted the Circular Performance Indicator method from Huysman et al. (2017) to consider waste management pathways for bioplastics and biodegradability.

Finally, a rather unique research work is devoted to both macro and micro levels, i.e., it can be applied to levels that are so different in dimension (region vs. company level). Paletto et al. (2021) focussed on forest-based CBE assessment. They established a set of 14 indicators and categorised them using the 4Rs (Reduce, Reuse, Recycle, and Recover) of CE and the three sustainability pillars (environmental, economic, and social).

In the case of technical-biological cycles, from the MCDM group, Kayal et al. (2019) created the so-called Circonomics Index for wastewater. This index is composed of three indicators: wastewater production efficiency, composite wastewater re-use and wastewater recycling. Droege et al. (2021) developed an assessment framework that targets policy makers and public organisations and that considers resources, operations, and processes as well as social and employee related activities. Finally, when it comes to MCDM, it is worth mentioning the work from Ellen McArthur Foundation and the Circularytics approach (Ellen Macarthur, 2015). This is a free tool available online that demonstrates how much circularity a company has attained throughout all its processes. For the mixed methodologies approach, Petit et al. (2018b) focussed on defining eco-social and environmental indicators to assess the performance of value chains from a sustainability perspective. Hence, a group of indicators was defined by combining LCA, Corporate social responsibility and Multiple-Attribute Decision-Making. As for DEA and Input-Output methods, Lindahl et al. (2022) produced the Green Performance Map, which focuses on three key areas: manufacturing and sourcing, product consumption, and product end-of-life. Laso et al. (2018) worked on an eco-efficiency methodology based on CE thinking. Specifically, a weighting of environmental and economic indicators-based eco-label grading system was produced. Then, to evaluate scenarios with various feedstock source and waste management options, LCA-LCC outcomes are integrated with linear programming to develop an eco-efficient index. Another mix of methodologies is used by Wurster and Ladu (2022) when developing their Triple – C indicator, a multidimensional indicator tailored to public procurers that encompasses the STAR-ProBio-IAT concept, ecological scarcity concept, and global and European sustainability criteria and indicators. As for MFA methods, Kakwani & Kalbar in 2022 developed the Water Circularity Indicator based in the Material Circularity Indicator developed by the Ellen MacArthur Foundation. Finally, for other methods, Diéguez-Santana et al. (2021) generated a tool consisting of a checklist with 91 items and 9 research variables, based on a descriptive quantitative analysis.

At micro-nano level, Di Maio et al. (2017) defined the Value-based Resource Efficiency terminology, linked to evaluating both resource efficiency and CE using the market value of 'stressed' resources. The Ellen MacArthur Foundation is worth mentioning here as they developed the Material Circular Indicator (Ellen Macarthur, 2015). This indicator assesses how restorative a product's material flows are, which may be combined to form a product portfolio or even reach business level. Finally, Rocca et al. (2021) created the Circular Economy Performance Assessment methodology that addresses three different fields of analysis: Circularity Product/Cost/Environmental Assessment.

At nano level, only 2 approaches have been found. Vimal et al. (2021) used MCDM method to create a framework to evaluate circularity throughout phases of the product life cycle, covering the five angles of sustainability: economic, environmental, and social perspectives, material circularity and circular model. Alternatively, Ng & Martinez Hernandez in 2016 used MCDM and other methods to define a framework for process design and decision-making that takes energy, environment, and economy into account.

Besides, it is worth pointing out an approach that is supposed to address all levels, macro-*meso*-micro-nano. Ahmed et al. (2022) produced a multi-level assessment framework that considers quantitative as well as qualitative indicators, and where the assessment customisable process is divided in four steps involving different actors.

4.4. *Open areas for future work*

From the information presented in this section, open areas for future work can be spotted according to the approaches reviewed. Related to CBE, there are just a few approaches at macro level. Research in this direction would benefit all the regions that are developing and implementing their CBE strategies so they can better evaluate the impact of policy actions and measures. Also, no approach has been identified for CBE and meso level. Bioeconomy devoted parks like the Bioeconomy Park in Reims (France) or mixed industrial parks would benefit from research activities in this direction. Moreover, micro and nano levels lack of approaches devoted to sector A. This sector addresses agriculture, forestry and fishing, areas were the bioeconomy is being extensively adopted, being the agriculture sector the one that contributes the most in economic terms to the bioeconomy in Europe (Ronzon et al., 2020). This calls for more research efforts devoted to assessing the real effect of CBE implementation in these areas. Another open area is that, for the biological cycle, the methodologies DEA & I/O and MFA have not been used (although there are some examples for the technical-biological cycle). As these methodologies provide information about process and economic performance and streams and stocks, it would be interesting to delve into how these methodologies can appraise CBE cases.

4.5. *Limitations of this research*

The main limitation of the current research lies in the rapidly evolving landscape of CE, circular business models, bio-based products, and related fields. The dynamic nature of these domains necessitates a continual review and reassessment of methodologies to ensure their relevance and effectiveness. As new technologies emerge, market dynamics shift, and regulatory frameworks evolve, the approaches employed for circularity assessment must adapt accordingly. Therefore, ongoing vigilance and engagement with emerging literature, industry practices, and policy developments are essential to maintain the applicability of the proposed framework in the face of rapid change.

5. Conclusions

CE, for both technical and biological cycles, is gaining relevance at a considerable speed due to its relevant role in meeting the Sustainable Development Goals and the Green Deal Objectives. After large steps towards its implementation, recent research activities are being devoted to its evaluation as well. It becomes necessary to review the options available to industry practitioners in order to evaluate bio-based systems circularity at micro and nano level.

So far, 2113 information sources have been identified through a literature review. From them, 105 were selected and classified in a new positioning framework conceived as a 3D cube where each ax represents one category used to classify the selected CE assessment approaches: Level; Methodology; and Cycle.

Using this information, a free decision support tool available online has been developed. Building the workflow on top of the question posed by the user allows overcoming the barrier that private companies face when assessing CE due to the lack of specific and deep knowledge about the methodologies. Linking the information sought to the methodologies circumvents the problem of not being familiar with all the included methodologies.

Only 12 of the selected papers and publications are devoted explicitly to the biological cycle (CBE), being possible to add 22 approaches in case technical-biological cycle is considered. As for micro and nano levels, there would be 10 for the biological cycle and 14 for the technical-biological one. An analysis of the sectors and sub-sectors reveals that the most relevant ones are sectors *E - Water supply; sewerage; waste management and remediation activities and C - Manufacturing*. Finally, concerning the methodologies used, the most relevant one for CBE appraisal is MCDM as it can be easily implemented without deeper experience or a specific software by most of practitioners.

Open areas for future work regarding the assessment of CBE have been identified. Research efforts would be needed for the macro and meso levels as there are almost no approaches available. At micro and nano level, the sector *A - Agriculture, forestry and fishing* is the less explored so more investigations devoted to this area would be required as this sector is the one that contributes the most to bioeconomy economics and employment. Lastly, there is a need for more approaches that delve into process efficiency and economics during CBE implementation.

The following key recommendations for stakeholders can be drafted. Industry practitioners would need to stay updated on emerging CE and CBE assessment methodologies, invest in training, and collaborate with research institutions to address gaps in assessment frameworks, particularly focusing on process efficiency and economics within CBE implementation. Policy makers are encouraged to allocate resources for research, foster cross-sectoral collaboration, and integrate stakeholder insights into policymaking to support the integration of circularity measurement in action plans. Research institutions could prioritize innovative CE assessment methodologies, facilitate interdisciplinary collaboration, and conduct empirical studies to validate and refine existing tools based on industry feedback.

Finally, the next steps to be done as a future research is to test the tool with a pool of stakeholders from different sectors so as to improve its user interface, functionalities, etc. In addition, it would be interesting to conduct a similar review concerning sustainability assessment at micro and nano level for bioeconomy related systems. CE and sustainability are usually entwined so it would be noteworthy to expand the research by delving into how the different methodologies and approaches. Then, once both reviews of CE and sustainability assessment approaches are completed, it could be interesting to study if they have similarities, differences, usability, target end-users, etc.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Marta Macias Aragonés: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Fátima Arroyo Torralvo:** Conceptualization, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are provided in the Supplementary materials.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107493.

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