D2.1. Report on identification of circularity indicators methodologies for industrial bio-based systems

MONITORING SYSTEM OF THE ENVIRONMENTAL AND SOCIAL SUSTAINABILITY AND CIRCULARITY OF INDUSTRIAL BIO-BASED SYSTEMS

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ACRONYMS

Abbreviation	Definition
BS	British Standard
BTI	Bio-based Transition Indicators
CE	Circular Economy
CEI	Circular Economy Index
CEPI	Circular Economy Performance Indicator
CF	Circular Flow
CI	Circularity Index
C-indicator	Circularity Indicator
CIN	Circularity Indicator of Nutrient
EGD	European Green Deal
Em	Emergy
EoL	End of Life
ERB	Ecological Resource Budget
EU	European Union
G	Quality Indicator
GPFI	Green Protein Food Index
ISI	Industrial Symbiosis Indicator
KPIs	Key Performance Indicators

Abbreviation	Definition
LCA	Life Cycle Analysis
LFI	Linear Flow Index
MCI	Material Circularity Indicator
MDI	Material Durability Indicator
MEM	Material Efficiency Metric
MFA	Material Flow Analysis and Accounting
MIND	Method for analysis of INDustrial energy systems
MRS	Material Reutilization Score
MSIASM	Multiscale integrated analysis of societal metabolism
NERI	Nutrient Removal Efficiency Indicator
NRI	Nitrogen Recycling Index
NUE	Nitrogen Use Efficiency
OECD	Organisation for Economic Co-operation and Development
QMRP	Quality Model for Recycled Plastics
QRF	Quality of Recycling Framework
RE	Recycling Effectiveness
RP	Resource Pressure
WP	Work package

EXECUTIVE SUMMARY

This report presents a comprehensive overview of circular economy indicators available in scientific literature as part of the BIORADAR project. It has a primary focus on three key bio-based industry sectors, namely fertilisers, textiles, and packaging. The review is focused specifically on the nano (product) level.

Circular economy is gaining more and more attention by policymakers, producers, academia, and consumers, as a mean to tackle climate change and increasing environment degradation. One founding document of this shift is the European Green Deal. which emphasizes the need to promote a bio-based economy as a strategic move towards reducing reliance on non-renewable energy and materials, ensuring food security, and decarbonizing the economy. The most widespread concept of circular economy is that of a system that aims to eliminating waste and pollution from design, promoting the continuous use of products and materials, and regenerating natural systems. It is also widely recognised that to advance in the circular transition, it is necessary to introduce monitoring and evaluation tools, such as indicators.

The BIORADAR project's objective to which this report is linked is to select the most appropriate circularity indicators for the selected bio-based products. Specifically aiming for one cross-sector indicator, and one specific indicator per sector.

This was performed through a systematic literature review aimed at obtaining such indicators for bio-based fertilisers, textile and packaging products. The final portfolio was composed by 81 scientific publications, from which 29 indicators were identified. These indicators were tagged, classified and screened based on: (1) not containing Life Cycle Assessment and/or economic inputs, as these aspects will be covered by other project metrics (which narrowed the list down to five indicators of general use, five for fertilisers, three for packaging, and one for textile), and (2) complying with the highest number of criteria, namely material sourcing, renewable energy inputs, waste handling, recovery, recycling, and product lifetime.

The selected indicators were: Circular Index – CirculAbility model, for general use, Circular Indicator of Nutrient, for fertilisers, Resource Pressure, for textiles, and Recycling Effectiveness for packaging.

Relevant aspects were found, such as the high presence of Life Cycle Assessment-based variables or tools for measuring product circularity, as well as the elevated use of the Material Circularity Indicator. Combining sustainability and circularity aspects is a highly contested topic, and the approach adopted in the research is that both spheres have to complement each other, rather than absorbing one another. Also, an important number of biases were identified, such as the pre-eminence of material sourcing and recyclability, neglecting quality, material and energy efficiency, product lifetime, etc.

These results set the foundations for the next task: applicating the selected indicators to the project's target products and propose new metrics to bridge the identified gaps.

1. INTRODUCTION

1.1 DESCRIPTION OF THE DOCUMENT AND PURSUE

This document aims to provide a comprehensive overview of circular indicators available in the literature due to the lack of a consensus on the most suitable metrics for the bio-based industry. **The BIORADAR project has a primary focus on three key industry sectors, namely fertilisers, packaging, and textiles**. In the literature, several indicators to measure circular economy (CE) strategies at different levels, including government (macro), industrial symbiosis (meso), companies (micro), and products (nano) are available. Considering BIORADAR's scope of work, **this review aims to focus on circularity indicators at nano level.** The reason for this is further explained in section *2.3 CIRCULARITY INDICATORS*. This review aims to understand the specific aspects that C-indicators measure to effectively utilize them and incorporate them into the BIORADAR Bio-based Transition Indicators (BTI) framework[1].

1.2 WPS AND TASKS RELATED WITH THE DELIVERABLE

This deliverable refers to Task 2.1 in Work Package 2 (WP2): *Identifying and Assessing Circularity Aspects of Industrial Bio-based Systems and integrating them into the BTI Framework*. Performing T2.1 allows to achieve one of the milestones of the project (Milestone 3: *List of existing sustainability indicators for industrial bio-based systems*) through the presentation of this deliverable.

The identified circularity indicators will play a pivotal role in evaluating the level of circularity of bio-products selected in T1.1 at a later stage of the project (Table 1). The selection process can be consulted in D1.1 – *Report on identification of bio-industrial bio-based value systems for project analysis*. These data will later be transferred to WP3 and WP4 to develop a digital monitoring tool for bio-based industries, policymakers, certificate companies, traders, and investors.

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[1] The BIORADAR Bio-based Transition Indicators (BTI) framework involves metrics to monitor industrial bio-based systems for sustainability, environmental, economic, social and circularity aspects. This framework includes the use of digital tools such as data-driven benchmarking and an analytics platform based on automation, dynamic analysis, and diverse data sources facilitated by artificial intelligence-based algorithms. The BTI framework will empower bio-based companies to make informed decisions, enhancing their sustainability, circularity, and overall performance within the industry.

Table 1: Target BIORADAR's products.

Fertilisers	Packaging	Textile
Algae biomass	Cardboard	Bio-nylon
Compost	Paper	Hemp fibre
Feather meal	Bio-polyethylene	Lyocell
Wood vinegar	Polyethylene Furanoate (PEF)	Wool

2. BACKGROUND

2.1 EU BIO-ECONOMY STRATEGY

The European Green Deal (EGD) emphasizes the need to promote a bio-based economy as a strategic move towards reducing reliance on non-renewable energy and materials, ensuring food security, and decarbonizing the economy. The concept of the bio-economy encompasses all sectors and systems that rely on biological resources such as animals, plants, micro-organisms, and derived biomass, including organic waste. This framework harmonises the relationship between land and marine ecosystems, and the services they provide. It includes primary production as well as sectors that use and generate biological resources, such as agriculture, forestry, fisheries, and aquaculture. Furthermore, it extends to economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy, and services.

In order for the European bio-economy to flourish, it needs to give priority to sustainability and circularity. This is essential for revitalizing industries, modernizing primary production systems, protecting the environment, and promoting biodiversity. To achieve this goal, an action plan was initiated in 2019, which outlines 14 specific measures based on three main priorities (European Commission, 2022):

1. Strengthen and scale up the bio-based sectors, unlock investments and markets;
2. Deploy local bio economies rapidly across the whole of Europe;
3. Understand the ecological boundaries of the bio-economy.

Nevertheless, achieving sustainability and fostering the development of industrial bio-based systems requires focused consideration of resource consumption and the environmental, economic, and social impacts these systems have on the European Union (EU). Two conceptual frameworks to advance towards this direction are the bio-economy and circular economy which, in essence, complement each other by promoting a holistic approach to resource management, emphasizing the importance of regenerating natural systems, reducing waste, and fostering sustainable practices across various industries. Integrating these concepts can contribute to a more resilient and environmentally friendly economic model.

BIORADAR, a monitoring system designed to assess the environmental, economic, and social sustainability, as well as circularity of bio-based systems and their products, seeks to address the existing gap in indicators related to material circularity and sustainability within the bio-based sector.

2.2 CIRCULAR ECONOMY (CE)

The concept of CE has become increasingly important for both governments and businesses as a way to encourage economic growth while reducing environmental impact. The concept appeared in 1989 in the sustainability literature (Pearce & Turner, 1989) summarizing the ideas of previous authors such as closed-loop systems (Boulding, 1966), and industrial economy loops (Stahel & Reday-Mulvey, 1981).

There has been a substantial increase in peer-reviewed articles on this realm in recent years (3,685% increase in the last ten years[2]). However, the concept of CE is defined in various ways and resonates with different dimensions for different individuals. Kirchherr et al. (2017) reviewed all these different concepts and concluded that CE is most frequently depicted as a combination of reduce, reuse, and recycle activities, whereas it is oftentimes not highlighted that it necessitates a systemic shift.

The most widely-adopted concept is built upon three pillars: **eliminating waste and pollution from design, promoting the continuous use of products and materials, and regenerating natural systems** (Bassi et al., 2021). The central goal of CE is to enhance the harnessing of materials by prolonging their use, minimizing the reliance on resource extraction (e.g., materials, nutrients), by promoting practices such as reusing, repairing, and recycling in contrast to the traditional linear "extract-use-discard" consumption model, and endorsing innovative business models (Bao et al., 2019; Rashid et al., 2013).

While there is no universally agreed-upon definition of CE (Geisendorf & Pietrulla, 2018) and its legislation varies across different geographical regions (McDowall et al., 2017), the predominant focus in CE policies and literature revolves around waste recovery and recycling to close material loops (Ghisellini et al., 2016; Merli et al., 2018; Morseletto, 2020). Circular transition incentives have been integrated into various policies around the world including the *Circular Economy Action Plan* from the European Commission (2015, 2020), coupled with the *EU Waste Framework Directive,* and the *Packaging and Packaging Waste Directive*. More recently, the European Union has been advancing towards the “right to repair” and the extended producer responsibility as means to strengthen the circular practices in the union.

From a standardization point of view, the British Standards Institution (BSI) released in May 2017 a guideline titled “*Framework for Implementing the Principles of the Circular Economy in Organizations - Guide*”. This is the first

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[2] Increase in the number of results obtained through Web of Science when looking up “circular economy”: 167 results in 2013 vs. 6,321 results in 2023.

standard that aims to provide guidelines to organizations in the transition towards a more circular and sustainable mode of operation by drawing on the experiences and lessons learned from a range of organizations already involved circular transition. According to BS 8001:20,017, CE is "*an economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" (British Standards Institution, 2018). According to the BS 8001:2017 standard, the responsibility of choosing the appropriate performance indicators is borne by the implementing organization (Pauliuk, 2018).

Likewise, in November 2022 the Italian normalization body (UNI, part of BIORADAR consortium) released the standard UNI/TS 11820 entitled "*Circular economy measurement – Methods and indicators for the measurement of circular processes in organizations*". There, circular economy is defined as an "*economic system that, through a systemic and holistic approach, aims to maintain the flow of resources circulating, conserving, regenerating or increasing their value while contributing to sustainable development*" (Ente Italiano di Normazione, 2022).

The debate on the identification of the most suited metrics is very much open and no consensus has been reached yet, which creates a subjective methodological framework for assessing circular economy.

2.3 CIRCULARITY INDICATORS

There is a widespread recognition that, **to advance in the circular transition, it becomes imperative to introduce monitoring and evaluation tools, such as indicators**, to assess and quantify the progress in this regard. Circularity can be assessed using different "Circular Indicators", also called C-indicators (Ellen MacArthur Foundation & Granta Design, 2015). Several synonyms like indices (De Pascale et al., 2021), index (Elia et al., 2017), meter (Geraedts, 2016), scale (Nuñez-Cacho et al., 2018), and in a few cases, framework (Dams et al., 2021) is also used by various authors in the context of circularity measurement. This variety of terminology for C-indicators can lead to confusion. Thus, it becomes necessary to define the term indicator for better clarification in this project. In particular, the BIORADAR project adopts the definition of the Organisation for Economic Co-operation and Development, which describes an indicator as **"*a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor*"** (OECD, 2013).

More specifically in the circularity realm, the Italian standard UNI/TS 11820 defines a circular economy indicator as "*qualitative, semi-quantitative and/or quantitative data required for the measurement of achievements in the pursuit of circular economy objectives*" (Ente Italiano di Normazione, 2022).

Saidani et al. (2019) emphasized that indicators serve as valuable analytical instruments employed to simplify complex information. The primary objectives of utilizing indicators revolve around the tracking, monitoring, and measurement of the progress and performance of specific systems or processes, encompassing both quantitative and qualitative assessments, as outlined by Bilal et al., (2020). It is noteworthy that an indicator may consist of various sub-indicators or standalone variables.

Currently, numerous circularity indicators have been developed, each employing distinct sub-indicators or variables associated with materials, products, and/or services. Circularity indicators can be categorized into different levels—macro, meso, and micro circularity levels—, as indicated by Kirchherr et al. (2017).

The macro level pertains to circular economy at the city, province, region or country scale, involving the redesign of infrastructural systems such as clean energy, transportation, cultural frameworks, and social systems (Ghisellini et al., 2016). Macro-level indicators include Material Flow Analysis and Accounting (MFA) (Pinter et al., 2006) or Multiscale integrated analysis of societal metabolism (MSIASM) (Geng et al., 2011). The meso level involves CE strategies applied to industrial eco-parks or inter-enterprise associations, known as industrial symbiosis. A few examples of meso-level indicators include the Method for analysis of INDustrial energy systems (MIND) (Karlsson & Wolf, 2008) or Industrial Symbiosis Indicator (ISI) (Felicio et al., 2016).

Conversely, the micro-level is associated with the consumer, individual company, or product and its components level (Franklin-Johnson et al., 2016). Given the broad scope of the micro level, several metrics labelled as micro-level indicators may not adequately capture the complexity of circular practices, potentially leading to diverse interpretations of the target during assessments (Roos Lindgreen et al., 2021). To address this, Saidani et al. (2017) introduced a novel product-centred term in the CE context: **the nano level, which characterizes "*the circularity of products, components, and materials, included in three wider systemic levels, all along the value chain and throughout their entire lifecycle*"** (Saidani et al., 2017).

Circularity indicators have the potential to translate intricate information into comparable figures (Saidani et al., 2019). However, its research is still in its early stages and has gained momentum only in recent years. Existing indicators, while to some extent overlapping, exhibit variations in their goals, scopes, and potential applications (Corona et al., 2019; Saidani et al., 2019). The nascent state of development, diversity, and oversupply of indicators complicates the assessment of circular economy concepts, needing a meticulous process for identification and selecting suitable indicators for specific products and processes.

Taking this into account, **the objective of this task within the BIORADAR project is to select the most appropriate circularity indicators for each of the previously selected bio-based products belonging to the packaging, textile, and fertilisers sectors for monitoring circular bio-based systems**.

3. MATERIALS AND METHODS

This research provides a **systematic literature review aimed at extracting the most appropriate circularity indicators at nano level for the three bio-based sectors covered in the project's scope**. Furthermore, a detailed analysis has been carried out, considering the previously selected bio-products and their sectors, which will be evaluated in terms of circularity performance in a later stage. The literature review approach consists of a research process based on a selection of academic databases, types of literature and delimitations, choice of search terms, and a practical reading/screening process.

Originally, a review of corporate sustainability reports, European project deliverables and sustainability standards was considered. Notwithstanding, when reviewing these documents, only macro and meso level indicators were found, and there was no evidence of indicators applied specifically in bio-based industries. Thus, the research scope was adjusted to scientific literature, where plenty of relevant indicators were found, as detailed below.

3.1. LITERATURE SEARCH

The first step in the review process involved a search to access published studies related to C-indicators implementation. To obtain an appropriate selection of academic literature, a systematic review was performed beginning with the following string in Web of Science. A set of keywords encompassing both business and CE-related terms were selected. The search was conducted through the combination of such keywords using Boolean operators (AND/OR). The search string applied to the scientific database was:

("MEASUR*" OR "METRIC*" OR "INDICATOR*") AND ("CIRCULAR ECONOMY" OR "CIRCULAR BIOECONOMY" OR "CIRCULARITY") AND ("FERTILIZ*" OR "FERTILIS*" OR "BIOFERTILIZ*" OR "BIOFERTILIS*" OR "BIO-FERTILIZ*" OR "BIO-FERTILIS*" OR "TEXTILE*" OR "BIO-TEXTILE*" OR "BIOTEXTILE*" OR "PACKAG*" OR "BIOPACKAG*" OR "BIO-PACKAG*")

The time period covered during this step was from 2000 to 2023. The search generated 518 results that were screened based on their titles and abstracts using the informatic tool Rayyan ® (Ouzzani et al., 2016), rejecting 456 for: not including relevant indicators (361), considering a wrong scale (e.g., macro, meso and micro levels) (57) or a wrong sector (e.g., only applied to building sector) (38). After the initial compilation, 62 papers supplemented by 19 additional papers that were identified by snowballing references (i.e., sources cited by the 62 papers that passed the title and abstract review) composed the final compilation.

The compilation of the final portfolio, which consisted of the initially 81 scientific publications, was organized using Notion® web application and subsequently transferred to a spreadsheet for further analysis (refer to Supplementary Material, Table 8 for the final portfolio). The arrangement of the portfolio was based on bibliometric information, including authors, year of publication, title, journal, type of publication, location, and keywords. These scientific publications were then subjected to a comprehensive full text analysis and circularity indicator screening. Out of these, 35 were excluded due to the absence of relevant indicators: duplicity of indicators (18), incorrect scale consideration (9), mismatched sector (7), or lack of disclosure regarding the calculation rationale (1) (see Supplementary Material, Fig. 3 for details). Consequently, the final review was composed by 46 scientific publications. An overview of the methodology followed in this study is shown in Figure 1.

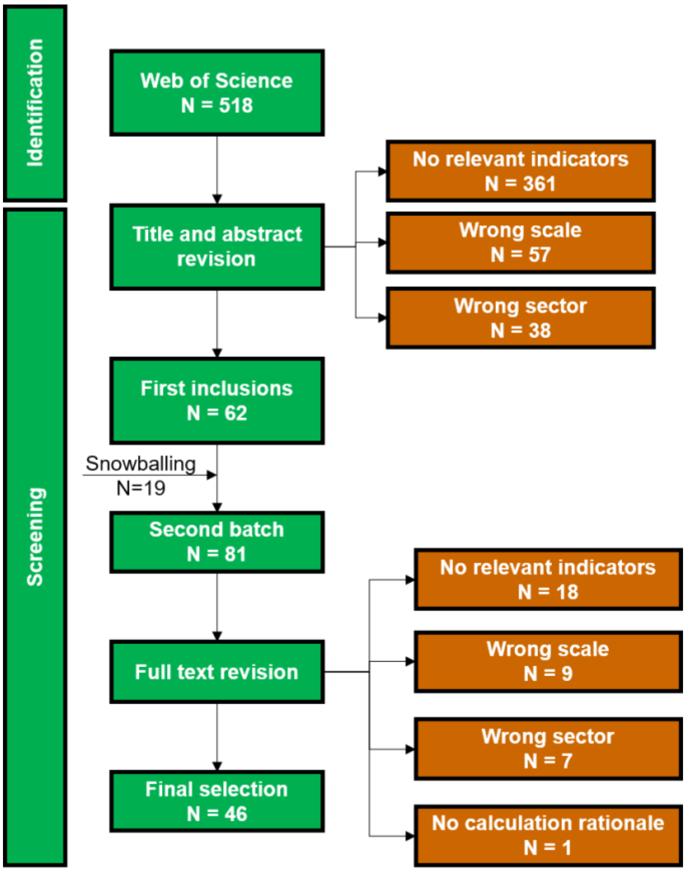


Figure 1. Methodology overview for literature search.

3.2. CHARACTERISATION, CLASSIFICATION, EVALUATION AND SELECTION PROCESS

3.2.1. Characterisation and classification

From the remaining publications, **a total of 29 circularity indicators were extracted. These indicators underwent a comprehensive analysis, with several tags assigned to each one depending on its characteristics**. These tags were selected to classify and characterise the circularity indicators, taking into consideration whether they were broadly applicable or specifically designed for a particular sector (e.g., fertiliser, packaging, textile). Additionally, the analysis considered whether the indicators were based on well-established frameworks like LCA or MCI, and if they accounted for economic inputs, environmental impacts, life cycle stages covered, and other factors, as detailed in the Table 2.

Table 2: Tags used for characterising the indicators.

Tag	Rationale
Sector	
General	Applicable to any industry
Fertilisers	Specific for fertilisers
Packaging	Specific for packages and packaging materials
Textile	Specific for textiles
Aspects included	
Recycled input	Indicator considers the usage of recycled materials in the production process
Efficiency	Indicator includes an efficiency factor (e.g., key material recovery, energy efficiency, etc.)
Product lifetime	Indicator includes the lifetime of the product
End of life processes	Indicator includes one or more end of life processes (e.g. recycling, energy recovery, remanufacturing, etc.)
Recyclability	Indicator considers the suitability of the product for being recycled
Energy	Indicator considers the energy consumption linked to the product
Environmental impact	Indicator includes any type of environmental impact within its calculation rationale
Entropy	Indicator includes the entropy within its calculation rationale
Founded on well-stablished frameworks	
LCA-based	Indicator is based on Life Cycle Assessment, includes its results or adjusts its indicators
MCI-based	Indicator is based on the Material Circularity Indicator, includes its value or adjusts its calculation rationale
Type of value	
Relative value	Indicator is presented as a relative value (e.g., percentage, index, etc.)
Absolute value	Indicator is presented as an absolute value
Additional features	
Economic input	Indicator includes any economic or monetary value within its calculation rationale
Benchmarked against the linear option	Indicator includes the linear option, and calculates the target product deviation from it

Taking into account that in WP1 environmental, economic and social impacts will be already measured and later incorporated into the monitor system framework in task 2.3, circularity indicators that considered any of these dimensions were discarded.

Figure 2 illustrates the synergies between Life Cycle Assessment, circular economy and conventional economics that led to the aforementioned decision of striving for complementing information instead of overlapping.

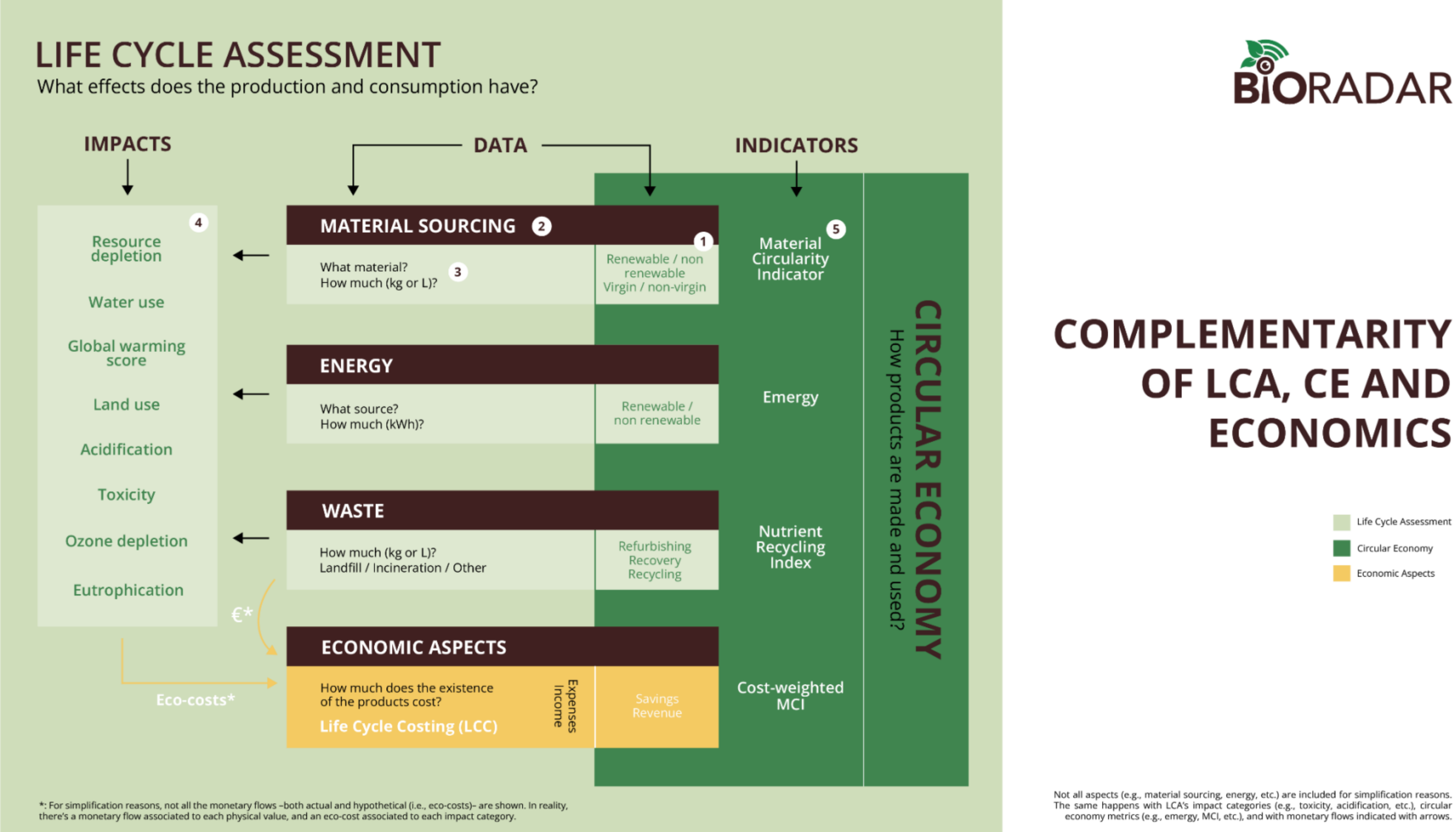
The light green box represents the LCA scope (i.e., all the activities involved in the lifecycle of a product or service), therefore circular economy (dark green box) and economic aspects (yellow box) are contained into it.

There are aspects of circularity that fall out of the LCA scope: CE data (1) associated to each shared data category (2); they are of interest to the CE and not to LCA, even though they pertain to the same data category. The same happens the other way around: LCA data (3) within each data category and out of the CE box pertain to the LCA methodology alone.

Life Cycle Assessment then takes its data and, through emission factors and systems modelling, obtains impacts such as global warming score and resource depletion (4). Circular economy, on the other hand, takes its data (variables) and calculates indicators (5). The idea of focusing on non-LCA indicators is therefore not to mix these CE and LCA, and rather complement the information generated by them. It's important to highlight that the list of shared data categories (2), impacts (4), and indicators (5) is not exhaustive and only comprises examples, for simplification purposes.

A similar approach is taken regarding conventional economics. The intersection of LCA and economics is the Life Cycle Costing (LCC), which can be conducted either in a conventional way (the costs incurred by the producing company in the life cycle of the product) or in an environmental way (the costs incurred by all the stakeholders involved in the life cycle of the product). In both cases, expense and income streams are accounted for (€). Additionally, LCA’s impact categories can be ‘converted’ into monetary values applying the eco-costs methodology. In the CE scope the differences are subtle: the focus would be on how the company saves money producing more circular products, or how it increases its benefit. Since these aspects are tied to income and expenses, they are not accounted for in a separate way.

As mentioned in Figure 2’s footnote, not all the monetary flows (either actual or symbolic) are depicted in the diagram for simplification reasons.



*: For simplification reasons, not all the monetary flows –both actual and hypothetical (i.e., eco-costs)– are shown. In reality, there's a monetary flow associated to each physical value, and an eco-cost associated to each impact category.

Not all aspects (e.g., material sourcing, energy, etc.) are included for simplification reasons. The same happens with LCA's impact categories (e.g., toxicity, acidification, etc.), circular economy metrics (e.g., emergy, MCI, etc.), and with monetary flows indicated with arrows.

Figure 2: Diagram depicting the complementarity of life cycle assessment, circular economy and conventional economics

3.2.2. Evaluation and final selection

This extensive analysis enabled the filtering and selection of the most suitable circularity indicators for BIORADAR's designated bio-based industry sectors and bio-products. The final selection of indicators was based on the extent to which it captured the principles of circular economy, as presented by Gursel et al., (2023). In this way, each indicator was analysed for its ability to capture information on intrinsic product circularity: material sourcing, renewable energy inputs, waste handling, recovery, recycling, and product lifetime. Each criterion is defined below:

- **Material sourcing**: indicator measures the nature of feedstock utilised during production such as virgin, recycled, reused, and biological materials.
- **Renewable energy inputs**: indicator takes into account the types of energy inputs utilised during production processes, distinguishing between renewable sources (such as solar, wind, hydropower, and geothermal) and non-renewable sources (fossil fuels, etc.)
- **Waste handling**: indicator measures the amount of waste generated during the lifetime of a product and the methods employed for waste treatment, encompassing recycling, landfilling, and other disposal practices.
- **Recovery**: indicator measures materials from waste streams, emphasizing whether key compounds are reclaimed and to what quality extent.
- **Recycling**: indicator considers the feasibility of recycling the product at the end of its life.
- **Product lifetime**: indicator considers the duration of the product’s lifetime during the use phase.

This classification process aimed to select one indicator per sector (namely, fertiliser, textile and packaging), and one general indicator, suitable to compare products from different sectors. Thus, the characterization process leads to the selection of four indicators, comprising the highest number of relevant criteria.

4. RESULTS

4.1. LIST OF CIRCULARITY INDICATORS

A total of 29 indicators were identified. These indicators are currently adopted by both scholars and practitioners to estimate circularity. Table 3 details the indicators found with their respective sources.

Table 3. List of the circularity indicators identified in the present study.

#	Indicator	Acronym	Source
1	Material Reutilization Score	MRS	Cradle to Cradle Products Innovation Institute (2016)
2	Material Circularity Indicator	MCI	Ellen McArthur Foundation & Ansys Granta (2019)
3	Cost-weighted-average MCI	-	Tashkeel et al. (2021)
4	MCI coupled with LCA	-	Rufí-Salís et al. (2021)
5	MCI based on economic and residual value	-	Jiang et al. (2022)
6	Nutrient Removal Efficiency Indicator	NERI	Preisner et al. (2022)
7	Nitrogen Recycling Index	NRI	Moller et al. (2023)
8	Circular Material Use Rate	CMU	Havrysh et al. (2023)
9	Circularity Indicator of Nutrient	CIN	Cobo et al. (2019)
10	Resource Pressure	-	Desing et al. (2021)
11	Material Durability Indicator	MDI	Mesa, González-Quiroga, & Maury (2020)
12	In-use occupation of materials	-	Moraga et al. (2021)
13	Circular Index – CirculAbility model	-	Enel (2018)
14	Indicators of circular economy for biofertilizer	-	Molina-Montero et al. (2017)
15	Green Protein Food Index	GPFI	Laso et al. (2018)
16	Recycling Effectiveness	RE	Roithner& Rechberger (2020)
17	Quality Model for Recycled Plastics	QMRP	Golkaram et al. (2022)
18	Quality of Recycling Framework	QRF	Roosen et al. (2023)
19	Emergy	Em	Wang et al. (2019)
20	Nitrogen Use Efficiency	NUE	Silva et al. (2021)
21	Circularity Index (CI) for textiles	-	(De Oliveira Neto et al., 2022)
22	Circular Economy Index	CEI	Di Maio & Rem (2015)
23	Circular Economy Performance Indicator	CEPI	Huysman et al. (2017)
24	Circularity Index	CI	Cullen (2017)
25	Product-level circularity metric	-	Linder et al. (2017)
26	Process yield / Net recovery	-	Lase et al. (2022)
27	Quality indicator	G	Lase et al. (2022)
28	Cyclical Use Rate Indicator	-	Ministry of Environment of Japan (2003)
29	Longevity Factor	-	Figge et al. (2018)

4.2. DESCRIPTION

The upcoming section contains a brief description of each circularity indicator previously identified.

(1) Material Reutilization Score (MRS) (General use)

This concept was developed by the Cradle to cradle Products Innovation Institute (2016). It measures a product's potential to be recycled by considering its intrinsic recyclability (the percentage of the product that can be recycled at least once after its initial use stage) and the percentage of recycled content. The values are weight-averaged, with the intrinsic recyclability assigned twice the weight of the percentage of recycled content. The final value ranges from 0 to 100, indicating the product's recyclability potential as shown in Equation 1.

Equation 1. Material reutilization score formula

$$MRS = \frac{2 \cdot \%IR\ of\ the\ product + \%RC\ in\ the\ product}{3} \cdot 100$$

where

MRS is the material reutilization score, %IR is the percentage of intrinsic recyclability, and %RC is the percentage of recycled content. The MRS thus contains information of usage of recycled materials and recyclability of the finished product.

(2) Material Circularity Indicator (MCI) (General use)

The Material Circularity Indicator (MCI) is widely used both directly and as a basis for other indicators. It is a value between 0 and 1, with 1 indicating the highest level of circularity. According to the Ellen McArthur Foundation & ANSYS Granta (2019), the MCI measures "*the degree to which the flow of materials has been minimized and the restorative flow has been maximized for its component materials, as well as how long and intensively it is used compared to a similar product in the industry average*" (p. 22). The MCI is determined by three variables: the mass of virgin raw material (V), the mass of unrecoverable waste (W), and a utility factor that considers the length and intensity of the product's use (X). Below, the equations 2 to 12 explains the calculation rationale for the MCI.

Equation 2: Virgin feedstock formula

$$V = \ M(1 - F_R - F_U - F_S)$$

where

V is the mass of virgin material, M is the mass of the finished product, F_R is the fraction of feedstock derived from recycled sources, F_U is the fraction from reused sources, and F_S is the fraction of the biological materials used which originate from sustainable production.

Equation 3: Amount of waste going to landfill or energy recovery formula

$$W_0 = M(1 - C_R - C_U - C_C - C_E)$$

where

W_0 is the mass of unrecoverable waste, M is the mass of the finished product, C_R is the fraction of the mass of the product being collected for recycling at the end of its use phase, C_U is the fraction of the mass of the product going into component reuse, C_C is the mass of the product comprising uncontaminated biological materials that are being composted, and C_E is the mass of the product comprising biological materials from sustainable production being used for energy recovery.

Equation 4: Mass comprising biological materials from sustainable production being used for energy recovery formula

$$C_E = E_E \cdot B_C$$

where

C_E is the mass of the product comprising biological materials from sustainable production being used for energy recovery[3], E_E is the efficiency of the energy recovery process, and B_C is the carbon content of the biological material.

Equation 5: Efficiency of the energy recovery process formula

$$E_E = \frac{E_R}{HHV \cdot M_B}$$

where

E_E is the efficiency of the energy recovery process, E_R is the energy recovered (in MJ or BTU), HHV is the higher heating value (in MJ or BTU), and M_B is the mass of eligible biological material.

Equation 6: Quantity of waste generated in the recycling process formula

$$W_C = M(1 - E_C) \cdot C_R$$

where

W_C is the quantity of waste generated in the recycling process, M is the mass of the finished product, E_C is the efficiency of the recycling process used for

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[3] For a material to be considered within the energy recovery process, certain conditions have to be met such as demonstrably coming from a source of sustainable production, being uncontaminated by technical materials, etc. (Ellen McArthur Foundation & ANSYS Granta, 2019).

recycling the product at the end of its use phase, and C_R is the fraction of the mass of the product being collected for recycling at the end of its use phase.

Equation 7: Amount of waste generated to produce any recycled content used as feedstock formula

$$W_F = M\frac{(1-E_F)F_R}{E_F}$$

where
W_F is the amount of waste generated to produce any recycled content used as feedstock, M is the mass of the finished product, E_F is the efficiency of the recycling process used to produce the recycled feedstock, and F_R is the fraction of feedstock derived from recycled sources.

Equation 8: Overall amount of unrecoverable waste formula

$$W = W_0 + \frac{W_F + W_C}{2}$$

where
W is the overall amount of unrecoverable waste, W_0 is the mass of unrecoverable waste, W_F is the amount of waste generated to produce any recycled content used as feedstock, and W_C is the quantity of waste generated in the recycling process.
One of the standalone components of the MCI is the Linear Flow Index (LFI), it "*measures the proportion of material flowing in a linear fashion*" (Ellen McArthur Foundation & ANSYS Granta, 2019). It is derived as shown in the Equation 9.

Equation 9: Linear Flow Index formula

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

where
LFI is the linear flow index, V is the mass of virgin material, W is the overall amount of unrecoverable waste, M is the mass of the finished product, W_F is the amount of waste generated to produce any recycled content used as feedstock, and W_C is the quantity of waste generated in the recycling process. On the other hand, there is the Utility Factor (X) which accounts for the lifetime of the product and the intensity of its use, as shown in the Equation 10.

Equation 10: Utility factor formula

$$X = \left(\frac{L}{L_{av}}\right)\cdot\left(\frac{U}{U_{av}}\right)$$

where
X is the utility factor, L is the lifetime of the product, L_{av} is the industry average lifetime of an equivalent product, U is the number of functional units achieved during the use of the product, and U_{av} is the industry average of functional units achieved during the use of an equivalent product.
Finally, the MCI^*_p is defined as in the Equation 11, noting that for products with mainly linear flows ($LFI \approx 1$) and a utility factor worse than average product ($X < 1$), the value of MCI could be negative, therefore keeping "very linear" products from being compared through this metric (Ellen McArthur Foundation & ANSYS Granta, 2019).

Equation 11: Material Circularity Indicator formula

$$MCI_P^* = 1 - LFI \cdot F(X)$$

where
MCI^*_p is the Material Circularity Indicator, LFI is the Linear Flow Index, and F(X) is a function of the utility factor.

Equation 12: Function the utility factor formula

$$F(X) = \frac{0.9}{X}$$

where
F(X) is the function of the utility factor formula, and X is the utility factor.

(3) Cost-weighted-average MCI (General use)
Tashkeel et al. (2021) introduced a modification to MCI to consider an economic aspect: the cost of recycling the materials. They proposed to obtain the average MCI of all the materials composing the product and weight it by the cost of recycling. The modification proposed by Tashkeel et al. (2021) is presented in the Equation 13.

Equation 13: Cost-weighted-average MCI formula

$$MCI_e = \frac{\sum_{i=1}^{n} MCI_i \cdot C_i}{\sum_{i=1}^{n} C_i}$$

where
MCI_e is the cost-weighted-average material circularity indicator, MCI_i is the material circularity indicator of the material i, and C_i is the cost of recycling the material i.

(4) MCI coupled with LCA (General use)

In an effort to combine in a single indicator the MCI and the LCA's impact categories, Rufí-Salís et al. (2021) derived a coupled indicator, as shown in Equation 14. It weights the environmental impact of a subsystem "i" against the total impact exerted by the system and multiplies it by the MCI of the subsystem.

Equation 14: LCA-coupled MCI formula for the example of Global Warming Potential

$$GW - MCI_{LCA} = \sum_{i=1}^{n} \left[\left(\frac{GW_i}{\sum GW} \right) \cdot MCI_i \right]$$

where
$GW - MCI_{LCA}$ is the LCA-coupled MCI for global warming, GW_i is the global warming potential of the subsystem i, GW is the global warming potential of the entire system, and MCI_i is the material circularity indicator of subsystem i. Therefore, it originates a set of indicators comprised by the MCI coupled with each one of the impact categories considered by the LCA.

(5) MCI based on economic and residual value (General use)
Jiang et al. (2022) incorporated the "economic value" within the calculation framework of the MCI as well as the "residual value" ("the ratio of the value after EoL compared with the new one or the input", p. 4). The original MCI formulas and the modified ones are compared in the Table 4.

Table 4: MCI and MCI based on economic and residual value formulas.

Formulas MCI	Formulas MCI'
$V=M*(1-F_u-F_r-F_b)$	$V'=E*(1-F_{u'}-F_{r'}-F_{b'})$
$W_o=M*(1-C_u-C_r)$	$W_{o'}=E*R*(1-C_{u'}-C_{r'})$
W=Wo+Wc	W'=Wo'+Wc'
LFI=(V+W)/2M	LFI'=(V'+W')/(E+E*R)
MCI=max [0, 1-LFI * F(X)]	MCI'=max [0, 1-LFI' * F(X)]

where
V/V' is the virgin feedstock expressed by mass or economic value, W/W' is the unrecoverable waste expressed by mass or economic value, $F_u/F_{u'}$ is the fraction of reused resources based on material mass or economic value, $F_r/F_{r'}$ is the fraction of recycled sources based on material mass or economic value, $F_b/F_{b'}$ is the fraction of bio-based sources based on material mass or economic value, $C_r/C_{r'}$ is the fraction of materials collected for recycling based on material mass or economic value, $C_u/C_{u'}$ is the fraction of materials collected for reuse based on material mass or economic value, $W_c/W_{c'}$ is the waste generated in the recycling process expressed by mass or economic value, $W_o/W_{o'}$ is the materials going to landfill/incineration expressed by mass or economic value, LFI/LFI' is the Linear

Flow Index based on mass or economic value, M is the material mass, E is the economic value, R is the residual value and F(X) is a function of the product utility.

(6) Nutrient Removal Efficiency Indicator (NERI) (Fertilisers)

Developed for urban wastewater systems, the Nutrient Removal Efficiency Indicator (NERI) accounts for the amount of nutrients (N or P) that are recovered from the sewage stream. The formula is displayed in the Equation 15 as Preisner et al. (2022) reported it.

Equation 15: Nutrient Removal Efficiency Indicator Formula

$$I_{RE(X)} = \frac{Ci_X - Ce_X}{Ci_X} \times 100$$

where

$I_{RE(X)}$ is the nutrient removal efficiency indicator, Ci_X is the total content of the nutrient (N or P) in raw wastewater (influent) (mg/L), Ce_X is the total content of the nutrient (N or P) in treated wastewater (effluent) (mg/L), X is the nutrient of interest (i.e., N or P).The nutrient removal efficiency indicator can also be expressed as nutrient loads in the influent and effluent per year, for instance, MgN/year or MgP/year.

(7) Nitrogen Recycling Index (NRI) (Fertilisers)

Similar to the NERI, Møller et al. (2023) reported the Nitrogen Recycling Index (NRI), which considers the recycled nitrogen as a proportion of total nitrogen, as displayed in Equation 16. It becomes useful when a mixture of circular and non-circular N-rich raw materials or fertilisers is used.

Equation 16: Nitrogen Recycling Index formula

$$NRI = \frac{NR}{NR + IN}$$

where

NRI is the nitrogen recycling index, NR is the recycled nitrogen, and IN is the imported nitrogen.

(8) Circular Material Use Rate (CMU) (General use)

Developed by the statistical office of the European Union (Eurostat, 2018) as a macroeconomic indicator, it is used by Havrysh et al. (2023) to assess the circularity of biofertilizers and biofuels. Its formulas are explained in the Equation 17Equation 18.

Equation 17: Circular material use rate formula

$$CMU = \frac{U}{M}$$

where

CMU is the circular material use index, U is circular use of materials, and M is the overall material use.

Equation 18: Overall material use formula

$$M = DMC + U$$

where
M is the overall material use, DMC is the domestic material consumption, and U is the circular use of materials.

(9) Circularity Indicator of Nutrient (CIN) (Fertilisers)

Cobo et al. (2019) analysed a system comprised of a waste management system that produces fertilisers (compost, digestate, $(NH_4)_2SO_4$ and $NH_4MgPO_4 \cdot 6H_2O$) and applies them to corn crops. Based on that, they developed a Circularity Indicator of Nutrients, which they apply specifically to nitrogen and phosphorus. Its formula is detailed in the Equation 19.

Equation 19: Circularity indicator of nutrient formula

$$CI_i(x,y) = \frac{\sum_{k=1}^{m}\sum_{j=1}^{n} R_{ijk}(x,y) \cdot \eta_{r_{ij}} \cdot \eta_{p_{ik}}}{W_i}$$

where
CI_i is the circularity indicator of nutrient i, W_i is the amount of nutrient i present in the collected waste (kg), R_{ijk} is the amount of nutrient i that enters the recycling unit process j, and the subsequently recovered nutrient i enters the corn production unit process k (kg), η_{rij} is the recycling efficiency of the recycling unit process j for nutrient i (kg of nutrient i recovered per kg of nutrient i that enters the unit process j), and η_{pik} is the efficiency of the corn production unit process k at taking up the recovered nutrient i (kg of nutrient i taken up per kg of nutrient i entering the process k).

(10) Resource Pressure (RP) (Textile)

Lama et al. (2022) studied the environmental sustainability of carpets through an indicator called “resource pressure”, developed previously by Desing et al. (2021) as detailed in the
Equation 20.

Equation 20: Resource Pressure formula

$$\tau = \frac{1}{2} \times \frac{m_{product}}{ERB} \times \frac{1}{t_L} \times (1+\gamma_m) \times (1+\alpha'(1-\eta_r) - \eta_r - \eta_c)$$

where

τ is the resource pressure, $m_{product}$ is the mass of the product, ERB is ecological resource budgets, TL is the product lifetime, γ_m is the manufacturing losses, α' is the recyclability, η_r is the recyclability, and η_c is the cascadability.

(11) Material Durability Indicator (MDI) (Packaging)

Mesa et al. (2020) proposed an indicator designed specifically for polymeric materials, but “potentially applicable to any material after adjusting the reference values” (p. 4), that tries to convey the durability aspect of the materials, involving its mechanical and chemical durability, as well as its environmental impact. Its calculation rationale is explained in Equation 21Equation 25.

Equation 21: Material Durability Indicator formula

$$MDI = D_{ch} \cdot D_m \cdot E$$

where
MDI is the Material Durability Indicator, D_{ch} is the chemical durability, D_m is the mechanical durability, and E is the environmental impact.

Equation 22: Chemical durability formula

$$D_{ch} = \sqrt[4]{a_1 \cdot a_2 \cdot a_3 \cdot a_4}$$

where
D_{ch} is the chemical durability, a_1 is the flammability resistance, a_2 is the resistance to UV radiation, a_3 is the resistance to water, and a_4 is the resistance to organic solvents.

Equation 23: Mechanical durability formula

$$D_m = \sqrt[2]{b_1 \cdot b_2}$$

where
Dm is the mechanical durability, b_1 is the yield strength (MPa), and b_2 is the fatigue strength at 107 cycles (MPa).

Equation 24: Environmental impact formula

$$E = 1 - \frac{I}{I_{max}}$$

where
E is the environmental impact, and I is an environmental-impact factor.

Equation 25: Environmental impact-factor formula

$$I = \sqrt[2]{c_1 \cdot c_2}$$

where
I is an environmental-impact factor, c_1 is the carbon footprint (kg CO_2/kg), and c_2 is the energy consumption (MJ/kg).

(12) In-use occupation of materials ratio (General use)

Moraga et al. (2021) deepened in the aspect of slowing material cycles through a set of indicators aiming to capture this circularity principle. Its calculation rationale is explained in Equation 26Equation 28.

Equation 26: Maximum in-use occupation of a material formula

$$Occ_{Umax} = m_{s,1} \cdot TH$$

where

Occ_{Umax} is the theoretical maximum in-use occupation of a material in n product cycles during a given time horizon (kg•year), $m_{s,1}$ is the mass of the material going into the in-use occupation of the first product cycle j (kg), and TH is the time horizon (years).

Equation 27: In-use occupation ratio of a material formula

$$UOR = \frac{\sum_{j=1}^{n} Occ_{U,j}}{Occ_{Umax}} \times 100$$

where

UOR is the in-use occupation ratio of a material in n product cycles during a given time horizon (%), $Occ_{U,j}$ is the in-use occupation of a material in a product cycle j (kg•year), and Occ_{Umax} is the theoretical maximum in-use occupation of a material in n product cycles during a given time horizon (kg•year).

Equation 28: Final retention of a material in society formula

$$FRS = \frac{m_{TH}}{m_{s,1}} \times 100$$

where

FRS is the final retention of a material in society (%), m_{TH} is the mass of primary raw material initially used in the first product cycle j still available at year 25 (in n product cycles j), and $m_{s,1}$ is the mass of the material going into the in-use occupation of the first product cycle j (kg).

(13) Circular Index – Circulability Model (General use)

As part of the so-called CirculAbility Model, Enel (2018) developed an indicator package that results in a single indicator called Circular index (CI), which is defined in the

Equation 29.

Equation 29: Circular index formula

$$CI = CF + \frac{(1 - CF) \times (CU - 1)}{2 \times CU}$$

where

Ci is the Circular Index, Cf is the Circular flow, that considers the contribution in terms of circular inputs and outputs of material and energy, and Cu is the circular use that represents the circularity in the use approach.

(14) Indicators of Circular Economy for Biofertiliser (Fertilisers)

Molina-Moreno et al. (2017) developed a set of indicators applicable specifically to the production of biofertilisers from pig manure. The calculation formulas of the aforementioned indicators are displayed in the Equation 30Equation 31.

Equation 30: Indicator of circular economy efficiency for biofertiliser formula

$$I_{bf,ce} = \frac{\sum_{i=1}^{n} m_{bf,i}}{m_{digestate}} \cdot 100$$

where

$I_{bf,ce}$ is the indicator of circular economy efficiency for the biofertiliser, $m_{bf,i}$ is the mass flow rate of biofertiliser obtained during stage i, and $m_{digestate}$ is the mass flow rate of digestate generated during the anaerobic digestion stage.

Equation 31: Indicator of technological nutrient performance for biofertiliser formula

$$I_{bf,tn} = \frac{\sum_{i=1}^{n} m_{bf,i}}{Q_{sw}}$$

where

$I_{bf,tn}$ is the indicator of technological nutrient performance for the biofertiliser, $m_{bf,i}$ is the mass flow rate of biofertiliser obtained during stage i, and Q_{sw} is the volumetric flow rate of pig manure treated during the process.

(15) Green Protein Footprint Index (GPFI) (Fertilisers)

Laso et al. (2018) developed an indicator to measure the “environmental cost” of producing anchovies. They called it “Green protein footprint” (GPF), and even though it is designed for proteins, as shown in the Equation 32, it could be adapted for nutrients, for instance.

Equation 32: Green protein footprint formula

$$GPF = \frac{Environmental\ impact \Big/ kg\ protein}{\left(Environmental\ impact \Big/ kg\ protein\right)_{reference\ scenario}}$$

where

GPF is the green protein footprint, and Environmental impact refers to any LCA impact category to be highlighted.

(16) Recycling Effectiveness (RE) (Packaging)

To address the problem of loss of quality upon recycling, Roithner & Rechberger, (2020) postulated a method to calculate the recycling effectiveness of plastic based on its statistical entropy, which “measures the concentrating or diluting effect of a process on a specific material” (p. 587). The ultimate indicator proposed by Roithner & Rechberger (2020) is the recycling effectiveness, as displayed in Equation 33.

Equation 33: Recycling effectiveness formula

$$RE = \left(1 - H_{out,rel}\right)$$

where

RE is the recycling effectiveness, and $H_{out,rel}$ is the relative statistical entropy, which is obtained by the ratio between the entropy of the output and the maximum statistical entropy. The relative statistical entropy is a dimensionless value between 0 and 1. The higher the result of $H_{out,rel}$ is, the worse the recycling performance is.

(17) Quality Model for Recycled Plastics (QMRP) (Packaging)

Golkaram et al. (2022) developed a complex indicator (I_{total}) that merges the quality of recycled plastic (ξ_q) with LCA impacts. Its calculation rationale is explained in Equation 34.

Equation 34: Quality model for recycled plastics formula

$$I_{total} = I_{MR} - \xi_q \times I_{Polymer}$$

where

I_{total} is the total environmental impact of the recycling of waste plastic and is the sum of the mechanical recycling process burdens and the avoided impacts from the production of the virgin plastic that is replaced, I_{MR} is the environmental impacts or the mechanical recycling including sorting, washing, pelletizing, ξ_q is the aggregated value for the quality of the material, and $I_{Polymer}$ is environmental impacts to produce 1 kg of virgin plastic pellets.

(18) Quality of Recycling Framework (QRF) (General use)

Roosen et al. (2023) developed a framework to quantify the quality of recycling through three dimensions: Virgin Displacement Potential (VDP), In-Use Stocks Lifetime (IUSL), and Environmental Impact (EI). The formulas of the first two are detailed in the Equation 35Equation 36.

Equation 35: Virgin Displacement Potential formula

$$VDP_{\boldsymbol{j}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} (TSS \times W_m \times EOL_{RR} \times EBCs)_{\boldsymbol{i}}$$

where

VDP_j is the Virgin Displacement Potential of a secondary material j, TSS is the Technical Suitability for Substitution, W_m is the market weight, EOL_{RR} is the End of Life Recycling Rate, and EBCs are the economic boundary conditions.

Equation 36: In-Use Stocks Lifetime formula

$$IUSL = \int_{T_0}^{T_1} M(t)\, dt$$

where

IUSL is the In-Use Stocks Lifetime,T_1 is the number of years it takes to have a residual mass of the material of less than 1% mass,T_0 equals zero years, and M(t) is the function that describes the relationship between time and a given material's mass.

(19) Emergy (Em) (General use)

Wang et al. (2019) used the emergy concept to assess circularity in terms of diminishing the amount of energy required to produce a good. Emergy is "the total amount of available energy needed directly and indirectly to make one product or service". The formula they proposed is explained in the Equation 37.

Equation 37: Emergy formula

$$Em = \sum_{i=1}^{n} Em_i = \sum_{i=1}^{n} f_i \times UEV_i$$

where

Em is total emergy, i is one individual flow associated with the investigated system, Em_i is the emergy used for supporting the investigated system in terms of flow i, f_i is the amount of individual flow of i (expressed in g, J, or monetary units), and UEV_i is the amount of emergy required for generating one unit of the individual flow of i (expressed in sej/unit, i.e., solar emergy joules (sej), for instance: sej/g, sej/J, or sej/€).

Its calculation rationale is explained in Equation 38Equation 41.

Equation 38: Emergy yield ratio formula.

$$EYR = \frac{Y}{F}$$

where

EYR is Emergy Yield Ratio, Y is the system emergy output, and F is purchased resources.

Equation 39: Environmental loading ratio formula

$$ELR = \frac{(N + F)}{R}$$

where
ELR is Environmental Loading Ratio, N is local nonrenewable resources, F is purchased resources, and R is local renewable resources.

Equation 40: Environmental investment ratio formula.

$$EIR = \frac{F}{(R + N)}$$

where
EIR is Emergy Investment Ratio, F is purchased resources, R is local renewable resources, and N is local nonrenewable resources.

Equation 41: Emergy sustainability index formula

$$ESI = \frac{EYR}{ELR}$$

where
ESI is Emergy Sustainability Index, EYR is Emergy Yield Ratio, and ELR is Environmental Loading Ratio.

(20) Nitrogen Use Efficiency (NUE) (Fertilisers)

Silva et al. (2021) studied the efficiency of nitrogen use on fertiliser production. To measure it, they proposed the nitrogen use efficiency indicator, which is explained in the Equation 42.

Equation 42: Nitrogen use efficiency formula

$$NUE = \frac{N\ output}{N\ input}$$

where
NUE is the Nitrogen Use Efficiency, N output is the mass of nitrogen coming from the system (kg), and N input is the mass of nitrogen entering the system (kg).

(21) Circularity Index (CI) for textiles (Textile)

De Oliveira Neto et al. (2022) developed a calculation scheme to obtain a circularity index designed for the textile industry. It considers biotic “compartments” (x), abiotic (w), air (z), and water (y). Its calculation rationale is explained in Equation 43Equation 46.

Equation 43: Circularity index formula.

$$Circularity\ Index\ = \frac{Mass\ Intensity\ Total\ Before}{Mass\ Intensity\ Total\ After}$$

Equation 44: Intensity-weighted mass formula.

$$MIF\ = M \times IF$$

where
MIF is the intensity-weighted mass, M is the mass, and IF is the intensity factor.

Equation 45: Mass intensity per compartment formula.

$$MIC_j = \sum_{i=1}^{n} IF \times (residue\ i\ compartment\ j)$$

where
MIC is the mass intensity per compartment, and IF is the intensity factor.

Equation 46: Mass intensity total formula.

$$MIT\ = MIC_w + MIC_v + MIC_z + MIC_n$$

where
MIT is the mass intensity total, and MIC_j is the mass intensity per compartment (biotic: x, abiotic: w, air: z, and water: y).

(22) Circular Economy Index (CEI) (General use)
Di Maio & Rem (2015) developed an index that appraises the economic value produced by the recycler in relation to that entering the recycling facility. Its formula is presented in the Equation 47.

Equation 47: Circular economy index formula.

$$CEI = \frac{Material\ value\ recycled\ from\ EoL\ product(s)}{Material\ value\ needed\ for\ (re-)producing\ EoL\ product(s)}$$

The economic (material) value (€, $, etc.) was selected over others (mass, volume, embedded energy, carbon footprint, etc.) “because it aligns best with the present EU policies” (Di Maio & Rem 2015).

(23) Circular Economy Performance Indicator (CEPI) (General use)
Based on a case study on post-industrial plastic waste, Huysman et al., (2017) proposed an indicator that embodies the ratio of the actual obtained environmental benefit in relation to the ideal environmental benefit according to quality, as explained in the Equation 48.

Equation 48: Circular Economy Performance Indicator formula.

$$CPI = \frac{actual\ benefit}{ideal\ benefit\ according\ to\ quality}$$

The environmental benefits are thought to be obtained from life cycle assessments that assess both the actual technology and the (waste management) technology “to which the stream should be directed according to its composition/quality with a minimal required effort, assuming option I (closed-loop recycling) is better and option IV (incineration is less preferable)” (Huysman et al., 2017).

(24) Circularity Index (CI) (General use)

Conceding that losses in both quantity and quality when reprocessing materials are usually neglected yet relevant, Cullen (2017) proposed a circularity index that can be obtained as explained in the equations. Under his rationale, the theoretical circularity would be assigned a CI = 1. Its calculation rationale is shown in the Equation 49Equation 51.

Equation 49: Circularity index formula.

$$CI = \alpha \cdot \beta$$

where
CI is the Circularity Index, α is the ratio that describes the combined effects of stock dynamics and dissipative losses, and β is the ratio that quantifies the energy needed for material recovery relative to the energy required for primary material production from virgin ore.

Equation 50: Combined effects of stock dynamics and dissipative losses ratio formula.

$$\alpha = \frac{recovered\ EoL\ material}{total\ material\ demand}$$

where
α is the ratio that describes the combined effects of stock dynamics, and dissipative losses.

Equation 51: Energy needed for material recovery to energy required for primary material production ratio formula.

$$\beta = 1 - \frac{energy\ required\ to\ recover\ material}{energy\ required\ for\ primary\ production}$$

where
β is the ratio that quantifies the energy needed for material recovery relative to the energy required for primary material production from virgin ore.

(25) Product-level circularity metric (General use)

Abounding in the economic value approach, Linder et al. (2017) proposed a product-level circularity metric (c) that accounts for the economic value of the circular parts in relation to the total economic value of the product, as depicted in Equation 52.

Equation 52: Product-level circularity metric formula.

$$c = \frac{economic\ value\ of\ recirculated\ parts}{economic\ value\ of\ all\ parts}$$

(26) Process yield and net recovery (Packaging)

In the field of plastic recycling, Lase et al. (2022) proposed the evaluation of quality recycling process (QRP). Their contributions are explained in the Equation 53Equation 54 through the process yield and net recovery formulas. Here is shown the percentage of mass recovery (μ^R) to the recycled material against the total mass of the material (μ^I).

Equation 53: Process yield formula.

$$Y = \frac{\mu^R}{\mu^I}$$

where

Y is the process yield, μ^R is the recovered mass (e.g., into regranulates), and μ^I is the mass of waste input.

Equation 54: Net recovery formula.

$$R = \frac{f^T_{regranulate}}{\mu^T_I}$$

where

R is the net recovery, $f^T_{regranulate}$ is the fraction of waste T found in the desired form (e.g., regranulates), and μ_I^T is the mass of waste T entering the recycling facility.

(27) Quality indicator (G) (Packaging)

At the same time, Lase et al. (2022) proposed quality parameters that can play an interesting role in the understanding of the circularity of the process. They measure the concentration of the waste category T in the material “i” (G_i). It is explained in Equation 55.

Equation 55: Quality indicator formula.

$$G_i = \frac{f_i^T}{\sum_{m=1}^{M} f_i^m}$$

where

G_i is the quality indicator, f_i^T is the mass of the targeted waste (T) in the desired form (i), and f_i^m is the total mass of the desired form of the product (i).

(28) Cyclical use rate indicator (General use)

According to Tashkeel et al. (2021), the use of "cyclical" indicators contributes to assessing circularity beyond recycling. The cyclical use rate indicator expresses the ratio of secondary materials that are consumed in relation to the total materials used. Kovanda (2014) specifies that it connects the topics of material consumption and waste management as shown in Equation 56.

Equation 56: Standard format of the cyclical use rate indicator formula

$$PU_C = \frac{U_C}{DMI + U_C}$$

where

PU_C is the indicator of the cyclical use rate in percent, U_C is the cyclical use of materials, and DMI is the direct material input. Nevertheless, the standard cyclical use rate was modified by Kovanda (2014), specifying that DMI includes imports of waste, secondary materials and scrap, so it is sensible to subtract them from DMI and them to U_C. Additionally, domestically produced secondary materials are also added to U_C, therefore obtaining the Equation 57.

Equation 57: Modified cyclical use rate indicator formula

$$PU_{cm1+2} = \frac{U_{cm1+2}}{DMI_{-im} + U_{cm1+2}}$$

where

PU_{cm1+2} is the cyclical use rate indicator as a percentage with modifications made for waste imports, secondary raw materials, and scrap along with domestically produced secondary materials, U_{cm1+2} is the cyclical use rate of all materials, and DMI_{-im} is the direct material input, excluding waste imports (Tashkeel et al., 2021).

(29) Longevity Factor (General use)

This indicator tries to capture the slowdown of the material cycles, given that "the longer a resource is used, the higher the contribution to a circular economy" (Figge et al., 2018, p. 300). For Figge et al. (2018), longevity is determined in three ways: "the time for which a resource is first used (A), the time for which a resource is used due to product refurbishment (B), and due to recycling (C)" (p. 300). These are the main components of the Longevity factor formula, as depicted in the Equation 58.

Equation 58: Longevity factor formula

$$Longevity = L^A + L^B + L^C$$

where
L^A is the initial lifetime of the product, L^B the refurbished lifetime contribution, and L^C the recycled life time contribution, all of them expressed in units of time (e.g., years, months, etc.).

4.3. EVALUATION AND SELECTION

The first characterisation of indicators allowed to identify the most common and the most overlooked aspects of the mapped indicators. Table 5 displays the applied tags, considering the sector for which the indicator was built, the aspects included in the calculation, the presence of well-stablished frameworks within the indicators' rationale —namely LCA and MCI—, the type of value obtained through the indicator, and additional aspects.

Table 5: Results of the tag-based indicator characterisation

Tag	Number of indicators	%
Sector		
General	16	55.17%
Fertilisers	6	20.69%
Packaging	5	17.24%
Textile	2	6.90%
Aspects included		
Recycled input	9	31.03%
Efficiency	7	24.14%
Product lifetime	7	24.14%
End of life processes	5	17.24%
Recyclability	5	17.24%
Energy	4	13.79%
Environmental impact	4	13.79%
Entropy	1	3.45%
Founded on well-stablished frameworks		
LCA-based	4	13.79%
MCI-based	4	13.79%
Type of value		
Relative value	23	79.31%
Absolute value	6	20.69%
Additional features		
Economic input	6	20.69%
Benchmarked against the linear option	4	13.79%

After excluding the indicators containing environmental and/or economic values[4], **the resulting list was composed by five indicators applicable to any sector (general), five indicators for fertilisers, three indicators for packaging, and one indicator for textile** (Table 6).

Table 6. List of filtered general and sector specific circularity indicators. The tag of each indicator is in brackets.

General	Fertiliser	Textile	Packaging
(1) Material Reutilization Score (MRS)	(6) Nutrient Removal Efficiency Indicator (NERI)	(10) Resource Pressure	(16) Recycling Effectiveness
(2) Material Circularity Indicator (MCI)	(7) Nitrogen Recycling Index (NRI)		
(12) In-use occupation of materials	(9) Circularity Indicator of Nutrient (CIN)		(26) Process yield/Net recovery
(13) Circular index – CirculAbility model	(14) Indicators of circular economy for biofertiliser		
(19) Emergy	(20) Nitrogen Use Efficiency (NUE)		(27) Quality indicator (G)

Thereafter, “runner-up” indicators were assessed, as displayed in Table 7, by examining its compliance with the criteria explained in section3.2.2 *3.2.2 Evaluation and final selection*.

With regard to the general indicators, it is clear that the one that captures the highest number of criteria is (13) Circular Index – CirculAbility model outscoring the (2) Material Circularity Indicator for including the renewable energy aspect.

In the fertiliser sector, all the indicators are very similar, and therefore obtained the same score (recovery). Notwithstanding, there is one differential element that makes the (9) Circularity Indicator of Nutrient (CIN) stand out: that it includes a factor that accounts for the efficiency of the recovery process. Thus, based on this advantage, the CIN was selected for the fertiliser sector.

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[4] As explained in the methodology, this was done because the BIORADAR monitoring framework will already include LCA and LCC (Life Cycle Costing) results. Therefore, in order not to redound, the quest is to complement them with *stricto sensu* circularity indicators.

The selection for textile was really straightforward since there was only one indicator in the final selection stage: (10) Resource Pressure (RP).

Table 7. Results from evaluation process of indicator compliance with selected criteria

	Indicator	**Material sourcing**	**Renewable energy use**	**Waste handling**	**Recovery**	**Recycling**	**Lifetime**
General	(1) Material Reutilization Score (MRS)	√			√	√	
	(2) Material Circularity Indicator (MCI)	√		√		√	√
	(13) Circular Index – CirculAbility model	√	√	√		√	√
	(12) In-use occupation of materials	√			√		√
	(19) Emergy		√				
Fertiliser	(6) Nutrient Removal Efficiency Indicator (NERI)				√		
	(7) Nitrogen Recycling Index (NRI)				√		
	(9) Circularity Indicator of Nutrient (CIN)				√		
	(14) Indicators of circular economy for biofertilizer				√		
	(20) Nitrogen Use Efficiency (NUE)				√		
Textil	(10) Resource Pressure (RP)	√				√	√
Packaging	(16) Recycling Effectiveness (RE)				√		
	(26) Process yield/Net recovery				√		
	(27) Quality indicator				√		

Regarding packaging, a similar situation to the fertiliser sector was obtained: all the indicators scored the same criterion (recovery). In this case, there was also an indicator that stood out: (16) Recycling Effectiveness (RE). It was favored for incorporating quality losses in the production process.

5. DISCUSSION & CONCLUSIONS

The circularity performance measurement is still in full swing, with new sets being published and tested frequently. Even though initiatives such as the Circle Economy's Knowledge Hub (Circle Economy, n.d.) have mapped 134 indicators, and (Saidani et al., 2019) mapped 55, there is still a lot of room for specialization, specially at the product level, and even more in the bio-based sector.

This is especially clear when looking at corporate sustainability reports, EU-funded projects, and reporting standards. Most of the data available there is for the macro and meso levels, and when approaching the product level, there is no relevant circularity measurement being widely used other than those already reported in scientific literature.

Therefore, the following sections deepen into the main characteristics found in the review such as LCA and MCI being used as circularity measurement tools, and the debate on circularity vs. sustainability. The selected indicators are further described in detail, and finally the main data gaps found in the research are highlighted.

LCA and MCI as for circularity measurement tools

It was found during the research that **Life Cycle Assessment-based indicators are the most common and are being widely used (49% of the 46 articles that reached the end of the screening contained LCA-based indicators). Also, the Material Circularity Indicator (MCI) has a non-negligible presence (28% of the articles).** This could signal that there are growing efforts in including circularity alongside sustainability assessments.

Circularity vs. Sustainability

It is actually an ongoing discussion among academics and practitioners. While some assert that LCA is a good complement for assessing circular economy initiatives (either by conducting LCA of circular solutions or by complementing it with circularity indicators) (Ingemarsdotter & Dumont, 2022; Rigamonti & Mancini, 2021), others criticize that "LCA favours short term gain over systemic change, ignores hard to measure impacts, only measures what you tell it to measure, and relies on assumptions" (Ellen McArthur Foundation, n.d.).

Regarding usefulness, C-indicators may be better suited, as they are seen as time-savers, easy-to-understand, and easier to communicate than multiple-point metrics (Brändström & Saidani, 2022).

There are also contrasting opinions among scholars on what C-indicators at product level should measure and whether indicators addressing single or multiple issues are more suited. Linder et al. (2017) recommended that a circularity metric at the product level should focus exclusively on measuring circularity, i.e., the fraction of a product that comes from used products, as a single attribute of product quality and not on environmental performance or competitiveness. Pauliuk (2018) provides, instead, a dashboard of new and established indicators for the quantitative assessment of CE for product systems and organizations. Such list addresses different categories of indicators, measuring both physical circularity, monetary value, and potential environmental impacts, mostly based on material flow analysis (MFA), material flow cost accounting (MFCA) and life cycle assessment (LCA). Saidani et al., (2017) criticized the ability of three existing approaches, i.e., Material Circularity Indicator (MCI) (EMF and Granta Design, 2015), Circular Economy Toolkit (CET) (Evans and Bocken, 2013) and Circular Economy Indicator Prototype (CEIP) (Griffiths and Cayzer, 2016), to measure product circularity performance both in terms of their applicability in industry and their accordance with CE principles.

At any rate, it is to be noted that **"increased circularity does not guarantee increased sustainability" (Earthshift Global, 2022). Rather, they are two spheres that need to be assessed simultaneously, to better understand the performance of the target products.** For example, Saidani et al. (2021) contrasted circularity and LCA's environmental impacts through a matrix of potential trade-offs, describing four quadrants: (1) win-win situation, (2) trade-off on environmental impacts, (3) lose-lose situation, and (4) trade-off on circularity. EU-funded project ReTraCE also proposes a mix of indicators, namely LCSA, Emergy Accounting (EMA), and Sustainable Value Stream Mapping (sus-VSM) indicators, to address the individual limitations that they have had for assessing circular production systems (Coleman et al., 2020).

Therefore, the decision to filter-out the indicators based on, or containing LCA's impact categories is judged to be sound. **BIORADAR's WP1 will conduct the LCAs of the target products, and thus the selection of circularity indicators is aimed to complement those results and not to redound.**

The same logic is applicable to the indicators that include economic inputs in its calculation (21% of the 29 identified indicators). The economic values are a relevant aspect of circularity, and thus are being included in the analyses conducted by academics and practitioners. BIORADAR's **WP1 is currently conducting the Life Cycle Costing assessment of the target products. Therefore, indicators containing economic variables were discarded, in order not to redound when the results of both sustainability and circularity assessments are displayed together.**

Selected indicators

As a result of the applied screening, four indicators were selected to be used for the circularity assessment of BIORADAR's target bio-products.

The selected general indicator —applicable to any industry— is the **(13) Circular Index – CirculAbility Model** (Enel, 2018). It is composed by two variables: circular flow (CF), and circular use (CU).

- **The circular flow** "measures the circularity in the use of resources" (Enel, 2018) by considering the weight of not sustainable inputs on total inputs (i.e., including inputs from recycling, reuse, and both material and energy renewable sources), and the weight of waste that goes to final disposition (i.e., including outputs sent to recycling, reuse).
- **The circular use** "considers the solutions adopted to increase the load factor of an asset" (Enel, 2018), and is comprised by factors accounting for extended useful life (as a result of design or maintenance activities), the standard useful

life, the time of use of a product in case of sharing, in 'service as a product' case, and in the 'business as usual' case.

It is a holistic approach to the circularity of the product that considers plenty of cases and aspects, from material sourcing, recycling potential, (renewable) energy use, end of life of the products, and other circular activities such as sharing, repairing, and product-as-a-service business models.

The indicator selected for the fertiliser products is the **(9) Circular Indicator of Nutrient (CIN)** developed by Cobo et al. (2019) which is defined as the amount of a nutrient that prolongs its lifetime by providing a service in the upstream processes as a proportion of the total amount of that nutrient in the collected waste (Cobo et al., 2018).

To do so, the indicator hinges on measuring the amount of nutrient present in the waste stream, the amount of nutrient that enters the recycling or preparation for reuse process, and the efficiency of both the recycling or preparation for reuse process and the production process that 'incorporates' the recovered nutrient into a product.

It therefore follows the same scheme of all the indicators found (of relating the amount of nutrient recovered with the total amount of nutrient originally available), but including the recycling/recovery processes efficiency, which allows to highlight this aspect and identify potential efficiency losses.

For textile, the selected indicator is the **(10) Resource Pressure (RP)**, which was designed by Desing et al. (2021) and used by Lama et al. (2022) in the carpet industry, but that can be extrapolated to all the textile sector. It considers six design parameters, namely mass in product, product lifetime, manufacturing losses, primary material content (i.e., materials coming from direct extraction), recyclability, and cascadability (the ability of a material that cannot be used for the same function after being recycled, to serve as an input to another product function with a lower quality level) (Desing et al., 2021).

Regarding packaging, the selected indicator is the **(16) Recycling Effectiveness (RE)** postulated by (Roithner & Rechberger, 2020). Like other indicators, it aims to capture the amount of material recovered as a fraction of the total material present in the stream. Nevertheless, the RE indicator does so by resorting to statistical entropy, as a mean to model the efficiency of the recycling process. Entropy, in turn, is calculated based on the mass flow, and the concentration of the target material, and related to the maximum statistical entropy estimated by modelling the best-case scenario.

Identified gaps

The screening process shed light on different gaps. About general C-indicators, it is worth noting that out of five indicators, four included the material sourcing, and three the recycling potential and the lifetime. This reflects the **material circularity bias, in which the main aspects considered are the origin of the materials and its recyclability, neglecting other aspects such as the quality, the efficiency, and the lifetime of the product**.

The biases are even more clear in the fertiliser and packaging indicators, where all of the indicators that came out the screening comprised the same aspect: (nutrient) recovery in fertilisers, and (target material) recovery in packaging. When talking about material recovery **in packaging, it is mostly based on producing packaging materials from secondary raw materials (e.g., post-consumer plastic, cardboard, etc.) but does not capture the production of packaging materials from primary biological sources, as is the case for bio-polyethylene produced from sugar cane.**

In fertilisers, the five "runner-up" indicators capture the same aspect: the recovery of nutrients. They do so by dividing the amount of recovered nutrient by the total amount of nutrient in the waste stream. The differences are mostly on the way the model this aspect, with the only nuance of the Circularity Indicator of Nutrient (CIN), which incorporates the recovery efficiency in the calculation.

Other areas are not fully assessed through these indicators, being the most relevant the fact **that materials lose quality upon each recycling step** (for textile and recycled packaging materials), or the **speed of nutrient release** for fertilisers (linked to the "slow the loop" principle of circular economy), as well as the **material and energy efficiency** in all the cases.

Moreover, additional considerations are needed for including circular bioeconomy aspects within a measurement framework. For instance, Navare et al. (2021) specified characteristics of biological cycles that are not addressed by existing monitoring systems like renewability, potential for cascading use of material, and closing the nutrient cycle.

Bos & Broeze (2020) also highlights four "cycles" that are undermonitored by currently available frameworks specifically for the agro-food system: (1) soil carbon through management and improved use of side-streams, (2) livestock production and circular nutrient management, (3) replacement of fossil sources by renewables, valorisation of side stream and recapturing carbon and nutrients after consumption of food, materials and energy, and (4) carbon capture in materials, reuse, refurbish, and recycle.

All these gaps both identified through the research and from scientific literature are the first aspects that the following tasks of the project will aim to bridge.

6. NEXT STEPS

Following the logic of the project, after mapping and identifying currently available indicators, which allowed to pinpoint the gaps and areas requiring further development, the upcoming efforts will be devoted to bridging them. **The aim will therefore be to produce a comprehensive measurement framework that can provide a more holistic and comprehensive picture of the circularity level of the target products**, designed to be used in conjunction with other sustainability indicators (i.e., life cycle assessment, life cycle costing, and social LCA).

It is to be highlighted the transitional aspect of this effort, as the subject are either emerging or evolving industries that are aiming to become more circular, more sustainable, more efficient, and more profitable in order to displace linear- and fossil-based economic activities within the context of the economic transition that is taking place driven by climate change and regulatory changes.

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8. SUPPLEMENTARY MATERIAL

Table 8: Final scientific publications portfolio

Title	Year	Journal	Author(s)	DOI
Circularity of Brazilian silk: Promoting a circular bioeconomy in the production of silk cocoons	*2021*	*Journal of environmental management*	*Barcelos, SMBD and Salvador, R and Barros, MV and de Francisco, AC and Guedes, G*	*10.1016/j.jenvman.2021.113373*
Coupling material circularity indicators and life cycle-based indicators: A proposal to advance the assessment of circular economy strategies at the product level	*2019*	*Resources conservation and recycling*	*Niero, M and Kalbar, PP*	*10.1016/j.resconrec.2018.10.002*
Material flow analysis of forest biomass in Portugal to support a circular bioeconomy	*2021*	*Resources conservation and recycling*	*Goncalves, M and Freire, F and Garcia, R*	*10.1016/j.resconrec.2021.105507*
Cost-Normalized Circular Economy Indicator and Its Application to Post-Consumer Plastic Packaging Waste	*2021*	*Polymers*	*Tashkeel, R and Rajarathnam, GP and Wan, WL and Soltani, B and Abbas, A*	*10.3390/polym13203456*
Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases	*2020*	*Journal of cleaner production*	*Rossi, E and Bertassini, AC and Ferreira, CD and do Amaral, WAN and Ometto, AR*	*10.1016/j.jclepro.2019.119137*
Comparing a material circularity indicator to life cycle assessment: The case of a three-layer plastic packaging	*2022*	*Sustainable production and consumption*	*Vadoudi, K and Deckers, P and Demuytere, C and Askanian, H and Verney, V*	*10.1016/j.spc.2022.08.004*
Combining LCA and circularity assessments in complex production systems: the case of urban agriculture	*2021*	*Resources conservation and recycling*	*Rufi-Salis, M and Petit-Boix, A and Villalba, G and Gabarrell, X and Leipold, S*	*10.1016/j.resconrec.2020.105359*
Keep circularity meaningful, inclusive and practical: A view into the plastics value chain	*2023*	*Waste management*	*Cimpan, C and Iacovidou, E and Rigamonti, L and van Velzen, EUT*	*10.1016/j.wasman.2023.04.049*
Circularity measurement of external resource flows in companies: The circular flow tool	*2023*	*Waste management*	*Barros, MV and Salvador, R and Gallego-Schmid, A and Piekarski, CM*	*10.1016/j.wasman.2023.01.001*

Analysis of Textile Circularity Potential	*2023*	*Environmental and climate technologies*	*Valtere, M and Bezrucko, T and Blumberga, D*	*10.2478/rtuect-2023-0017*
Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector	*2022*	*Journal of environmental management*	*Preisner, M and Smol, M and Horttanainen, M and Deviatkin, I and Havukainen, J and Klavins, M and Ozola-Davidane, R and Kruopiene, J and Szatkowska, B and Appels, L and Houtmeyers, S and Roosalu, K*	*10.1016/j.jenvman.2021.114261*
A Multi-level Resource Circularity Index based in the European Union's Circular Economy Monitoring Framework	*2023*	*Waste and biomass valorization*	*de Souza, VM and Frohling, M and Pigosso, DCA*	*10.1007/s12649-023-02193-6*
Impact of water as raw material on material circularity - A case study from the Hungarian food sector	*2023*	*Heliyon*	*H-Hargitai, R and Somogyi, V*	*10.1016/j.heliyon.2023.e17587*
Circularity indicators and added value to traditional LCA impact categories: example of pig production	*2023*	*International journal of life cycle assessment*	*Moller, H and Lyng, KA and Roos, E and Samsonstuen, S and Olsen, HF*	*10.1007/s11367-023-02150-4*
Exploring the effectiveness of grey literature indicators and life cycle assessment in assessing circular economy at the micro level: a comparative analysis	*2021*	*International journal of life cycle assessment*	*Lindgreen, ER and Mondello, G and Salomone, R and Lanuzza, F and Saija, G*	*10.1007/s11367-021-01972-4*
Circular economy indicators for measuring social innovation in the Brazilian textile and fashion industry	*2022*	*Journal of cleaner production*	*Galatti, LG and Baruque-Ramos, J*	*10.1016/j.jclepro.2022.132485*
Process performance evaluation of faecal matter treatment via black soldier fly	*2023*	*Journal of water sanitation and hygiene for development*	*Oyoo, V and Riungu, JN and Dey, P and Kirimi, JG and Matheka, RM*	*10.2166/washdev.2023.010*
Definition of agronomic circular economy metrics and use for assessment for a nanofertilizer case study	*2023*	*Plant physiology and biochemistry*	*Escriba-Gelonch, M and Butler, GD and Goswami, A and Tran, NN and Hessel, V*	*10.1016/j.plaphy.2023.02.042*

Application of circular economy principles to pastoral farming: development of an assessment framework	*2022*	*Animal production science*	*Burggraaf, VT and Mazzetto, AM and Romera, AJ and Mercer, GJK and Ledgard, SF*	*10.1071/AN21167*
Sunflower Residues-Based Biorefinery: Circular Economy Indicators	*2023*	*Processes*	*Havrysh, V and Kalinichenko, A and Pysarenko, P and Samojlik, M*	*10.3390/pr11020630*
Circular Economy Concept at the Micro-Level: A Case Study of Taruna Mukti Farmer Group, Bandung Regency, West Java, Indonesia	*2023*	*Agriculture-basel*	*Latif, A and Cahyandito, MF and Utama, GL*	*10.3390/agriculture13030539*
The circular economy in the textile and apparel industry: A systematic literature review	*2020*	*Journal of cleaner production*	*Jia, F and Yin, SY and Chen, LJ and Chen, XW*	*10.1016/j.jclepro.2020.120728*
Circular Economy Sustainability Analysis Framework for Plastics: Application for Poly(ethylene Terephthalate) (PET)	*2023*	*Acs sustainable chemistry & engineering*	*Gracida-Alvarez, UR and Xu, H and Benavides, PT and Wang, MC and Hawkins, TR*	*10.1021/acssuschemeng.2c04626*
Design of Indicators of Circular Economy as Instruments for the Evaluation of Sustainability and Efficiency in Wastewater from Pig Farming Industry	*2017*	*Water*	*Molina-Moreno, V and Leyva-Diaz, JC and Llorens-Montes, FJ and Cortes-Garcia, FJ*	*10.3390/w9090653*
Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment	*2019*	*Sustainability*	*Pauer, E and Wohner, B and Heinrich, V and Tacker, M*	*10.3390/su11030925*
Improvement of Packaging Circularity through the Application of Reusable Beverage Cup Reuse Models at Outdoor Festivals and Events	*2021*	*Sustainability*	*Suskevice, V and Kruopiene, J*	*10.3390/su13010247*

Circular Economy in Basic Supply: Framing the Approach for the Water and Food Sectors of the Gulf Cooperation Council Countries	*2021*	*Sustainable production and consumption*	*Al-Saidi, M and Das, P and Saadaoui,*	*10.1016/j.spc.2021.03.004*
Linking LCA literature with circular economy value creation: A review on beverage packaging	*2021*	*Science of the total environment*	*Sazdovski, I and Bala, A and Fullana-i-Palmer, P*	*10.1016/j.scitotenv.2021.145322*
A dynamic capabilities perspective on implementing the Circular Transition Indicators: A case study of a multi-national packaging company	*2023*	*Corporate social responsibility and environmental management*	*Walker, AM and Simboli, A and Vermeulen, WJV and Raggi, A*	*10.1002/csr.2487*
Municipal solid waste management in a circular economy: A data-driven bibliometric analysis	*2020*	*Journal of cleaner production*	*Tsai, FM and Bui, TD and Tseng, ML and Lim, MK and Hu, JY*	*10.1016/j.jclepro.2020.124132*
A Framework to Assess Manufacturers' Circular Economy Readiness Level in Developing Countries: An Application Case in a Serbian Packaging Company	*2023*	*Sustainability*	*Demko-Rihter, J and Sassanelli, C and Pantelic, M and Anisic, Z*	*10.3390/su15086982*
Economics of Enhancing Nutrient Circularity in an Organic Waste Valorization System	*2019*	*Environmental science & technology*	*Cobo, S and Levis, JW and Dominguez-Ramos, A and Irabien, A*	*10.1021/acs.est.8b06035*
Aiding the Design of Innovative and Sustainable Food Packaging: Integrating Techno-Environmental and Circular Economy Criteria	*2019*	*Proceedings of the 2nd international conference on sustainable energy and resource use in food chains including workshop on energy recovery conversion and management; icsef 2018*	*Rivera, XCS and Leadley, C and Potter, L and Azapagic, A*	*10.1016/j.egypro.2019.02.081*

Using LCA and Circularity Indicators to Measure the Sustainability of Textiles-Examples of Renewable and Non-Renewable Fibres	*2022*	*Sustainability*	*Wiedemann, SG and Nguyen, QV and Clarke, SJ*	*10.3390/su142416683*
Recirculation potential of post-consumer /industrial bio-based plastics through mechanical recycling - Techno-economic sustainability criteria and indicators	*2021*	*Polymer degradation and stability*	*Briassoulis, D and Pikasi, A and Hiskakis, M*	*10.1016/j.polymdegradstab.2020.109217*
Circular economy in the agro-industry: Integrated environmental assessment of dairy products	*2021*	*Renewable & sustainable energy reviews*	*Oliveira, M and Cocozza, A and Zucaro, A and Santagata, R and Ulgiati, S*	*10.1016/j.rser.2021.111314*
Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management	*2021*	*Journal of cleaner production*	*Rashid, MI and Shahzad, K*	*10.1016/j.jclepro.2021.128467*
Technical Limits in Circularity for Plastic Packages	*2020*	*Sustainability*	*Brouwer, MT and van Velzen, EUT and Ragaert, K and ten Klooster, R*	*10.3390/su122310021*
Detailed nitrogen and phosphorus flow analysis, nutrient use efficiency and circularity in the agri-food system of a livestock-intensive region	*2023*	*Journal of cleaner production*	*Vingerhoets, R and Spiller, M and De Backer, J and Adriaens, A and Vlaeminck, SE and Vlaeminck, E and Meers, E*	*10.1016/j.jclepro.2023.137278*
Introducing the Green Protein Footprint method as an understandable measure of the environmental cost of anchovy consumption	*2018*	*Science of the total environment*	*Laso, J and Margallo, M and Serrano, M and Vazquez-Rowe, I and Avadi, A and Fullana, P and Bala, A and Gazulla, C and Irabien, A and Aldaco, R*	*10.1016/j.scitotenv.2017.11.148*
Implementing the dimension of quality into the conventional quantitative definition of recycling rates	*2020*	*Waste management*	*Roithner, C and Rechberger, H*	*10.1016/j.wasman.2020.02.034*

Organic recycling of post-consumer/industrial bio-based plastics through industrial aerobic composting and anaerobic digestion - Techno-economic sustainability criteria and indicators	*2021*	*Polymer degradation and stability*	*Briassoulis, D and Pikasi, A and Hiskakis, M*	*10.1016/j.polymdegradstab.2021.109642*
Evaluation of the fertiliser replacement value of phosphorus-saturated filter media	*2021*	*Journal of cleaner production*	*Arenas-Montano, V and Fenton, O and Moore, B and Healy, MG*	*10.1016/j.jclepro.2021.125943*
Quality model for recycled plastics (QMRP): An indicator for holistic and consistent quality assessment of recycled plastics using product functionality and material properties	*2022*	*Journal of cleaner production*	*Golkaram, M and Mehta, R and Taveau, M and Schwarz, A and Gankema, H and Urbanus, JH and De Simon, L and Cakir-Benthem, S and van Harmelen, T*	*10.1016/j.jclepro.2022.132311*
EnvPack an LCA-based tool for environmental assessment of packaging chains. Part 1: scope, methods and inventory of tool	*2019*	*International journal of life cycle assessment*	*Ligthart, TN and van Velzen, EUT and Brouwer, M*	*10.1007/s11367-018-1530-0*
Closing the loop: A case study on pathways for promoting sustainable waste management on university campuses	*2023*	*Science of the total environment*	*Jakimiuk, A and Matsui, Y and Podlasek, A and Koda, E and Goli, VSNS and Voberkova, S and Singh, DN and Vaverkova, MD*	*10.1016/j.scitotenv.2023.164349*
Environmental and economic assessment of CO2-based value chains for a circular carbon use in consumer products	*2022*	*Resources conservation and recycling*	*Kaiser, S and Gold, S and Bringezu, S*	*10.1016/j.resconrec.2022.106422*
Life Cycle Assessment of Reusable Plastic Crates (RPCs)	*2019*	*Resources-basel*	*Tua, C and Biganzoli, L and Grosso, M and Rigamonti, L*	*10.3390/resources8020110*
Proposal of Package-to-Product Indicator for Carbon Footprint Assessment with Focus on the Czech Republic	*2020*	*Sustainability*	*Seresova, M and Kaci, V*	*10.3390/su12073034*
Reinventing refills: guidelines for design	*2017*	*Packaging technology and science*	*Lofthouse, V and Trimingham, R and Bhamra, T*	*10.1002/pts.2337*

Quantifying the Separation Complexity of Mixed Plastic Waste Streams with Statistical Entropy: A Plastic Packaging Waste Case Study in Belgium	*2021*	*Acs sustainable chemistry & engineering*	*Nimmegeers, P and Billen, P*	*10.1021/acssuschemeng.1c02404*
Operational Framework to Quantify "Quality of Recycling" across Different Material Types	*2023*	*Environmental science & technology*	*Roosen, M and Tonini, D and Albizzati, PF and Caro, D and Cristobal, J and Lase, IS and Ragaert, K and Dumoulin, A and De Meester, S*	*10.1021/acs.est.3c03023*
A Socio-economic Indicator for EoL Strategies for Bio-based Products	*2020*	*Ecological economics*	*D'Adamo, I and Falcone, PM and Imbert, E and Morone, P*	*10.1016/j.ecolecon.2020.106794*
Addressing the complex challenge of understanding and quantifying substitutability for recycled plastics	*2021*	*Resources conservation and recycling*	*Demets, R and Van Kets, K and Huysveld, S and Dewulf, J and De Meester, S and Ragaert, K*	*10.1016/j.resconrec.2021.105826*
Comprehensive emergy evaluation and optimization of corn straw power generation system: a case study	*2019*	*Chinese journal of population resources and environment*	*Wang, QS and Gao, ZL and Yuan, XL and Wang, JT and Wang, MS*	*10.1080/10042857.2019.1610652*
What material flow analysis and life cycle assessment reveal about plastic polymer production and recycling in South Africa	*2022*	*South african journal of science*	*Goga, T and Harding, K and Russo, V and Von Blottnitz, H*	*10.17159/sajs.2022/12522*
Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: An appraisal of big data from commercial farms	*2021*	*Field crops research*	*Silva, JV and Van Ittersum, MK and Ten Berge, HFM and Spatjens, L and Tenreiro, TR and Anten, NPR and Reidsma, P*	*10.1016/j.fcr.2021.108176*
Material flow analysis and recycling performance of an improved mechanical recycling process for post-consumer flexible plastics	*2022*	*Waste management*	*Lase, IS and Bashirgonbadi, A and van Rhijn, F and Dewulf, J and Ragaert, K and Delva, L and Roosen, M and Brandsma, M and Langen, M and De Meester, S*	*10.1016/j.wasman.2022.09.002*

Toward sustainable crop production in China: An emergy-based evaluation	*2019*	*Journal of cleaner production*	*Liu, ZX and Wang, YY and Geng, Y and Li, RD and Dong, HJ and Xue, B and Yang, TH and Wang, SS*	*10.1016/j.jclepro.2018.09.183*
Comparative LCA study of different methods of the feed phosphates (FPs) production	*2019*	*Journal of cleaner production*	*Smol, M and Kowalski, Z and Makara, A and Henclik, A*	*10.1016/j.jclepro.2019.117963*
Proposed Green Development Reporting Framework for Enterprises from a Life-Cycle Perspective and a Case Study in China	*2019*	*Sustainability*	*Ding, N and Ruan, XH and Yang, JX*	*10.3390/su11236856*
An Integrated Industry-Based Methodology to Unlock Full-Scale Implementation of Phosphorus Recovery Technology	*2020*	*Sustainability*	*Bianchini, A and Rossi, J*	*10.3390/su122410632*
Circularity measurement of external resource flows in companies: The circular flow tool	*2023*	*Waste management*	*Vetroni Barros, M., Salvador, R., Gallego-Schmid, A., Moro Piekarski, C.*	*10.1016/j.wasman.2023.01.001*
Assessment of the Eco-Efficiency of the Circular Economy in the Recovery of Cellulose from the Shredding of Textile Waste	*2022*	*Polymers*	*De Oliveira Neto, G.C., Teixeira, M.M., Souza, G.L.V., Arns, V.D., Tucci, H.N.P., Amorim, M.*	*10.3390/polym14071317*
Measuring product-level circularity performance: An economic value-based metric with the indicator of residual value	*2022*	*Resources, conservation and recycling*	*Jiang, L., Bhochhibhoya, S., Slot N., de Graaf, R.*	*10.1016/j.resconrec.2022.106541*
Towards a new supply chain manager dashboard under circular economy constraints: A case study on France textile and clothing industry	*2023*	*Business strategy and the environment*	*Hrouga, M., Michel, S.*	*10.1002/bse.3473*

Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions	*2018*	*Journal of cleaner production*	*Huysveld, S., Hubo, S., Ragaert, K., Dewulf, J.*	*10.1016/j.jclepro.2018.11.110*
Environmental impacts in the textile sector: A Life Cycle Assessment Case Study of a Woolen Undershirt	*2023*	*Sustainability*	*Bianco, I., De Bona, A., Zanetti, M., Panepinto, D.*	*10.3390/su151511666*
Resource pressure of carpets: Guiding their circular design	*2022*	*Sustainability*	*Lama, V., Righi, S., Quandt, B.M., Hischier, R., Desing, H.*	*10.3390/su14052530*
Integrating LCA and blockchain technology to promote circular fashion - A case study of leather handbags	*2022*	*Journal of cleaner production*	*Shou, M., Domenech, T.*	*10.1016/j.jclepro.2022.133557*
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Table 9: BIORADAR C-indicators database with tags

Nr.	Name	Source	Tags
1	Material Reutilization Score	Cradle to Cradle Products Innovation Institute (2016)	General, Recyclability, Recycled input, Relative value
2	Material Circularity Indicator	Ellen McArthur Foundation & Ansys Granta (2019)	Benchmarked against the linear option, End of Life processes, General, MCI-based, Product life time, Recyclability, Recycled input, Relative value
3	Cost-weighted-average MCI	Tashkeel et al. (2021)	Economic input, General, MCI-based, Relative value
4	MCI coupled with LCA	Rufí-Salís et al. (2021)	General, LCA-based, MCI-based, Relative value
5	MCI based on economic and residual value	Jiang et al. (2022)	Economic input, General, MCI-based, Relative value
6	Nutrient Removal Efficiency Indicator	Preisner et al. (2022)	Fertilizers, Recycled input, Relative value
7	Nitrogen Recycling Index	Moller et al. (2023)	Fertilizers, Recycled input, Relative value
8	Circular Material Use Rate	Havrysh et al. (2023)	General, Recycled input, Relative value
9	Circularity Indicator of Nutrient	Cobo et al. (2019)	Efficiency, Fertilizers, Relative value
10	Resource Pressure	Desing et al. (2021)	Efficiency, Product life time, Relative value, Textile
11	Material Durability Indicator	Mesa, González-Quiroga, & Maury (2020)	Absolute value, LCA-based, Packaging, Product life time
12	In-use occupation of materials	Moraga et al. (2021)	Absolute value, General, Product life time
13	Circular Index – CirculAbility model	Enel (2018)	Absolute value, End of Life processes, Energy, Environmental impact, General, Product life time, Recycled input, Relative value
14	Indicators of circular economy for biofertilizer	Molina-Montero et al. (2017)	Fertilizers, Recycled input, Relative value
15	Green Protein Food Index	Laso et al. (2018)	Benchmarked against the linear option, Fertilizers, LCA-based, Relative value

16	Recycling Effectiveness	Roithner& Rechberger (2020)	Efficiency, Entropy, Packaging, Relative value
17	Quality Model for Recycled Plastics	Golkaram et al. (2022)	End of Life processes, Packaging, Recyclability, Relative value
18	Quality of Recycling Framework	Roosen et al. (2023)	Absolute value, Economic input, End of Life processes, Environmental impact, General, Product life time
19	Emergy	Wang et al. (2019)	Absolute value, Energy, General
20	Nitrogen Use Efficiency	Silva et al. (2021)	Efficiency, Fertilizers, Relative value
21	Circularity Index (CI) for textiles	(De Oliveira Neto et al., 2022)	Benchmarked against the linear option, Economic input, Environmental impact, Relative value, Textile
22	Circular Economy Index	Di Maio & Rem (2015)	Economic input, General, Recyclability, Relative value
23	Circular Economy Performance Indicator	Huysman et al. (2017)	End of Life processes, Energy, Environmental impact, General, LCA-based, Recyclability, Relative value
24	Circularity Index	Cullen (2017)	Efficiency, Energy, General, Relative value
25	Product-level circularity metric	Linder et al. (2017)	Economic input, General, Relative value
26	Process yield / Net recovery	Lase et al. (2022)	Efficiency, Packaging, Recycled input, Relative value
27	Quality indicator	Lase et al. (2022)	Efficiency, Packaging, Relative value
28	Cyclical Use Rate Indicator	Ministry of Environment of Japan (2003)	General, Recycled input, Relative value
29	Longevity Factor	Figge et al. (2018)	Absolute value, Benchmarked against the linear option, General, Product life time