



Deliverable D4.1. Critical evaluation of circularity assessment methods & indicators

August 2024

Cristian Pérez Hernández, Pieter Nachtergaele



Document Information

Work package and deliverable number WP4, Deliverable D4.1

Authors Cristian Pérez Hernández, Pieter Nachtergaele

Involved organisations UGENT

Reviewers ESCIB Consortium

Document date/version Final version

Project Information

Project acronym ESCIB

Project title: Developing environmental sustainability & circularity assessment methodologies for industrial bio-based systems

Project number: 101135071

Coordinator WIP Renewable Energies

Project website www.escib.eu

Start date: 1 January 2024

Duration: 48 months

Dissemination level of this document

Public

Sensitive

Disclaimer



The ESCIB project has received funding from the European Union's Horizon Europe Framework Programme under grant agreement No.101135071.

The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

ACKNOWLEDGMENT & DISCLAIMER

The ESCIB project has received funding from the European Union's Horizon Europe Framework Programme under grant agreement No.101135071.

The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Reproduction is authorised provided the source is acknowledged.

EXECUTIVE SUMMARY

This deliverable represents the efforts under Task 4.1 on ESCIB's WP4, which focuses on the identification and selection of circularity indicators, sets of indicators and tools to assess circularity via a critical review of the state-of-the-art. The overarching goal of WP4 is to enhance existing metrics or develop new ones tailored to industrial bio-based systems. This includes considering the cascading approach to biomass use, resource efficiency, and renewable sourcing of biomass, all considered in a life-cycle perspective. Additionally, the project aims to eventually develop or adapt circularity metrics for application in low TRL bio-based systems

Bio-based products present specific characteristics that make assessing circularity at the micro (product/company) level particularly challenging, such as their renewable origin, the potential cascades in value that bio-based materials present and the potential of nutrient recovery to close the overarching biological cycle, merging circularity and sustainability approaches in one. The circular bioeconomy (CBE) integrates the principles of the circular economy (CE) in the bioeconomy (BE). This deliverable aims to critically review and evaluate indicators, sets of indicators and tools applicable to bio-based product systems (BBPS). First, a comprehensive bio-based systems flowchart is proposed, illustrating the complex and interconnected nature of flows within bio-based systems. Secondly, this deliverable compiles a practical and comprehensive list of 73 Circularity Assessment Indicators (CAIs) applicable to bio-based systems at the micro level for use by researchers and practitioners. Each CAI is evaluated against a wide range of key characteristics to identify gaps, challenges, and opportunities in current practices: sector-specificity, complexity, implementation level, dimensionality, application, measured flow type, functional value measurement, sustainability-related inputs, energy and utilities coverage, criticality coverage, biotic and abiotic material differentiation, bio-based flowchart regions coverage, flow perspective, and Circular Economy Strategies (CES) assessed for each CAI. This evaluation led to a curated shorter list of 34 CAIs that meet all key characteristics, ultimately providing a balanced, concise, yet complete and practical list of CAIs.

The results of the CAI analysis highlight that key BBPS characteristics such as renewable sourcing, cascading in value and nutrient recovery are often neglected when assessing circularity in bio-based products, especially the latter two, with less than 15 CAIs covering these essential aspects. Furthermore, the majority of CAIs (44) do not differentiate between biotic and abiotic materials, treating all materials uniformly in their assessments. 17 CAIs account exclusively for biotic materials, being these CAIs focused solely on BBPS. It is concluded that a properly representative assessment of a BBPS would need the implementation of CAIs that include both abiotic and biotic materials, highlighting the particular benefits of using bio-based materials by improving the metric value. In this respect, 12 CAIs make a clear distinction between biotic and abiotic materials, allowing for more tailored assessments that consider such particular characteristics in different ways. Additionally, there is a need for more CAIs that cover functional value beyond just material flow, with only 4 indicators that cover this as the main reference of value for the CAI.

By addressing all the abovementioned gaps, this deliverable aims to set the foundations of the future work in ESCIB, particularly in WP4, to kick off the developments of innovative circularity assessments in bio-based systems, contributing to the advancement of CE principles to BBPS and fostering sustainability and circularity together as one of the core objectives of ESCIB.

Table of contents

1	Introduction	1
1.1	Background on Circular Economy	1
1.1.1	Circular Economy at the macro level.....	1
1.1.2	CE at the meso and micro level	1
1.2	Bioeconomy	3
1.2.1	Bio-based industries	3
1.2.2	Circular Bioeconomy and the particularities of the biological cycle	4
1.3	Circularity assessment for bio-based product systems (BBPS)	5
1.3.1	Product circularity assessment.....	5
1.3.2	CAIs for bio-based product systems	7
1.4	Deliverable Objectives	7
2	Materials and methods	8
2.1	Systematic literature review	8
2.2	Development of the bio-based systems flowchart	9
2.3	Key criteria assessed at the paper level	9
2.4	Key characteristics assessed at the CAI level	10
2.5	Elaboration of the short list of CAIs	12
3	Results and discussion.....	14
3.1	Bio-based systems flowchart	14
3.1.1	Regions of the Bio-based Systems Flowchart.....	14
3.2	Paper-level analysis.....	17
3.3	CAI-level analysis.....	18
3.3.1	CAI Characteristics and Application.....	18
3.3.2	Flows and functional value.....	19
3.3.3	Sustainability and Criticality	20
3.3.4	Biogenic carbon coverage	21
3.3.5	Bio-based flowchart flows	24
3.3.6	Circular Economy Strategies (CES)	25
3.4	CAI-level analysis: Shortlist of CAIs	27
4	Conclusions	30
5	References.....	31

Glossary

BBPS	Bio-based Product Systems
CAI	Circularity Assessment Indicator
CBE	Circular Bioeconomy
CE	Circular Economy
CEAP	Circular Economy Action Plan
CEP	Circular Economy Principle
CES	Circular Economy Strategy
CPA	European Statistical Classification of Products by Activity
CRM	Critical Raw Material
EC	European Commission
EMF	Ellen MacArthur Foundation
EOL	End-of-life
EOU	End-of-use
EU	European Union
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
OECD	Organisation for Economic Co-operation and Development
SDG	Sustainable Development Goals
UN	United Nations
VRP	Value-retention process

1 Introduction

1.1 Background on Circular Economy

1.1.1 Circular Economy at the macro level

The concept of circular economy (CE) has become increasingly popular as a more sustainable alternative to the traditional linear economy model. It is one of the key sustainability drivers formulated in the past decade, with a growing community of researchers and practitioners (Kirchherr et al., 2023). Major inter-governmental and institutional actors such as the United Nations (UN), the Organisation for Economic Co-operation and Development (OECD), and the European Union (EU) have had a key role in defining and advancing CE principles (CEPs) at the macro (national and international) level (EC, 2020; Joanicjusz Nazarko et al., 2022; OECD, 2024; Yang et al., 2023). According to many relevant actors in the CE at the European level, including the EC and the EMF, the CE is based on three CEPs:

- CEP1. Minimising virgin inputs to the economy.
- CEP2. Circulating products and materials, at their highest value.
- CEP3. Minimising outputs from the economy.

The UN also emphasises the CE as a needed economic system for achieving its Sustainable Development Goals (SDGs), highlighting the importance of responsible consumption and production patterns, which align closely with the CEPs. The UN Environment Programme reports the potential of circular practices to significantly reduce greenhouse gas emissions and material usage. These so-called value-retention processes (VRPs) are presented as vital strategies for businesses aiming to enhance sustainability and economic efficiency in what they consider the “manufacturing revolution” (UN Environmental Programme, 2018).

The OECD has also been active in monitoring progress towards a resource-efficient CE. In its 2024 report, the OECD outlines various indicators and frameworks to track CE advancements and encourages member countries to adopt policies that foster circular practices. This includes enhancing product longevity, improving recycling rates, and reducing waste generation (OECD, 2024).

The EU’s strategy on CE is the Circular Economy Action Plan (CEAP), launched in 2015 and updated in 2020 (EC, 2020), which serves as a broad strategy to implement the CE principles across the EU. The CEAP focuses on promoting sustainable product design, reducing waste, and increasing market demand for secondary raw materials. Notable initiatives under this plan include the Sustainable Products Initiative, which aims to broaden the scope of the Eco-design Directive, and specific measures to enhance circularity in the listed key sectors, such as electronic, plastic, and textile industries (EC, 2022, 2020).

1.1.2 CE at the meso and micro level

The delineation of the different implementation scales for circularity, particularly concerning the meso and micro levels, is a debated topic in the literature (Erik Roos Lindgreen et al., 2020). Generally, the meso level is associated with eco-industrial parks and industrial symbiosis, while the micro level encompasses products, services, and organisations. (Ghisellini et al., 2016; Kirchherr et al., 2017; Moraga et al., 2019).

This document focuses on circularity at the micro level, more specifically at the bio-based product level. Product circularity strategies have already been implemented in many industries (Meath et al., 2022; Toni, 2023), with particular emphasis on strategies such as product lifetime extension, waste reduction, and resource efficiency to promote sustainable production practices. Although CE-related developments and their adoption have not been as extensive as anticipated in the current state-of-the-art (Upadhayay et al., 2024), the interdisciplinary nature of the CE model provides promising opportunities to

improve current production and consumption models (Ghisellini et al., 2016), with already visible benefits across the ecological, economic, and social frontiers (Siregar et al., 2023; van Zanten et al., 2023).

One of the primary limitations to the deployment of CE is the absence of a commonly agreed-upon definition, still persistent at both industry and policy levels (Stumpf et al., 2021). Multiple definitions have been proposed by both researchers and practitioners. Kirchherr et al. (2023) identified over 221 different definitions of CE, with diverse perspectives and approaches to implementing the CE principles. This multiplicity allows each actor to interpret CE in an individual manner rather than in a standardised way. Also, its connection with sustainability is not always clear (Kirchherr et al., 2017; Rohit Panchal et al., 2021; Saidani et al., 2019). The most widely accepted definition of CE, provided by the Ellen MacArthur Foundation (EMF), describes CE as a system designed to prevent materials from becoming waste and to restore natural ecosystems. This is achieved by maintaining the circulation of products and materials within the economy, while explicitly addressing climate change and other global issues, such as biodiversity loss, waste, and pollution, by decoupling economic growth from the consumption of finite resources (EMF, 2015). Furthermore, the recent release of the International Organisation for Standardisation (ISO) 59000 family of standards aims to establish a commonly agreed-upon definition, set of principles, and actionable guidelines for implementing CE. These standards also introduce a comprehensive circularity measurement taxonomy and a list of CAIs specifically designed for use at the micro level, including considerations for biological cycles. The provided list of CAIs is categorised into five groups: resource inflows, resource outflows, energy, water circularity, and economic circularity (ISO, 2024a, 2024b).

Some scholars align with the direct integration of sustainability within the definition of CE (Corona et al., 2019; Nobre & Tavares, 2021). Conversely, Geissdoerfer et al. (2017) identified eight different types of relationships between them in the literature, asserting that CE and sustainability describe different concepts and should not necessarily be linked, highlighting the existence of conditional, beneficial, and trade-off relationships between the application of CE strategies and their impacts on the economy, society, and the environment. Recognising these differences and interrelations, the CE can therefore be considered a tool to facilitate the ultimate goal of a sustainable economy at micro, meso, and macro levels instead of another dimension of sustainability. Understanding this may avoid pursuing "circularity for circularity's sake" (Harris et al., 2020). Figure 1.1 illustrates the two driving forces balancing the CE implementation at the product level: the drive to increase circularity (represented by the blue arrows) and the potential trade-offs affecting the sustainability dimensions (represented by the red arrows). The CE is depicted as a central system within the broader economy, showing how these forces interact to maintain a sustainable balance.

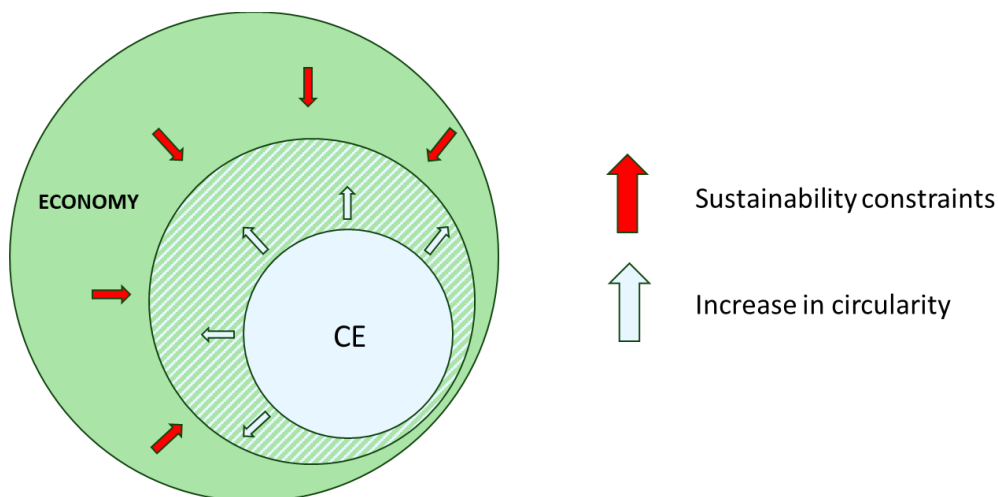


Figure 1.1. Balancing Forces in the Circular Economy

1.2 Bioeconomy

1.2.1 Bio-based industries

The bioeconomy (BE), as defined by the EC (2018), covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It therefore includes and interlinks all ecosystems and ecosystem services they provide; all primary production sectors that use and produce biological resources, and all economic and industrial sectors that use these to produce products and services. While biotechnology is at the heart of bio-based processes, health biotechnology and biological medicines are not included in this BE definition.

The objectives of the CE model are often linked to those of the BE as complementary policy strategies (EEA, 2018). At the European level, both CEAP and the European Bioeconomy Strategy share a common perspective on promoting circular applications to food waste, the use of biomass as feedstock in industry and the promotion of biobased products as areas of intervention (EC, 2018, 2020).

The broad definition of BE encompasses a wide range of economic sectors. This leaves the BE without a clear-cut list of industries or economic activities, given the different existing approaches to this relatively new phenomenon (Frivold et al., 2021). Muska et al. (2022) utilised the NACE classification of economic activities (EUROSTAT, 2022) to cluster the different industries that completely or can belong to BE, reporting sixteen industries into three groups according to the type of biomass generation or use: production of biomass, manufacture/use of biomass and production of bio-based electricity. **Error! Not a valid bookmark self-reference.** presents the proposed framework.

Table 1. Framework of Bio-based industries in line with the European classification of economic activities (NACE 2.1). Source: Muska et al. (2022).

Section	Industry	Type of industry
A	A01 Crop and animal production, hunting and related service activities	Biomass production
A	A02 Forestry and logging	Biomass production
A	A03 Fishing and aquaculture	Biomass production
D	D3511 Production of electricity	Biomass use only
C	C10 Manufacture of food	Biomass manufacturing only
C	C11 Manufacture of beverages	Biomass manufacturing only
C	C12 Manufacture of tobacco	Biomass manufacturing only
C	C15 Manufacture of leather and related products	Biomass manufacturing only
C	C16 Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	Biomass manufacturing only
C	C17 Manufacture of paper and paper products	Biomass manufacturing only
C	C13 Manufacture of textiles	Biomass manufacturing (possible)
C	C14 Manufacture of wearing apparel	Biomass manufacturing (possible)
C	C20 Manufacture of chemicals and chemical products	Biomass manufacturing (possible)
C	C21 Manufacture of basic pharmaceutical products and pharmaceutical preparations	Biomass manufacturing (possible)
C	C22 Manufacture of rubber and plastic products	Biomass manufacturing (possible)

Section	Industry	Type of industry
C	C31 Manufacture of furniture	Biomass manufacturing (possible)

1.2.2 Circular Bioeconomy and the particularities of the biological cycle

Building upon the concepts of BE and CE, the circular bioeconomy (CBE) represents an advanced and integrative approach to the sector that intertwines the principles of the CE with the BE in different ways. Stegmann et al. (2020) identified three common perspectives in literature that define CBE in terms of the relationships between BE and CE: (1) as the intersection of CE and BE, (2) as a larger concept encompassing both BE and CE, and (3) with CBE as a subset of CE (Figure 1.2).

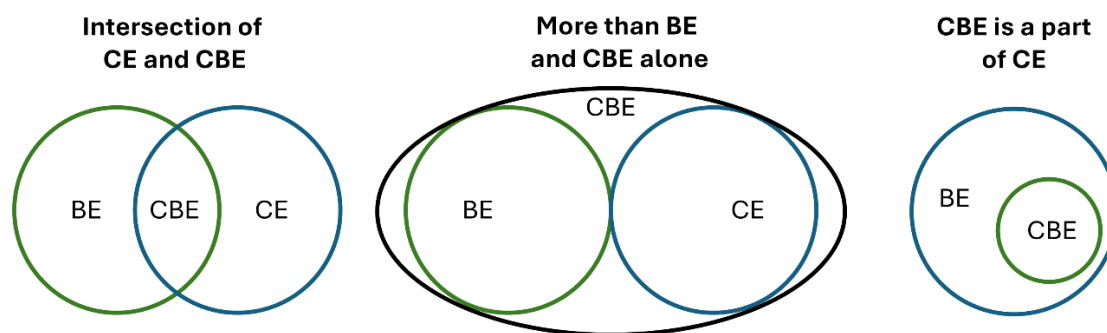


Figure 1.2. Perspectives on the CBE in relation to BE and CE. Adapted from Stegmann et al. (2020)

CBE is therefore, in one way or another, a combination of both CE and BE. Neither of these parent concepts have a universally accepted definition, which creates additional complexity in delineating what CBE represents (Kardung et al., 2021). Despite the differences in definition, common targets of both CE and BE are evident, such as the use of non-fossil inputs, the closure of the (biological) loop via (organic) recycling, and the cascading of products as key contributions of the BE to CE and vice versa (Carus & Dammer, 2018; Hetemäki et al., 2017; Navare et al., 2021). However, trade-offs exist within this framework. For instance, recycling biobased products is a better end-of-life option than landfilling from a resource efficiency perspective; yet, permanently storing (e.g., landfilling) biogenic non-biodegradable material leads to permanent carbon storage and thus provides climate benefits (Corona et al., 2022a).

Still, it is notable that the CE literature predominantly focuses on technical cycles, with an emphasis on actions that minimise imbalances within the technosphere by maintaining materials in use through recovery processes in technical cycles (Metic et al., 2021). The CBE extends these principles to bio-based resources, which present a characteristic nature: they can regenerate and return to the biosphere (Muscat et al., 2021; Navare et al., 2021; Vural Gursel et al., 2022). This regenerative capacity enables the withdrawal of dispersed matter from sinks that are inaccessible or hardly accessible in technical cycles, for instance, by capturing atmospheric carbon through photosynthesis to create new biomass. To fully achieve a transition toward a CBE, a deeper understanding of the role of bio-based resources within production systems and their contributions and impacts on other living and economic systems is essential (Muscat et al., 2021). Given these complexities, a representation of all potential flows that can take place in a bio-based system becomes highly relevant for the integration of the two concepts that the CBE concept joins together. There is a need for a clear and visual overview of the intricate interactions and pathways that biobased products may follow throughout their lifecycle, which would aid stakeholders in better understanding and agreeing on critical elements and processes that define circularity within the system.

Within the CBE field, carbon dynamics have received particular attention due to their role in environmental sustainability. According to the ISO (2017) standard 21930:2017, biogenic carbon refers to carbon that is originally sequestered by living organisms to produce biomass, such as plants and animals, as opposed to carbon from fossil sources or geological formations.

The key distinction between biogenic and fossil carbon lies in their respective cycles. Biogenic carbon is part of the natural carbon cycle, where carbon is absorbed from the atmosphere by living organisms through photosynthesis and released back into the atmosphere through natural or artificial decomposition, which leads to a need for accounting for biogenic carbon differently. However, there is no unified method for the calculation of credits from carbon sequestration (Corona et al., 2022; Navare et al., 2021; Sazdovski et al., 2024).

Beyond carbon, biodegradable products also offer opportunities to close the biological cycle of other essential nutrients, such as nitrogen, phosphorus, and sulphur, by enabling their recovery through processes like composting and anaerobic digestion (Fleitas Girett et al., 2023; Shaddel et al., 2019). These processes allow biodegradable products to break down naturally into non-toxic components, returning nutrients to the soil and supporting the regeneration of biological systems (Briassoulis et al., 2021a). Although the technical and biological cycles are often represented separately, as in the “butterfly” diagram from EMF (2019b), bio-based materials can participate in technical cycles Vural Gursel et al., 2022) as well as non-bio-based materials can take part in the biological cycle via biodegradation (Rosenboom et al., 2022).

Another characteristic that differentiates the circularity of bio-based from abiotic materials is their particular potential applications in cascades. This concept was originally formulated in the 1990s as a framework to optimise natural resource use (Sirkin & Houten, 1994) and gained momentum in the forestry sector (Keegan et al., 2013) motivated by the diverse range of products that can be derived from secondary biomass at different open-loop recirculation cascades. Jarre et al. (2020) developed a system-level analysis that identified different cascading approaches (in value, in function or in time) and identified several limitations in the implementation of wood cascading that can also be translated to other BBPS. Currently, the open-loop (OL) and closed-loop (CL) recirculation of bio-based products and materials is being studied and applied in multiple bio-based systems (Gursel et al., 2022; Navare et al., 2021; Olsson et al., 2018).

1.3 Circularity assessment for bio-based product systems (BBPS)

1.3.1 Product circularity assessment

Circularity assessment is the evaluation of how effectively a material, product, or system aligns with the CE principles. It implies the evaluation of how these maintain value, function, and resources within the economy (EMF, 2019a; ISO, 2024a). It therefore seeks to measure the degree to which linear resource flows are minimised. A growing body of literature has sought to operationalise these principles through measurable indicators that capture material, energy, and functional dimensions of circularity at various scales. For example, Ko et al. (2024) proposed a framework of circular product attributes, which describe desired features for a product with a focus on environmental and economic performance as a foundation for circularity assessment. These include: (1) the incorporation of value recovery strategies such as reuse, remanufacturing, and recycling; (2) lifecycle extension through durability, maintenance, and upgradability; (3) effective resource selection, prioritising renewable, recyclable, and safe materials; (4) closed-loop resource flow, reducing reliance on virgin inputs; (5) stakeholder collaboration and engagement to support transparent and coordinated value recovery; (6) the provision of environmental benefits through reduced emissions and resource use; (7) consideration of all lifecycle stages to ensure design coherence; and (8) the generation of economic benefits through resource efficiency and new business opportunities. While the framework provides a structured conceptual basis for defining circular product characteristics, it does not yet translate these attributes into measurable indicators or quantitative assessment tools. Numerous authors have explored different methods to organise an already existing and extensive list of indicators, sets of indicators, and tools used to assess circularity, drawing from both scientific and grey literature. Various taxonomies have been proposed in recent years, including those by Heidi Simone Kristensen et al. (2020), Mariana Cardoso Chripim et al. (2023), Moraga et al. (2019), Saidani et al. (2019), Baratsas et al. (2022), Erik Roos Lindgreen et al. (2020), Matos et al. (2023), Heidi Simone Kristensen et al. (2020) and Elia et al. (2017). Most studies conclude that the distribution of circularity indicators is uneven and that grouping CAIs by CEP coverage remains challenging. It is also remarkable that some aspects of circularity, such as recycling, have received much greater attention than others, such as lifetime extension, at a product assessment level. Understanding the many existing dimensions of circularity is crucial when using micro-level indicators to guide strategic decisions, as circularity assessment remains an

evolving field. In this work, a broad approach is taken to cover the different aspects identified in the reviewed literature, with the aim of providing a comprehensive understanding of the main clusters of indicators that will support the development of the ESCIB circularity assessment methodology.

Different terminology is often used in the literature to refer to similar concepts. In this work, circularity assessment indicators are distinguished into three main types based on their level of aggregation: single indicators, sets of indicators, and tools. Their definitions are presented below:

- **Indicator:** A single value (quantitative or qualitative factor) that assesses progress or change, considered the smallest unit of information that can be measured, as defined by Chrispim et al. (2023). The word “metric” and “index” are considered as synonyms of indicator in this document.
- **Set of indicators:** A Group of indicators that are used to assess a broader aspect of progress or change within a system, providing a multidimensional view of the system being evaluated, as formulated by Mesa et al. (2018).
- **Tool:** Online platform, software or any other digital application that enables the implementation of indicators or sets of indicators to assess and monitor one or multiple aspects of a system, as formulated by Verstraeten-Jochensen et al. (2018).

In this deliverable, multiple indicators, sets of indicators, and tools will be assessed. Due to their varied nature and terminology, they will collectively be referred to as **Circularity Assessment Indicators (CAIs)**.

One differential characteristic of circularity assessment at the product level lies in the use of complementary methodologies or software for its calculation. A commonly used methodology in CE research is Life Cycle Assessment (LCA) (Verstraeten-Jochensen et al., 2018), which is effective in providing a comprehensive view of a product’s impact through the implementation of circularity strategies (Hackenhaar et al., 2024; Hendriks et al., 2002; Huysman et al., 2017; Monia Niero et al., 2019; Simone Bastianoni et al., 2023). However, LCA is aimed at evaluating environmental impacts and not circularity per se. Anyhow, this integration aids in identifying hotspots where circular strategies can be most effective from an environmental perspective. However, a drawback is the level of expertise and time required for their application, leading to complex and variable results depending on methodological choices (Brändström & Eriksson, 2022). Besides, there is a growing body of literature now focusing on specific aspects of circularity without necessarily incorporating broader sustainability dimensions (Graedel et al., 2011; Haas et al., 2015; Vanegas et al., 2018).

The criticality of raw materials is also a relevant characteristic related to the circularity of products (Hackenhaar et al., 2024; Wang & Kara, 2019). The EC redacts every three years a list of raw materials that are critical for the European economy, based on an evaluation of 70 different raw materials, mostly metals but also including some biotic examples such as natural rubber, natural cork, roundwood, sapele wood, and natural teak wood (EC, 2023). Whereas none of these biotic materials were considered “critical” in the latest 2023 evaluation, the number of supply-risk indicators considered in the assessment and the coverage of the entire bio-based sector are limited. Additionally, the “criticality concept” and its measurements can significantly differ between actors (Helbig et al., 2016; Schrijvers et al., 2020).

Additionally, a key challenge in the assessment of circularity at the product level is defining what constitutes *value*. This remains a central, yet often ambiguous, element in the CE discourse, present in most definitions but rarely given a specific and detailed definition (Kirchherr et al., 2023); it can be interpreted in multiple ways depending on the context and the specific objectives of the assessment. Vulsteke et al. (2024) developed a framework that considers two primary forms of value in CE: (1) functional value (objective properties of materials, components, and products) and (2) created value (net positive and negative impacts over the lifecycle). In relation to circularity assessment, Hatzfeld et al. (2022) introduced a novel approach to modelling circularity over use-time in relation to product functionality, categorising the main challenges of value change and retention: (1) multi-cyclic longevity, (2) up- & downcycling effects, (3) measuring disruptive change instead of incremental change, and (4) integration into sustainability assessments.

1.3.2 CAIs for bio-based product systems

Given the specific characteristics of BBPS, additional challenges arise when assessing circularity at the bio-based product level. An effective circularity assessment for bio-based products must extend beyond simple resource tracking in the technosphere to address the characteristics of bio-based resources (Iglesias et al., 2025). Such assessments require a broader scope than those typically applied to abiotic materials, which do not follow organic cycles or include end-of-life options like anaerobic digestion and composting. Navare et al. (2021) proposed four key characteristics of the biological cycles in the context of C(B)E: *sustainable sourcing, cascading use of materials, closing biological nutrient cycles, and addressing environmental impacts specific to biological processes*. Vural Gursel et al. (2022) extended this framework to include the circularity of bio-based products within technical cycles and incorporated considerations of sustainability. The proposed principles include reducing reliance on fossil resources, using materials efficiently, valorising waste and residues, regenerating and recirculating biomass, and extending its high-quality use. The authors also highlighted the importance of combining intrinsic circularity indicators with complementary methods, such as life cycle assessment, to evaluate the sustainability impacts of circularity. This work, later applied in a review of circularity indicators for bio-based product assessment (Vural Gursel et al., 2023) and followed by other researchers such as Mesa et al. (2024), have underscored several persistent gaps in the field of circularity assessment for bio-based products, eventually pointing to a dual challenge: at the methodological level, CAIs must incorporate the regenerative capacity of renewable resources, capture the value that bio-based materials develop across cascading use stages, and address end-of-life options specific to bio-compatible resources, such as composting and anaerobic digestion; At the operational level, indicators must ultimately be applicable in practice. To achieve this, they should be scalable across sectors and product types, and presented in standardised, clearly interpretable formats to ensure usability by diverse stakeholders (e.g., industrial actors and policymakers). As a starting point to address these gaps, it is worth noting that the inclusion of life cycle thinking and sustainability assessments to complement circular bioeconomy decisions has been strongly advocated by several authors (Dahiya et al., 2020; Huysman et al., 2017; Ramos Huarachi et al., 2023). However, the different sustainability dimensions often fall outside the scope of a circularity assessment, which is already complex enough to be considered an independent methodology. In this work, circularity assessment is viewed as complementary to environmental life cycle assessment but not fully overlapping with it.

Given the diverse and often inconsistent classifications of circularity indicators, a comprehensive characterisation of indicators applicable to bio-based product systems would be beneficial to establish a clear basis for assessing circularity in practice. Building on the existing state of the art, such a characterisation should not only consolidate previous research but also support the development of consistent, transparent, and comparable approaches for evaluating circularity in bio-based systems. The distinct nature of these systems, including their reliance on renewable biological inputs and their diverse end-of-use and end-of-life pathways, calls for tailored assessment methods capable of capturing their specific circularity dynamics. This need will be addressed in future work within the ESCIB project through the development of a coherent circularity assessment methodology for high- and low-TRL bio-based systems, which will be informed by the outcomes of the work presented in this deliverable.

1.4 Deliverable Objectives

The primary objective of this deliverable is to conduct a critical review and evaluation of CAIs that are either applicable to or specifically formulated for evaluating bio-based product systems. The review particularly focuses on CAIs that do not rely on inputs from external software or methodologies, such as life cycle assessment. This intentional exclusion serves several purposes, but the main aim is to identify indicators that are methodologically independent and can be applied without relying on external tools or extensive datasets, thereby listing flexible and adaptable CAIs that can be used across different contexts. In doing so, this review also highlights indicators that offer complementary insights into the circularity of bio-based systems, which conventional sustainability methodologies may not fully capture.

The specific objectives are twofold: (1) to develop a comprehensive flowchart of bio-based systems that illustrates the complex and interconnected nature of material and value flows, and (2) to compile a practical and comprehensive list of CAIs

applicable to bio-based systems for use by researchers and practitioners. Each identified CAI is evaluated against a wide range of key characteristics to identify existing gaps, challenges, and opportunities in current circularity assessment practices. This evaluation will result in a curated shortlist of indicators that meet all key characteristics and will serve as a foundation for the upcoming methodological development in ESCIB, which will be further presented in future project deliverables

2 Materials and methods

2.1 Systematic literature review

A systematic literature review was conducted. The following search strings were used to retrieve relevant literature from SCOPUS and Web of Science databases:

Scopus: *“(TITLE-ABS-KEY (circular* AND (“bioeconomy” OR “bio-based” OR “biobased” or “bio based”))) AND (TITLE-ABS-KEY (indicator* OR metric* OR index* OR indices)) AND PUBYEAR > 2004 AND PUBYEAR < 2024”*

Web of Science: *“TS = (circular* AND (“bioeconomy” OR “bio-based” OR “biobased” OR “bio based”)) AND TS = (indicator* OR metric* OR index* OR indices) AND PY = (2004-2024)”*

Resulting in a pool of 424 papers (208 from SCOPUS, 216 from Web of Science). After duplicates removal, the combined search resulted in a list of 242 papers that were subjected to abstract screening.

The inclusion criteria for the papers were as follows:

“Literature that involves circularity assessment at the micro level to bio-based products or potentially applicable to bio-based products, with specific measurements via indicators, sets of indicators or tools, not dependent on inputs from any particular external methodology or tool, including LCA”

Following these criteria, a total of 53 articles were selected for full-text screening. Additionally, the snowballing method was employed to identify further relevant articles. This method, as defined by Greenhalgh and Peacock (2005) and Wohlin (2014), can make use of the citations of a screened paper to identify additional relevant papers. Through this process, 16 more papers were identified and included, leading to a final list of 69 papers for review. Figure 2.1 shows the PRISMA flow diagram of the literature review procedure.

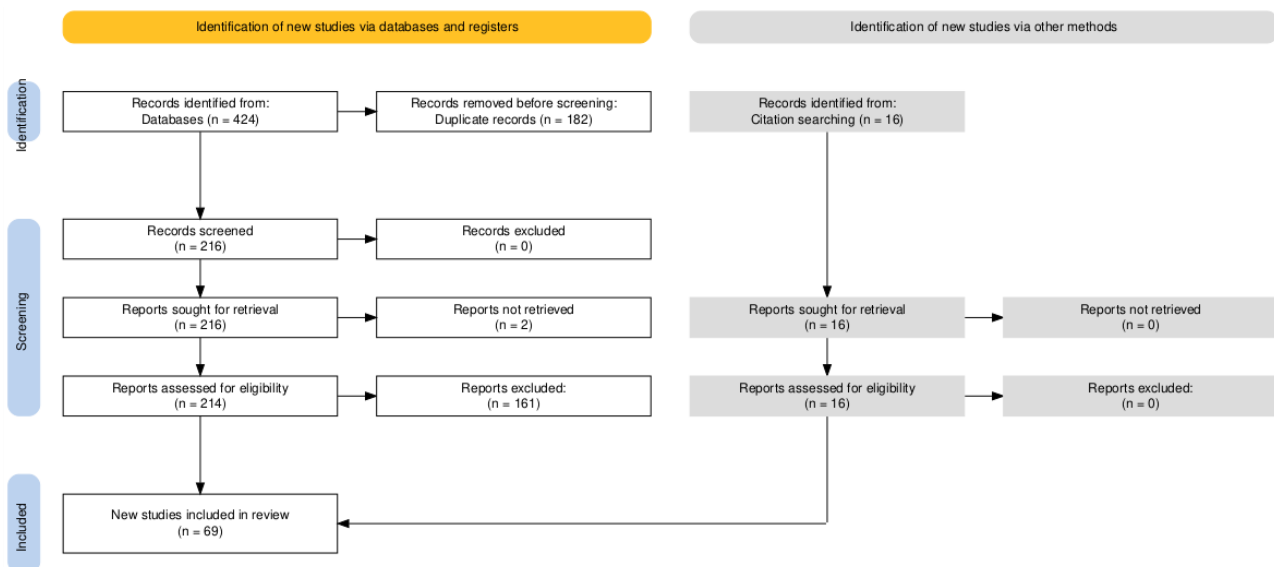


Figure 2.1. PRISMA Flow Diagram of the literature review process.

For the CAI compilation, the following inclusion criteria were applied:

- For indicators, they must function independently of complementary methods (e.g., LCA) and maintain a primary or exclusive focus on circularity assessment.
- For sets of indicators and tools, circularity assessment must be their primary focus or contain at least dedicated circularity indicators that meet the criteria above.

All identified records were screened by a single reviewer based on the inclusion criteria specified above. Screening was conducted in two stages: title/abstract screening followed by full-text screening.

2.2 Development of the bio-based systems flowchart

During the literature review phase, a detailed examination of the reviewed studies was conducted to examine the complex and interconnected nature of material flows within bio-based systems. The insights from this review were used to identify all potential flows that might occur in a generic bio-based system, focusing on their relevance for the assessment of circularity. This process involved understanding the different flows as belonging to distinct flowchart regions; the aggregation of all potential flows moving from, to, or within these regions results in the bio-based systems flowchart. Furthermore, during the CAI analysis, the flows to and from the flowchart regions covered by each CAI will be assessed. A region is considered “covered” by a CAI if it considers a flow that goes from, to, or within the region. This flowchart is aimed to provide a holistic visualisation of the intricate network of processes and interactions that characterise bio-based systems.

Additionally, this flowchart is also aimed at distinguishing the concepts of end-of-use (EOU) and end-of-life (EOL). EOU refers to the state following the use phase of the material, during which it still retains functional value that can be exploited. Conversely, the EOL represents the state at which the material is taken for final destructive treatment or disposal, either via landfill, incineration or through biodegradation processes such as composting or anaerobic digestion. A material may therefore undergo multiple EOU states before ultimately reaching its EOL. This distinction is critical for a comprehensive understanding and assessment of material flows within bio-based systems.

2.3 Key criteria assessed at the paper level

For each of the papers included in the review, three key criteria are assessed at the paper level:

(i) The first key criterion is the type of paper in relation to the CAIs that are referenced, proposed or developed. Papers are classified as CAI proposals (introducing new CAIs), CAI reviews, or circularity assessments case studies (using new or existing CAIs).

(ii) The second key criterion is the main product system under study. Each paper's primary product or service in scope is classified according to the European Statistical classification of products by activity (CPA) 2.1, which corresponds to the UN's Central Product Classifications (CPC) 2.1 and follows the Statistical Classification of Economic Activities in the European Community (NACE 2) structure based on economic origin.

(iii) The third key criterion is the use, proposal or review of CAIs in conjunction with LCA in a complementary manner, intending to discover the extent to which LCA and CAIs are integrated to comprehensively evaluate bio-based product systems.

2.4 Key characteristics assessed at the CAI level

To evaluate the relevant characteristics related to the CE and CAIs, previous contributions to the analysis of CAIs provided the foundation for a preliminary list of characteristics, including the works of De Pascale et al. (2021), Jerome et al. (2022), Kristensen & Mosgaard (2020), Matos et al. (2023), Moraga et al. (2019), Saidani et al. (2019), Parchomenko et al. (2019) and Corona et al. (2019). However, much of this work focuses on circularity in technical cycles, often overlooking dimensions specific to biological ones. This study builds on those foundations and extends them to encompass the characteristics of bio-based resources within a unified framework, drawing on prior conceptual work on bio-based product circularity (Navare et al., 2021; Vural Gursel et al., 2022). To ensure consistency with emerging international guidance, the list of characteristics was also developed in alignment with two recently published ISO standards on CE (ISO, 2024a; 2024b), which also address both biological and technical cycles in circularity assessment. During the CAI analysis, some additional characteristics were identified and integrated through an iterative refinement process. As a result, a total of fourteen key characteristics were assessed, structured into six groups: CAI characteristics and application, flows and functional value, sustainability and criticality, biogenic carbon coverage, bio-based flowchart flows, and circular economy strategies (CES). The characteristics are presented below:

Regarding the CAI characteristics and application group:

1. The first key characteristic is the sector-specificity of the CAI, identified as the applicability of the CAI across various industries or its limitation to a specific sector.
2. The second key characteristic is the complexity of the CAI, defined by three levels: single indicators, sets of indicators, or tools.
3. The third key characteristic is the implementation level. Although the focus of this deliverable is at the micro level, certain CAIs proposed for higher implementation levels (meso or macro) that are still applicable at the micro level are also included in the analysis and characterised.
4. The fourth key characteristic is the dimensionality of the CAI, classifying them as either dimensional or adimensional.
5. The fifth key characteristic is the application of the CAI in at least one circularity assessment of a product system within the screened literature, reflecting that CAIs may be formulated but have limited application in real BBPS.

Regarding the flows and functional value group:

6. The sixth key characteristic is the type of measured flow, considering component flows, material flows, economic flows, energy, time, or any other measurable variations the CAIs account for.

7. The seventh key characteristic is the considered functional value, as defined by Vulsteke et al. (2024). Differently to the sixth key characteristic, the embedded value beyond the actual flow taking place is what is evaluated.

Regarding the sustainability and criticality group:

8. The eighth key characteristic is the inclusion of any sustainability input in the CAI calculation, considering any parameter related to environmental, social, or economic inputs (e.g., GHG emissions, toxicity, economic revenue, employment generation, etc.).

9. The ninth key characteristic is the inclusion of energy, other utilities, or auxiliary material inputs in the CAI calculation, aiming to assess whether the CAI considers such peripheral product-system elements to assess circularity.

10. The tenth key characteristic is criticality coverage, defined as the inclusion of one (partial coverage) or both (full coverage) dimensions for a material to be considered a critical raw material (CRM) by the EU Raw Materials Act (EC, 2024), namely, supply risk and economic importance.

Regarding the coverage of biogenic carbon:

11. The eleventh key characteristic is the differentiation between biotic (biological) and abiotic (non-biological) materials, and it explores how this differentiation is addressed for those CAIs that distinguish between them.

Regarding the bio-based flowchart flows:

12. The twelfth key characteristic is the coverage of different flowchart regions, considering full coverage if a flow goes from, to, or within the region, and potential coverage if the regions could be covered with minor changes to the definition of the CAI and/or any existing parameters without adding new ones. (For example, a CAI that includes a parameter “P” defined as the amount of material recycled within the same value chain could be slightly modified to also compute the total material recycled to open-loop value chains. Thus, the “open-loop value chains” region of the flowchart would be considered potentially covered for this CAI).

13. The thirteenth key characteristic is the flow perspective. Given the long and complex list of potential combinations of flows, all flows within the bio-based systems flowchart were categorised into three perspectives, plus an additional holistic perspective, based on the flows they consider:

Inflow perspective: CAIs in this group focus on the input streams to the main product value chain, measuring the materials and resources entering the production process, including virgin, renewable, and recirculated materials from a recovery process.

Recirculation perspective: These CAIs concentrate on the flows connecting the end-of-use (EOU) product to a new secondary product lifecycle, either in an open-loop or closed-loop system. This includes CAIs tracking the reuse, refurbishment, repair, remanufacture, repurposing, and recycling of materials back into a secondary value chain.

Outflow perspective: These CAIs focus on streams that do not connect the EOU product to a new secondary product lifecycle but mainly encompass end-of-life (EOL) strategies. This category includes CAIs measuring the disposal or degradation of materials, components and products at the end of its useful life, such as anaerobic digestion, composting, biofuel production and use, incineration with or without energy recovery, and landfilling.

Holistic routes: These CAIs include measurements from/to all five regions (including open-loop and closed-loop recirculation) or from/to four regions (including only closed-loop recirculation). They provide a comprehensive overview of the material flows throughout the entire lifecycle of the product.

This categorisation directly reflects the life-cycle-stage approach established in ISO (2024), which structures circularity assessment around input, use, and output phases.

Regarding the CES:

14. Several authors have proposed different so-called CE criteria, elements, or strategies to apply to bio-based systems. In this analysis, all CES from the different approaches of Vural Gursel et al. (2023), Navare et al. (2021), and Kusumo et al. (2022) have been gathered to assess circularity in bio-based systems.

The ten CES considered in this analysis are:

- CES1. Use of recirculated/renewable feedstock.
- CES2. Resource efficiency in the value chain.
- CES3. Lifetime extension.
- CES4. Recycling the product/component/material.
- CES5. Reuse (via maintenance, refurbishment, remanufacture, etc.).
- CES6. Repurpose.
- CES7. Waste management.
- CES8. Maintaining functional value.
- CES9. Cascading in value.
- CES10. Nutrient recovery.

Most CES (1–6, 8, 9) correspond directly to ISO CRMAs such as *Circular sourcing, Reduce, Repair, Reuse, Refurbish, Remanufacture, Repurpose, Cascade, and Recycle*, ensuring coherence with the ISO framework. Two CES, *Waste management* and *Nutrient recovery*—extend beyond this scope by explicitly addressing end-of-chain operations and biological-cycle processes unique to bio-based systems. Conversely, some CRMAs—such as *Refuse, Rethink, Recover energy, and Re-mine*—were not explicitly included, as they either operate at higher design or systemic levels (e.g. *Refuse, Rethink*) or represent end-of-life recovery routes already encompassed within broader CES.

The fourteenth key characteristic is therefore the coverage of above above-listed CES by CAIs. Two levels of coverage were defined to reflect the extent to which a CES is addressed within a CAI: (i) Full coverage refers to cases where the CES is explicitly or clearly captured in the indicator’s formulation or objective, meaning that it directly measures or evaluates performance aspects related to that specific circular strategy, such as lifetime extension, reuse, or recycling; (ii) Partial coverage was considered when the CES is not explicitly mentioned or addressed in the core objective of the CAI, but can be considered indirectly covered for different reasons, e.g., being implied in the indicator’s logic, parameters, or intended outcomes without representing its main focus or scope. This distinction allows for a more nuanced interpretation of how comprehensively each indicator accounts for different circular economy strategies and helps identify where existing CAIs capture circularity effects only in an indirect or secondary way. While this assessment inevitably involves a certain degree of subjectivity, it was consistently carried out by the same reviewer to ensure coherence and comparability across all CAIs.

2.5 Elaboration of the short list of CAIs

The final step of the literature review is the development of a curated shortlist of CAIs that stand out for different characteristics, resulting in a concise yet balanced selection covering all relevant key characteristics.

The following criteria were used to elaborate this short list:

- *Frequency of Use or Mention*: CAIs that have been either employed or mentioned more than three times in the screened literature were shortlisted. This criterion ensures that the selected CAIs have been recognised and validated by multiple studies, as a sign of relevance and reliability.
- *Practical Application in BBPS*: CAIs that have been used in practical case studies of BBPS more than twice within the screened literature were included. This criterion emphasises the applicability and practical utility of the CAIs.

- *Exclusion of System-specific CAIs:* CAIs that are only applicable to a particular product system were excluded; the goal is to create a list of CAIs that can be broadly applied across various bio-based systems, enhancing their generalisability.
- *Comprehensive Coverage of Key Characteristics:* To ensure a diverse and inclusive list, additional CAIs were included ad hoc to guarantee that all categories of the key characteristic elements were represented. The rationale behind this criterion is explained below:
 - i. Each of the key criteria from the CAI-level analysis has to be covered by at least two CAIs to ensure robustness.
 - ii. Essential key characteristics for BBPS, namely:
 - a. Measures of value beyond material flow
 - b. Coverage of cascading value chains in the bio-based systems flowchart
 - c. Coverage of all ten considered CESshould be covered by at least five CAIs, ensuring a bigger coverage of these characteristics. All CAIs from the full list that cover any of these essential key characteristics were included for those whose number of CAIs is lower than five.

This approach aims to balance comprehensiveness with practicality, ensuring that the selected CAIs are both widely applicable and capable of providing detailed insights into the circularity and sustainability of BBPS.

3 Results and discussion

3.1 Bio-based systems flowchart

During the literature review, the examination of studies revealed the complex and interconnected nature of flows within bio-based systems. These flows encompass the movement of materials, energy, nutrients and other forms of value through different biological and technical processes. By analysing these flows, we identified a need for a comprehensive representation that encapsulates all relevant potential pathways and interactions within a bio-based system.

As a result, the potential material flows that might take place in a general bio-based system, which are relevant for the assessment of circularity, have been studied. These flows have been systematically grouped and arranged into five distinct regions, which together form what is defined as the bio-based systems flowchart (Figure 3.1). This flowchart serves as a holistic visualisation of the intricate network of processes and their interactions that characterise bio-based systems.

3.1.1 Regions of the Bio-based Systems Flowchart

As detailed in Section 3.1, the bio-based systems flowchart comprises multiple regions as follows:

Biosphere (Including Primary Production and Harvesting of Biomass):

This region represents the natural environment and the initial stages of biomass production. It includes the extraction and harvesting of primary raw materials, such as crops, forestry products, fishery, livestock and other renewable resources.

Main Product Value Chain:

This region covers the transformation of primary and secondary raw materials into intermediate and final products. It includes stages such as raw material pre-processing, material and component manufacturing, product assembly and the use phase.

End-of-Use Management:

This region addresses the processes involved in managing products at the end of their useful life. It includes collection, sorting, and various EOU/EOL strategies such as composting, anaerobic digestion and incineration with or without energy recovery. Notably, biofuels production and use are also included in this group. The goal of CE is to divert materials from an EOU scenario to new use stages instead of an EOL, fostering circularity through the recovery and recirculation of materials. Notably, not all EOU strategies are equally impactful; some even promote the closure of the biological loop and can be considered as circular strategies in a broad sense. This accentuates the need for differentiation among these strategies by CAIs.

Secondary Material Recovery to New Value Chains:

This region focuses on the recovery of secondary materials from EOU products and their reintegration into new value chains. It encompasses processes such as material recovery, component recovery, and the creation of secondary raw materials to new product value chains. This region acts as a bridge between the EOU products and their following OL or CL recirculation, extending the total functional value that materials provide across their lifecycle.

New Open-Loop Value Chains:

This region represents the cascading use of materials across different value chains. It involves the transfer of secondary materials and products into new life cycles, through which materials are aimed at being utilised to their fullest functional value before being returned to the biosphere or an EOL strategy. This cascading approach emphasises the sequential use of materials in various sectors to maximise their useful life extension and minimise waste generation.

The bio-based systems flowchart integrates the above-presented five regions to provide a comprehensive overview of the potential flows within bio-based systems. By visualising the presented interconnected pathways, the flowchart can also serve

as a tool for assessing and developing CAIs. This structured approach helps to ensure all relevant aspects of bio-based systems are considered, leading to more effective and targeted circular (bio)economy strategies.

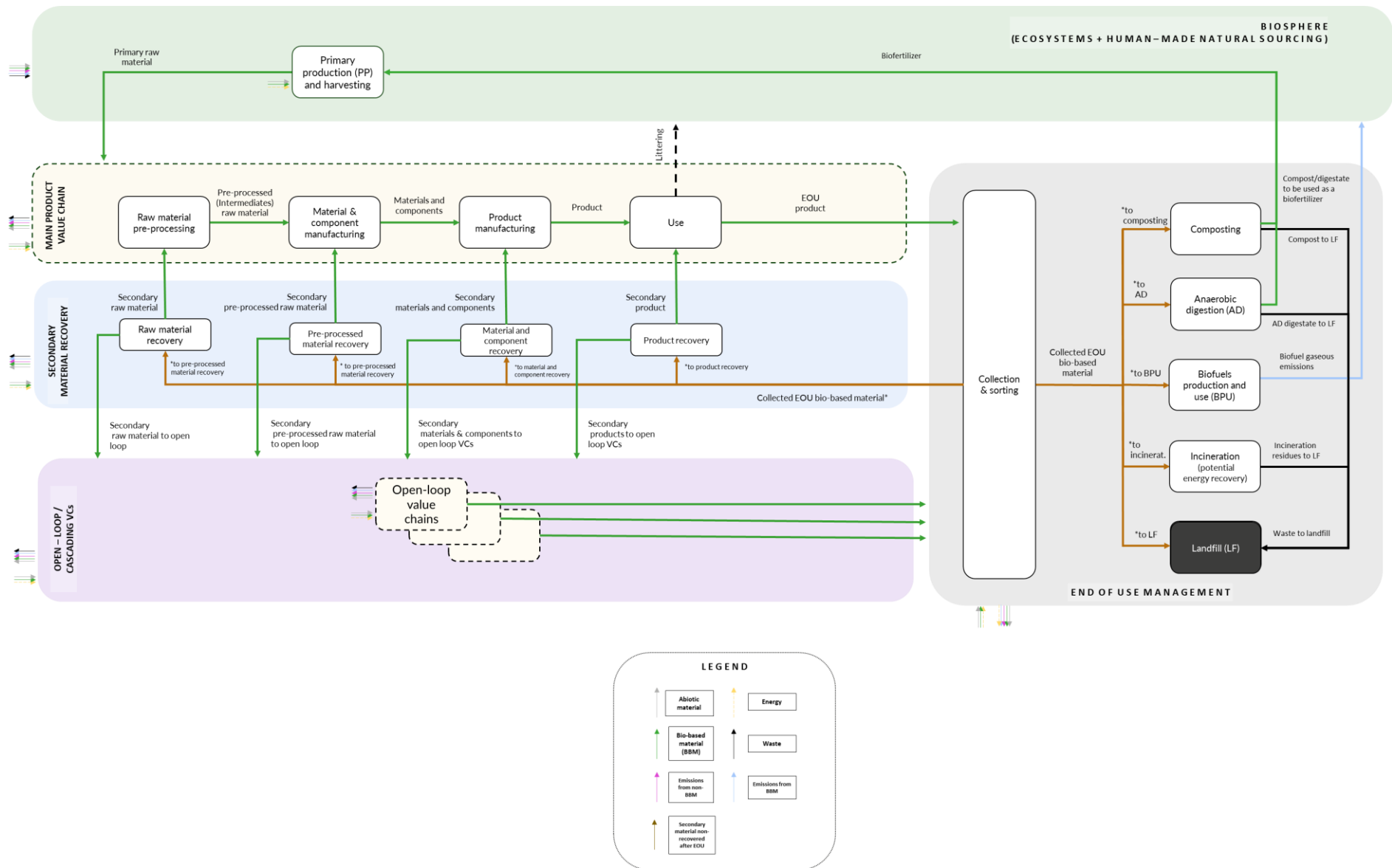


Figure 3.1. Bio-based systems flowchart

3.2 Paper-level analysis

A total of 69 papers that utilised or proposed CAIs applicable to bio-based systems, all of them non-reliant on inputs from any particular external tool (including LCA), were assessed. As expected, the majority of the screened literature referred to CAIs that evaluate circularity without carrying out any additional LCA analysis. However, 17 papers did incorporate LCA together with CAIs in a complementary manner, offering a more comprehensive assessment and occasionally providing comparisons between both evaluation methods.

The list of reviewed literature encompassed several types of papers on CAIs applied or proposed for BBPS and generic systems, yet applicable to BBPS. These included 10 reviews of CAIs for BBPS, 2 for generic systems, 22 assessments applying CAIs to BBPS, 4 assessments to non-BBPS, 7 CAI proposals for BBPS, and 24 CAI proposals for generic systems.

Regarding the product or system classifications where these CAIs were applied or discussed, the analysis (summarised in Figure 3.2) revealed that 24 papers did not focus on any specific system. Conversely, 3 papers focused on products of agriculture, forestry, and fishing, while 36 papers examined various manufactured products. Within these products, the papers covered a range of subcategories including food products (1 paper), textiles (2 papers), wood products and furniture (5 papers), paper products (1 paper), chemicals (10 papers) and rubber and plastic products (10 papers). Additionally, 6 papers focused on water supply, sewerage, waste management, and remediation services, all of which fall under bio-based systems. There were also some non-bio-based systems assessed with CAIs that could also apply to bio-based systems. These papers studied products falling into the other non-metallic mineral products (2 papers), computer, electronic, and optical products (2 papers), electrical equipment (1 paper), motor vehicles, trailers, and semi-trailers (1 paper), and other manufactured goods (1 paper) CPA 2.1 groups. This distribution highlights the diverse applications of CAIs across various systems and the predominance of studies within the product manufacturing sector, especially chemicals and plastic products.

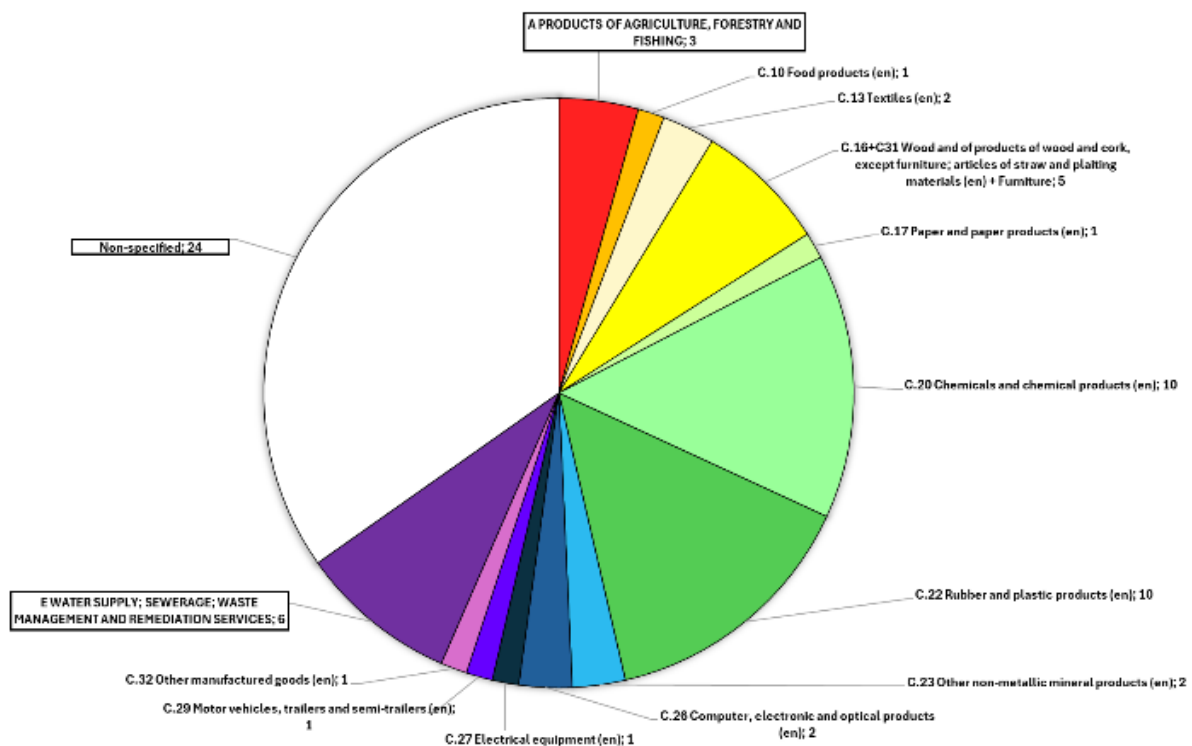


Figure 3.2. Product systems studied, according to the CPA 2.1 taxonomy.

3.3 CAI-level analysis

The analysis of the 69 reviewed papers culminated in the identification of a total of 73 CAIs. The full list of CAIs is detailed in Annex I, where they are presented, briefly described and characterised according to the 14 key characteristics proposed in this study in a tabulated format. This characterisation offers valuable insights into how differently circularity is understood and measured across the literature. The 73 identified CAIs vary widely, not only in their methodological structure and data requirements but also in what they actually consider to be circularity; this reflects the range of disciplines and motivations driving circularity research, from material science and industrial ecology to economics and policy analysis.

Such diversity is both enriching and challenging. On one hand, it highlights how flexible and evolving circularity thinking has become; on the other, it makes comparison and synthesis far from simple. Indicators designed for product-level applications cannot always easily be aligned with those for sectoral or national monitoring, and metrics that quantify mass or energy flows are difficult to compare with those based on value, functionality, or qualitative attributes. This diversity complicates the establishment of a coherent understanding of how circularity is achieved in bio-based systems.

Recognising these differences is therefore crucial. It allows identifying complementarities among indicators and clarifying where methodological gaps persist. The lessons drawn from all reviewed indicators will directly inform the next phases in ESCIB in Task 4.2 and Task 4.3, where these insights will feed into the development of circularity assessment methodologies for high- and low-TRL products that can accommodate the diversity of existing approaches while ensuring consistency and transparency.

3.3.1 CAI Characteristics and Application

The review of the 73 CAIs reveals their distribution among multiple key characteristics regarding their sector specificity, complexity, implementation level, and dimensionality.

A significant portion of the CAIs, 61, are not sector-specific, indicating broad applicability across various bio-based product systems. However, there are also product-specific or sector-specific CAIs used in products such as biofertilizers via anaerobic digestion or composting of biowaste (6 CAIs), apparel textiles (1 CAI), animal-based production (1 CAI), forest-wood supply chains (2 CAIs), and agriculture (primary production) (2 CAIs). This highlights both the versatility of many CAIs and the still-existing need for tailored metrics in specific sectors.

In terms of complexity, most CAIs (55) are single indicators, typically simpler and easier to apply than sets of indicators or tools. A smaller group (13) consists of sets of indicators that offer a broader perspective by combining several metrics, while only five are classified as tools. These results are summarised in Annex Figure 1. This distribution shows a clear preference for simple approaches, which also reflects the relatively low level of maturity of circularity assessment. It also highlights a trade-off: simplicity often comes at the cost of completeness, as single indicators may capture only one aspect of circularity, although some, such as the Material Circularity Indicator (MCI) (EMF, 2019a), manage to address multiple dimensions within a single formulation. In contrast, sets of indicators and tools, though less common, tend to provide a more nuanced and granular understanding of circularity but are more demanding to apply in practice. Finding the right balance between usability and analytical depth remains one of the main challenges ahead.

Regarding the implementation level, most CAIs (63) are formulated at the micro level, focusing on the analysis at the product or company scale. There are fewer CAIs designed for broader implementation levels, with 6 being macro-level CAIs applicable to the micro level and 4 being meso-level CAIs applicable to the micro level. These results are illustrated in Annex Figure 2. This distribution is consistent with the inclusion criteria of this review, which focused primarily on indicators applicable at the micro level. Nevertheless, it is worth noting that several CAIs formally developed for higher implementation scales (meso or macro) still apply principles, parameters, or calculation structures that can be meaningfully adapted to the product level with little or no modification. This highlights the interconnected nature of circularity assessment across scales and suggests

opportunities to better align methodologies that were originally conceived for system-wide evaluation with product-level applications.

When examining the dimensionality, a large majority of the CAIs (61) are adimensional. In contrast, only 12 CAIs are dimensional, as shown in Annex Figure 3. The dimensional or adimensional nature of a CAI was not found to have a strong influence on the type or quality of insights it provides. In practice, both forms can be equally useful depending on the purpose and context of application. For instance, adimensional indicators typically allow for easier benchmarking across systems, while dimensional ones—often expressed in mass, energy, or value units—can offer more tangible information about circular economy performance. Still, the choice between the two tends to reflect the intended use and data availability rather than a relevant conceptual difference in the understanding of circularity.

Among the 73 CAIs reviewed, 35 were applied in at least one circularity assessment of a product system in the screened literature. Notably, 28 of these CAIs have been applied specifically within the context of BBPS. Despite this, it is evident that a considerable number of CAIs (38 out of 73) have not been utilised in any circularity assessments reported in the screened literature of this work. This disparity highlights a gap between the development of indicators and their practical implementation, which underscores the need for ensuring that the indicators being developed are not only theoretically robust but also practically applicable and ready to be utilised in real system assessments. Among these CAIs, the MCI stands out as the most frequently used, having been applied five times in various circularity assessments. The MCI assigns a score between 0 and 1, where higher scores reflect the minimisation of linear flows and the maximisation of restorative flows for materials. It is driven by three key product characteristics: feedstock attributes, the destination of spent materials, and utility, which is a function of the length and intensity of product use. The 2019 update of the MCI provides specific considerations for biological materials, ensuring a more accurate assessment of bio-based systems. Other three CAIs have been applied in two systems' circularity assessments included in the systematic review, namely % Circular Inflow (%CI) and % Circular Outflow (%CO) from the Circular Transition Indicators documents developed by the WBCSD (2023) and the Cascade Factor (CF) from Mantau (2015).

3.3.2 Flows and functional value

The analysis of the 73 CAIs in terms of flow measurement shows that most CAIs (47) focus on assessing mass-based flows, highlighting the importance of tracking material in circularity assessments. Additionally, 11 CAIs measure multiple types of flows, while 6 measure economic flows. There are fewer CAIs focused on component flows (1), energy flows (2), and time (2). Four CAIs do not measure any flows directly, indicating alternative assessment approaches. This distribution underscores the predominance of material flow measurement in evaluating circularity.

Besides the flow being measured, the embedded functional value, as defined by Vulsteke et al. (2024) (objective properties of materials, components, and products) in the measurement might rely on factors beyond the flow itself, particularly for material flow-based CAIs. The analysis (Figure 3.3) reveals that 38 CAIs primarily reference material flow, underscoring the centrality of material tracking in circularity assessments. However, other forms of functional value were also found to play a significant role: 12 CAIs focus on material properties, such as the Reuse Potential Index (RPI), which aids in assessing potential recirculation strategies based on the technical ability of materials to be reused in commerce (Park & Chertow, 2014). Additionally, 10 CAIs measure multiple properties at once. Economic value is the reference for 6 CAIs, emphasising the financial aspects of circular practices, such as the Value-Based Resource Efficiency (VRE) indicator that considers circularity as the percentage of economic value of resources incorporated into the product (Di Maio et al., 2017). Aspects related to the function developed by the material are considered by 4 CAIs, while 2 CAIs focus on the lifetime of products. Only 1 CAI references a time measurement other than the use time as the form of value. This distribution highlights the multifaceted nature of functional value in circular economy assessments, with a predominant focus on material flow but also recognising the importance of various other properties.

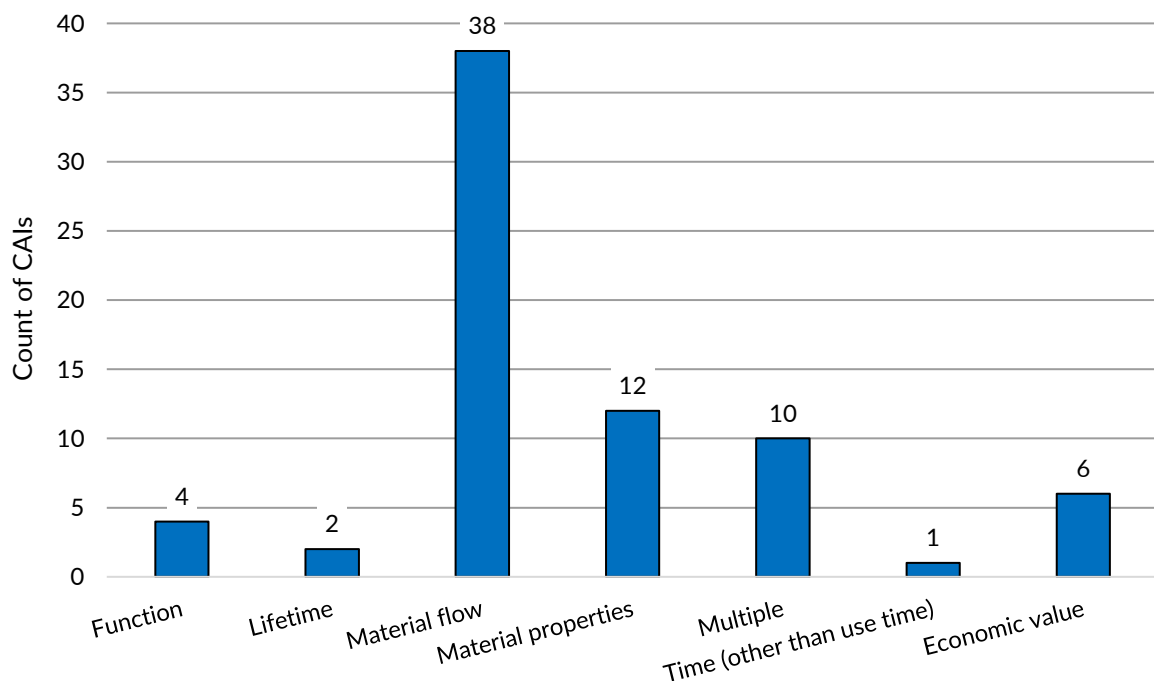


Figure 3.3. Classification of CAIs according to the intrinsic reference for value they measure.

3.3.3 Sustainability and Criticality

From the list of CAIs, only 11 explicitly include sustainability dimensions in their formulation or calculations. Breaking down the dimensions addressed, 7 CAIs directly consider environmental aspects, 5 address economic aspects, and only 2 include elements of social sustainability. These results are illustrated in Annex Figures 6 and 7. To obtain a more complete picture of both sustainability and circularity, CAIs are often integrated into broader system assessment methodologies, such as Life Cycle Assessment (LCA) or Life Cycle Sustainability Assessment (LCSA) (Hackenhaar et al., 2024). Several case studies reviewed in this work highlight the benefits of such integration, showing that combining CAIs with LCA can provide a more comprehensive and meaningful understanding of environmental sustainability and circular performance. Nevertheless, it remains unclear to what extent the scope of circularity assessment should encompass sustainability aspects. Expanding the

analytical boundaries to include the environmental, economic, or social dimensions inevitably increases methodological complexity, particularly at the product level, where circularity assessment is already challenging. This raises an open question on whether circularity should be evaluated as a stand-alone dimension or as an integrated part of broader sustainability assessment frameworks; this issue will be further addressed in future developments in ESCIB.

In terms of energy needs, auxiliary materials and utilities (catalysts, water, solvents, reagents, additives), the analysis reveals that 60 CAIs do not consider such aspects at all, as illustrated in Annex Figure 8. Besides, only 4 CAIs comprehensively consider all energy and auxiliary needs in the calculations. An example is the Hybridised Sustainability set of Indicators (HSI) from Lokesh et al. (2020), which includes hybridised indicators drawn from green chemistry and resource circularity principles. The HSI set includes considerations for hazardous chemical use, waste generated, resource circularity, renewability, and energy intensity, providing a more holistic approach to assessing the sustainability and circularity of bio-based systems. Other 4 CAIs specifically account for energy, while 1 CAI includes auxiliary materials and utilities. Furthermore, 4 CAIs indirectly consider energy needs, primarily through their inclusion in price parameters or similar factors. The limited consideration of energy and utilities in most CAIs suggests a potential gap in fully capturing the resource efficiency and environmental impacts associated with CE practices. Addressing this gap by integrating energy and utility considerations into CAIs can enhance the robustness and accuracy of circularity assessments and ease their integration into sustainability strategies, at the cost of some additional complexity.

With regards to the assessment of criticality inclusion in the calculations of CAIs, the results show that only 4 CAIs explicitly include criticality as a parameter in their calculation; one example is the % Critical Inflow (%CRI) indicator from the WBCSD (2023). This indicator highlights the share of the inflow considered critical, allowing companies to refer to internal critical materials lists or existing public lists such as those compiled by the EC (2023). Another 4 CAIs partially cover criticality, meaning they include at least one criterion of the CRM definition provided in the CRM Act (European Parliament and Council, 2024)—supply risk or economic importance—in their calculation or methodology. This partial coverage is mostly related to the economic dimension in all reviewed CAIs. These findings can be visualised in Annex Figure 9. From the review, it was concluded that while the inclusion of criticality is limited, its relevance in the circular bioeconomy is also lower than in technology- or metal-intensive sectors, where supply risk plays a more dominant role. Still, it remains worth considering, especially when bio-based systems depend on scarce resources, e.g., natural rubber. Therefore, addressing criticality is best understood as a complementary aspect that can enhance the overall evaluation of the product system.

3.3.4 Biogenic carbon coverage

In the analysis of CAIs, the differentiation between biotic (biological) and abiotic (non-biological) materials was evaluated. The results indicate a varied approach to this differentiation, presented in Figure 3.4. The majority of CAIs (44) do not differentiate between biotic and abiotic materials, treating all materials uniformly in their assessment. Besides, 17 CAIs account exclusively for biotic materials, with these CAIs focused on BBPS. Nevertheless, as reflected in the introduction section, a properly representative assessment would need to implement CAIs that are useful for real systems where both abiotic and biotic materials exist, by also highlighting the particular benefits of using bio-based materials. In this respect, 12 CAIs make a clear distinction between biotic and abiotic materials, allowing for more tailored assessments that consider such particular characteristics in different ways.

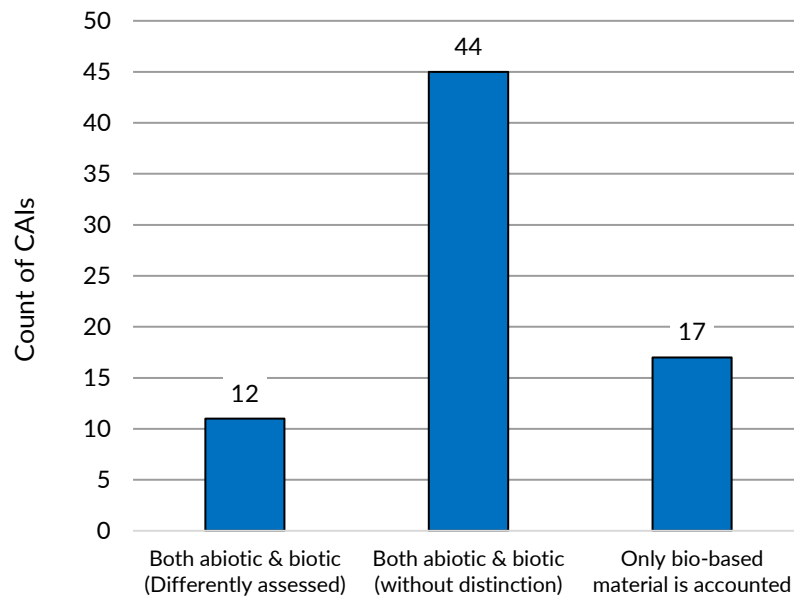


Figure 3.4. Differentiation of Abiotic and Biotic Materials in CAIs

Thus, recognising the unique attributes of biogenic resources is crucial for accurately assessing the sustainability and circular strategies of bio-based products (Dornburg et al., 2003; Hermann et al., 2011) but also to promote the inclusion of bio-based materials in sectors where traditionally these have not been either applied or considered for product manufacturing (Vinod et al., 2020; World Economic Forum, 2023). An extended analysis of those CAIs that assess biotic and abiotic materials differently (Table 2) reveals that differentiation often lies in the treatment and classification of materials based on their renewability, biodegradability, and the requirements to meet those aspects.

Table 2. List of identified CAIs that address abiotic and biotic material differently.

CAI (Acronym)	CAI (Name)	Source	Biogenic Carbon Consideration
MCI	Material Circularity Indicator (2019)	Ellen MacArthur Foundation, 2019	Biogenic carbon from “sustainably sourced” biomass is not considered unrecoverable waste when utilized for energy recovery or composting at the EOU stage.
MCI (mod. Razza)	Material Circularity Indicator (mod. Razza)	Razza et al., 2020	Rapid biogeochemical cycles are assumed, where carbon biodegradation is considered immediate, returning to the environment and biogeochemical cycles. Bio-based and biodegradable materials sent to incineration or landfill are not regarded as restorative.
HSI	Hybridised Sustainability Indicators	Lokesh et al., 2020	The "Product Renewability" indicator (PR) from this set defines any bio-derived primary feedstock as inherently renewable.
MRS	Material Reutilization Score	CradleToGate, 2016	Raw materials are classified as renewable if they are harvested from agricultural sources and can regenerate within 10 years.
%CO	% Circular outflow	WBCSD, 2022	Nutrients that the biosphere can fully absorb and utilise for new growth are considered to have 100% recovery potential. Toxic substances or those that nature cannot absorb have 0% recovery potential unless they are recoverable in the technical cycle.
%CI	% Circular inflow	WBCSD, 2022	Renewable inflow refers to sustainably managed resources, typically certified by organisations such as FSC, PEFC, or RSPO, that replenish their stocks through natural growth or replenishment processes faster than they are harvested.
FCR	Circular Materials Guidelines Feedstock Content Requirements	Fashionpositive, 2020	For products made from virgin cellulose, it requires certified transitional organic fibre production with principles for regenerative farming, including biodiversity and soil health, elimination of pesticides and GMOs, carbon sequestration, and water management for the “BEST” category. Additionally, it requires completion of the CanopyStyle audit, with a minimum ranking of a green shirt for "BETTER" category or a darker shade green shirt for "BEST" category in the Canopy's Hot Button Report.
SIAT	Sustainability Integrated Assessment Tool	Ladu and Morone, 2021	Biogenic carbon content is determined following the norm CEN EN 16640:2017.
TESA	TESA Indicators	Briassoulis et al., 2021	Biodegradability is considered without major clarifications. No specific definition for "biodegradable" is provided
CET	Circular Economy Toolkit	Evans and Bocken, 2014	Biodegradable materials are included in the "design" survey, but no specific definition for "biodegradable" is provided.
CMT	Circularity Measurement Toolkit	Garza-Reyes et al., 2019	The use of bio-based renewable feedstock is favoured, though there is no explicit reference to biogenic carbon.
Circularity degree	CD	Haas et al., 2015	It is noted that if biomass is produced sustainably—without harming soil or water resources and without depleting ecological carbon stocks—it can be considered renewable. The emitted CO ₂ and waste flows can largely be recycled into new primary biomass within ecological cycles.

For example, the MCI and its modified version by Razza et al. (2020) consider composting and energy recovery from sustainably sourced bio-based materials as circular, excluding the waste from these activities from the “unrecoverable waste” consideration. This indicator emphasises the immediate return of biodegradable carbon to soil and excludes the flow of bio-based materials that go to incineration or landfill from being considered restorative.

The HSI set of indicators from Lokesh et al. (2020) assumes any bio-derived primary feedstock as renewable by definition, while the Material Reutilization Score (MRS) from Cradle to Cradle Products Innovation Institute (2016) considers a raw material renewable if it is harvested from an agricultural source and can regrow within ten years. These CAIs highlight a fundamental distinction based on the renewability of the materials.

CAIs such as %CO and %CI from WBCSD (2023) also focus on sustainable resource management. The %CO indicator assigns a 100% recovery potential to nutrients that the biosphere can naturally absorb and use for new growth, emphasising the role of biodegradable materials in the biological cycle. On the other hand, %CI considers the renewable inflow from sustainably managed resources, often certified by international standards such as the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC) (WBCSD, 2023).

The Circular Materials Guidelines Feedstock Content Requirements (FCR) from Fashion Positive (2020) requires products made from virgin cellulose to adhere to principles of regenerative farming, including biodiversity, soil health, and carbon sequestration. This CAI covers sustainable practices and certifications of such practices in the production process, as well, applied to the apparel textile manufacture (Fashion Positive, 2020). The Circularity degree (CD) indicator from Haas et al. (2015) also mentions that if biomass is produced sustainably—that is, without damaging soil or water resources and without depleting ecological carbon—it can be considered as renewable. The emitted CO₂ and waste flows can largely be recycled into new primary biomass through biological cycles.

Other CAIs like the Circular Economy Toolkit (CET) from Evans & Bocken (2014), the TESA indicators from Briassoulis et al. (2021) and the Circularity Measurement Toolkit (CMT) from Garza-Reyes et al. (2019) mention biodegradable materials and the use of renewable feedstock, but lack explicit definitions or references to biogenic carbon. The Sustainability Integrated Assessment Tool (SIAT) from Ladu & Morone (2021) specifically determines biogenic carbon content according to the norm CEN EN 16640:2017, ensuring a standardised approach to assessing biogenic carbon.

The identified variety suggests that CAIs address the bio-based nature of resources through mainly two focus areas: the renewability of the resources, and their biodegradability or capacity to enable the closure of the biological cycles, which are both also linked to adherence to certification standards. This differentiation is crucial for accurately assessing the circularity of bio-based materials, reflecting their unique characteristics and impacts.

3.3.5 Bio-based flowchart flows

The analysis of the coverage of regions of the bio-based systems flowchart by CAIs (Figure 3.5) reveals varied levels of inclusion across different regions. The main product value chain is the most comprehensively covered region, with 67 CAIs including this in their assessments. This demonstrates a strong focus on the core stages of production and use by the CAIs.

Secondary material recovery to the main value chain is also well covered, with 55 CAIs covering this region. This also indicates a significant emphasis on the recovery and reintegration of secondary materials into the same or cascading primary production processes.

The potential for inclusion is particularly notable in the secondary material recovery to open-loop value chains (in line with cascading). Although only 33 CAIs currently cover this region, another 22 have the potential to include it with minor adjustments to their calculations. This suggests a substantial opportunity to extend the scope of many CAIs to better address cascading value chains, which are crucial for the effective assessment of bio-based materials circularity. One notable indicator that effectively covers multiple cascading value chains is the Biomass Utilisation Factor (BUF) proposed by Vom Berg et al. (2023). This indicator combines cascading use and production efficiency into a single metric for the CBE. It quantifies the extent to which biomass is utilised (production efficiency) and how often it follows a cascading use within a BBPS or even at a broader level. This dual focus makes the BUF a comprehensive tool for assessing the circularity and efficiency of biomass utilisation in bio-based systems.

Primary production and harvesting (PP sourcing) is considered by 21 CAIs, with 5 more having the potential to cover this region. EOU management is included in 14 CAIs, and 1 CAI has the potential to include it.

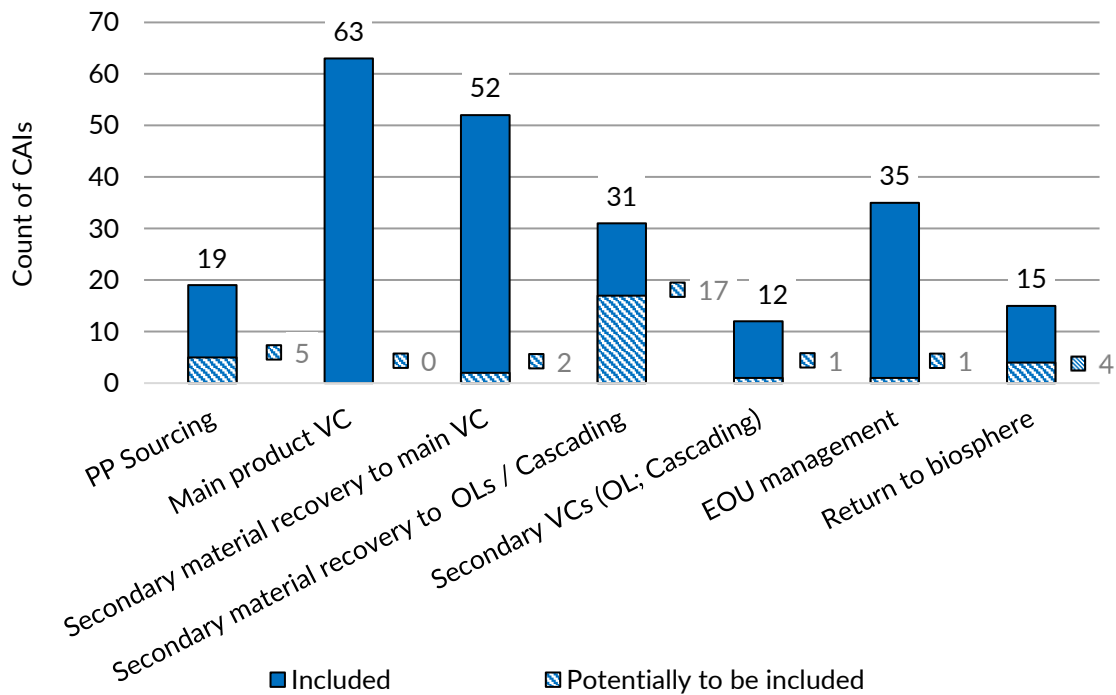


Figure 3.5. Coverage of the different regions of the bio-based systems flowchart by the CAIs. Secondary material recovery has been split into two depending on the recirculation route (open-loop vs. closed-loop recirculation).

Overall, the flowchart regions analysis helps to ensure a holistic coverage of the bio-based system when applying CAIs for a circularity assessment.

The analysis of CAIs also involved examining the flow perspective of the CAIs. The distribution of routes taken by the CAIs reveals that 9 CAIs adopt the inflow perspective, with a significant focus on the input streams to production processes. Recirculation routes are the most represented, with 35 CAIs, reflecting the importance of tracking material reuse and recycling. Outflow routes are covered by 16 CAIs, covering the need to account for the flows of EOU material to an eventual EOL. Lastly, holistic routes, which offer the most comprehensive view, are represented by 9 CAIs, indicating a recognition of integrated assessments that cover the various interconnected flows within biobased systems. These results are illustrated in Annex Figure 12. Building upon the previous discussion, this distribution suggests that circularity is still predominantly viewed through partial system boundaries, mainly inflows or recirculation, while relatively few indicators capture the full material life cycle from input to final outflow. A comprehensive circularity assessment should, however, adopt the broadest possible perspective, ideally combining multiple indicators that together achieve a holistic flow representation when necessary. Neglecting this multidimensional view can lead to an incomplete or even misleading interpretation of actual circular economy performance.

3.3.6 Circular Economy Strategies (CES)

Figure 3.6 presents the results of the coverage of the different CES identified for this assessment, illustrating how well each strategy is represented across the CAIs.

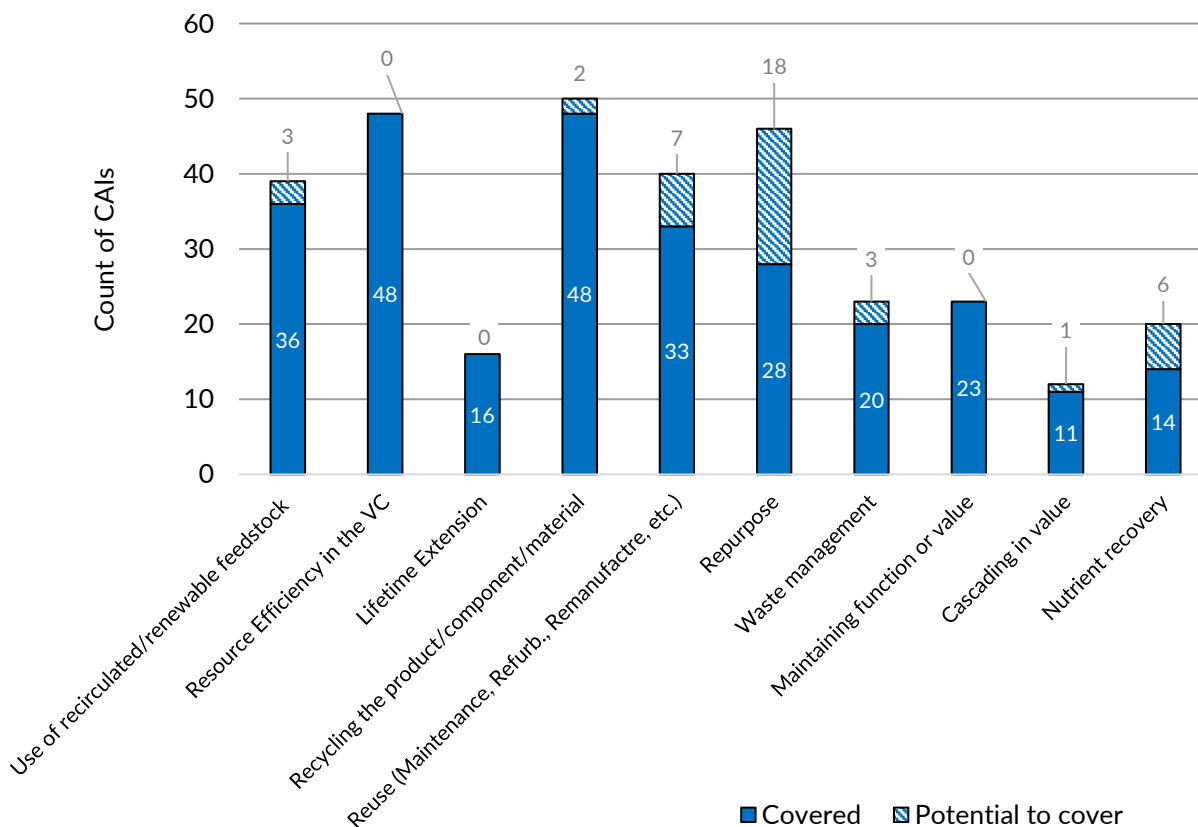


Figure 3.6. Coverage of Selected CESs in CAIs

The results show varying levels of coverage across these strategies. The most frequently covered CES are "Resource efficiency in the value chain" and "Recycling the product/component/material," with 48 CAIs each addressing these strategies. This highlights a strong focus on optimising resource use and recycling within current CAIs. "Use of recirculated/renewable feedstock" and "Maintaining function or value" are also well-represented, with 36 and 23 CAIs, respectively. These strategies emphasise the importance of utilising sustainable materials and preserving the functionality and value of products. "Reuse (via maintenance, refurbishment, remanufacture, etc.)", "Repurpose" and "Waste management" are covered by 33, 28 and 20 CAIs, respectively, also showing a moderate level of integration in current CAIs. The "Lifetime extension" strategy also has low coverage, with only 16 CAIs addressing it. This highlights a gap in the consideration of product lifetimes within current CAIs, suggesting a need for more comprehensive assessments that take product longevity into account. "Cascading in value" and "Nutrient recovery" are the least frequently addressed, with 11 and 14 CAIs, respectively. This suggests potential areas for further development and integration into CAIs. The relatively low coverage of the "Nutrient recovery" CES is particularly noteworthy given its critical importance in BBPS. The recovery of nutrients plays a crucial role in the closure of the biological loop, returning valuable nutrients to the ecosystem. Enhancing the integration of these strategies into CAIs would significantly improve the assessment and promotion of circularity in bio-based systems. For example, the Nutrient Recovery Indicator (NRI) from Shaddel et al. (2019) measures the extent to which nutrients like nitrogen and phosphorus are recovered after the EOU state.

In addition to the fully covered strategies, several CES are partially addressed across different CAIs. Partial coverage is particularly notable for Repurpose (18 CAIs), Reuse (7 CAIs), and Nutrient recovery (6 CAIs). This indicates that these strategies are often indirectly reflected in the logic or formulation of indicators rather than being explicitly targeted. Such partial inclusion shows that while many CAIs concentrate on specific circular actions, they often still capture secondary or

complementary circularity effects. Strengthening the explicit integration of as many strategies as possible could therefore help achieve a more holistic and transparent representation of circularity in bio-based systems assessment.

3.4 CAI-level analysis: Shortlist of CAIs

The literature review process culminated in the creation of a concise list of CAIs tailored to evaluate BBPS comprehensively and effectively. By adhering to the criteria outlined in Section 2.5, a total of 34 CAIs were shortlisted. These CAIs were selected based on their frequency of use, practical application in bio-based systems, broad applicability, and comprehensive coverage of essential key characteristics. The CAIs included in the shortlist are those that have demonstrated significant relevance and reliability across multiple studies, ensuring their applicability to a wide range of BBPS. The CAIs that were included to balance and extend the coverage to all key characteristics were selected to provide the most balanced and practical list of CAIs for assessing the circularity of generic bio-based systems. Table 3 presents the short list of CAIs. The full characterization of all CAIs, including the 34 shortlisted, is presented in the Annex.

The shortlisted CAIs not only reflect those that have proven to be most relevant to the objectives of this project but also serve as a foundation for developing a coherent set of indicators that collectively address the different dimensions of circularity relevant to BBPS. Building on this, future work will translate the shortlist into a comprehensive indicator set capable of capturing both material and functional perspectives of circularity, encompassing the circulation of bio-based inputs and outputs, the cascading use of materials, the retention of value across successive lifetimes, and the effectiveness of R-strategy loops. The methodological integration of these dimensions into a unified circularity assessment framework for bio-based systems will be further developed and presented in Deliverable D4.2

Table 3. Shortlisted CAIs

CAI (Acronym)	CAI (Name)	Source	Short description
%CI	% Circular inflow	WBCSD, 2022	Measures the proportion of materials entering a system that are non-virgin or renewable and sustainably managed.
%CO	% Circular outflow	WBCSD, 2022	Assesses the share of output materials from a system that are recovered and reused.
%CRI	% Critical inflow	WBCSD, 2022	Indicates the percentage of input materials that are classified as critical, based on own or public lists of criticality materials.
BCS100	Biogenic Carbon Stored Over a Period of 100 years	Corona et al., 2022	Quantifies the biogenic carbon stored in products over a 100-year horizon, indicating long-term carbon retention.
BUE	Biomass Utilization Efficiency	Nova Institute, 2015	Measures how efficiently biomass is used within a production process, specifically focusing on the share of initial biomass that ends up in the final product.
BUE-E	Energetic Biomass Utilization Efficiency	Nova Institute, 2015	Evaluates the efficiency of biomass use specifically for energy applications, focusing on the share of energy in terms of Highest Heating Value (HHV) that end up in the final product in a manufacturing process or chemical reaction
BUF	Biomass Utilization Factor	Vom Berg et al., 2023	Quantifies biomass use across multiple cascading stages, tracking its allocation to products, energy, and waste streams.
BUI	Bioresource Utilization Index	Vamza et al., 2021	Assesses the efficiency of bioresource utilization by weighting product and by-product outputs according to a value hierarchy.
C-BCS	Circular Biogenic Carbon Storage	Corona et al., 2022	Measures the share of biogenic carbon that follows a circular pathway through recycling, reuse, and/or long-term storage processes.
CC	Circularity Calculator	IDEAL & CO Explore, 2021	Online tool for designers to visualize circularity via flows of reuse, remanufacture, and recycling, informing product design.
CD	Circularity Degree	Haas et al., 2015	Evaluates the proportion of recycled material in output flows, offering a direct measure of material recirculation.
CEI	Circular Economy Index	Di Maio and Rem, 2015	Compares the market value of recycled materials to the value of materials entering a recycling facility to assess value recovery.
CEIP	Circular Economy Indicator Prototype	Cayzer et al., 2017	Points-based Excel tool that scores circularity of products via a questionnaire encompassing different parts of its lifecycle, rated from 'Poor' to 'Very Good'.
CET	Circular Economy Toolkit	Evans and Bocken, 2014	Checklist-based tool assessing product circularity through questionnaire scores (1–3) across lifecycle phases.
CF	Cascade Factor	Mantau, 2015	Set of indicators that quantify how often primary bio-based resources are reused, recycled, or recovered before disposal.
CIC	Circularity indicator of a component	Cobo et al., 2018	Measures the proportion of a component recovered and reintegrated into new production cycles relative to waste generated.
CM	Combination Matrix	Figge et al., 2018	Evaluates resource recirculation and product longevity by mapping multiple use cycles and their duration on a two-dimensional matrix.

CMT	Circularity Measurement Toolkit	Garza-Reyes et al., 2019	Questionnaire-based toolkit for SMEs that categorizes circularity into nine distinct levels, ranging from organizations with no CE practices (Linear) to those actively participating in developing new CE technologies and regulations (Circular Developer).
CUSI	Cascade Use Set of Indicators	Hildebrandt et al., 2017	Evaluates cascading use of biomass through sequential applications before energy recovery or disposal.
eDIM	Ease of Disassembly	Vanegas et al., 2018	Evaluates the effort required to fully or partially disassemble a product by quantifying the time necessary for various disassembly tasks.
FRS	Final Retention in Society	Moraga et al., 2021	Measures the percentage of a primary raw material that remains in society after a specified time horizon.
HSI	Hybridized sustainability Indicators	Lokesh et al., 2020	Combines indicators from green chemistry and circularity to assess resource efficiency, renewability, and energy use.
LI	Longevity Indicator	Kusumo et al., 2022	Estimates product lifetime performance by comparing actual and expected duration of use.
MCI	Material Circularity Indicator (2019)	Ellen MacArthur Foundation, 2019	Calculates the degree of material circularity in a product by assessing the share of virgin versus recycled inputs, product utility, and recovery at end-of-life. It integrates material flow efficiency and product lifespan into a single, dimensionless score between 0 (linear) and 1 (fully circular).
MCI (mod. Razza)	Material Circularity Indicator (mod. Razza)	Razza et al., 2020	Adaptation of the 2015 MCI to bio-based materials, including biogenic carbon storage and renewability considerations.
MRS	Material Reutilization Score	CradleToGate, 2016	Quantifies the share of materials eligible for safe reuse or recycling according to Cradle-to-Cradle principles, indicating overall material recovery potential.
NRI	Nutrient recovery Indicator	Shaddel et al., 2019	Quantifies the proportion of nutrients (e.g., N, P) recovered and reintegrated into reintroduced into productive use, particularly in fertilizers or soil improvement products.
PLCM	Product-level Circularity Metric	Linder et al., 2017	Quantifies the degree of circularity of a product based on the economic value of its recirculated components. It integrates both closed- and open-loop recirculation.
QC	Circularity of Material Quality	Steinmann et al., 2019	Measures the quality of recycled materials relative to those produced from primary inputs. It accounts for the additional energy required to achieve equivalent quality and functionality.
RDI	Recycling Desirability Index	Al Amin et al., 2017	Measures the desirability of recycling a product or component. It encompasses three standardized dimensions: product complexity, recycling technology readiness level (TRL), and simplicity of material separation.
RPI	Reuse Potential Indicator for Secondary Materials	Park and Chertow, 2014	Estimates the potential for reuse of secondary materials based on their composition and quality.
SCI-C	Sustainable Circular Index - Circularity Indicators	Azevedo et al., 2017	Integrates circularity and sustainability dimensions by combining indicators on material recirculation, resource efficiency, and environmental performance. It provides a composite measure.
UOR	In-use occupation ratio	Moraga et al., 2021	Quantifies the percentage of a material's utilization (measured as mass multiplied by time of use) relative to the maximum theoretical utilization within a defined time horizon.
VRE	Value-Based Resource Efficiency	Di Maio et al., 2017	Relates the economic value retained after resource recovery to the value of total resource input, emphasizing value preservation.

4 Conclusions

The literature review conducted in this study has addressed the unique challenges of assessing circularity in BBPS by critically evaluating 73 CAIs. Given the specific characteristics of BBPS, traditional CE indicators, sets of indicators, and tools often fall short in capturing the intricate flows and sustainability impacts unique to bio-based products. Therefore, by integrating the CEPs within the BE, the CBE offers a novel and evolving approach to this sector. As a result, a robust list of CAIs and their characterisation for assessing the circularity of BBPS has been elaborated. This was achieved by first creating a detailed bio-based systems flowchart, which provides a comprehensive overview of the complex and interconnected nature of flows within bio-based systems. Subsequently, a practical and comprehensive list of CAIs applicable to bio-based systems was compiled, serving as a valuable reference of CAIs for researchers and practitioners. Each CAI was meticulously evaluated against a wide range of key characteristics to identify existing gaps, challenges, and opportunities in current practices.

The rigorous literature review process culminated in the identification of 34 CAIs that are particularly suited for evaluating BBPS and covering all key aspects of circularity that were proposed, providing a balanced and effective list of CAIs. One significant finding from the review is the frequent neglect of key bio-based system characteristics, such as cascading in value, nutrient recovery, and renewable sourcing in existing CAIs in the literature. This gap highlights the need for more comprehensive CAIs that encompass such critical aspects. Additionally, the review identified a need for CAIs that go beyond merely assessing material flow to include functional value, thereby offering a deeper view of circularity.

The adoption of CAIs in BBPS assessments can contribute significantly to the advancement of CEPs, promoting sustainability and innovation within the bio-based sector. This study underscores the importance of developing tailored CAIs that not only capture the unique characteristics of bio-based systems but also integrate seamlessly into broader sustainability assessments. Ultimately, this work provides a valuable foundation for future research and practical applications, fostering a more sustainable and circular bio-based economy



5 References

- Adachi, Y. (2007). Application of Markov Chain Model to Calculate the Average Number of Times of Use of a Material in Society. An Allocation Methodology for Open-Loop Recycling. Part 2: Case Study for Steel (6 pp). *The International Journal of Life Cycle Assessment*, 12(1), 34–39. <https://doi.org/10.1065/lca2006.05.246.2>
- Azevedo, S. G., Godina, R., & Matias, J. C. de O. (2017). Proposal of a Sustainable Circular Index for Manufacturing Companies. *Resources*, 6(4), Article 4. <https://doi.org/10.3390/resources6040063>
- Baratsas, S. G., Pistikopoulos, E. N., & Avraamidou, S. (2022). A quantitative and holistic circular economy assessment framework at the micro level. *Computers & Chemical Engineering*, 160, 107697. <https://doi.org/10.1016/j.compchemeng.2022.107697>
- Blanca Corona, Blanca Corona, Li Shen, Li Shen, Denise Reike, Denise Reike, Jesús Rosales Carreón, Jesús Rosales Carreón, Ernst Worrell, & Ernst Worrell. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources Conservation and Recycling*. <https://doi.org/10.1016/j.resconrec.2019.104498>
- Bracquené, E., Dewulf, W., & Duflou, J. R. (2020). Measuring the performance of more circular complex product supply chains. *Resources, Conservation and Recycling*, 154, 104608. <https://doi.org/10.1016/j.resconrec.2019.104608>
- Brändström, J., & Eriksson, O. (2022). How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models. *Journal of Cleaner Production*, 342, 130973. <https://doi.org/10.1016/j.jclepro.2022.130973>
- Briassoulis, D., Pikasi, A., & Hiskakis, M. (2021a). Organic recycling of post-consumer /industrial bio-based plastics through industrial aerobic composting and anaerobic digestion—Techno-economic sustainability criteria and indicators. *Polymer Degradation and Stability*, 190, 109642. <https://doi.org/10.1016/j.polymdegradstab.2021.109642>
- Briassoulis, D., Pikasi, A., & Hiskakis, M. (2021b). Recirculation potential of post-consumer /industrial bio-based plastics through mechanical recycling—Techno-economic sustainability criteria and indicators. *Polymer Degradation and Stability*, 183, 109217. <https://doi.org/10.1016/j.polymdegradstab.2020.109217>
- Carus, M., & Dammer, L. (2018). The ‘Circular Bioeconomy’ – Concepts, Opportunities and Limitations. *Renewable Carbon Publications*. <https://renewable-carbon.eu/publications/product/nova-paper-9-the-circular-bioeconomy-concepts-opportunities-and-limitations---full-version/>
- Chripim, M. C., Mattsson, M., & Pia Ulvenblad. (2023). *The underrepresented key elements of Circular Economy: A critical review of assessment tools and a guide for action*. <https://doi.org/10.1016/j.spc.2022.11.019>
- Corona, B., Hoefnagels, R., Vural Gürsel, I., Moretti, C., van Veen, M., & Junginger, M. (2022). Metrics for minimising environmental impacts while maximising circularity in biobased products: The case of lignin-based asphalt. *Journal of Cleaner Production*, 379, 134829. <https://doi.org/10.1016/j.jclepro.2022.134829>
- Corona, B., Shen, L., Reike, D., Carreón, J. R., & Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources Conservation and Recycling*. <https://doi.org/10.1016/J.RESCONREC.2019.104498>
- Cradle to Cradle. (2021). *Cradle to Cradle Certified® Product Standard Version 4.1*. <https://c2ccertified.org/resources/cradle-to-cradle-certified-r-product-standard-version-4-1?scrollY=400>
- Dahiya, S., Katakojwala, R., Ramakrishna, S., & Mohan, S. V. (2020). Biobased Products and Life Cycle Assessment in the Context of Circular Economy and Sustainability. *Materials Circular Economy*, 2(1), Article 1. <https://doi.org/10.1007/s42824-020-00007-x>
- De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021). A systematic review for measuring circular economy: The 61 indicators. *Journal of Cleaner Production*, 281, 124942. <https://doi.org/10.1016/j.jclepro.2020.124942>

- Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, Conservation and Recycling*, 122, 163–171. <https://doi.org/10.1016/j.resconrec.2017.02.009>
- Dornburg, V., Lewandowski, I., & Patel, M. (2003). Comparing the Land Requirements, Energy Savings, and Greenhouse Gas Emissions Reduction of Biobased Polymers and Bioenergy. *Journal of Industrial Ecology*, 7(3–4), 93–116. <https://doi.org/10.1162/108819803323059424>
- EEA. (2018). *The circular economy and the bioeconomy—Partners in sustainability* [Publication]. <https://www.eea.europa.eu/publications/circular-economy-and-bioeconomy>
- Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*. <https://doi.org/10.1016/J.JCLEPRO.2016.10.196>
- EMF. (2015). *Circular economy introduction*. <https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview>
- EMF. (2019a). *Material Circularity Indicator (MCI)*. <https://www.ellenmacarthurfoundation.org/material-circularity-indicator>
- EMF. (2019b). *The butterfly diagram: Visualising the circular economy*. The Butterfly Diagram: Visualising the Circular Economy. <https://www.ellenmacarthurfoundation.org/circular-economy-diagram>
- Erik Roos Lindgreen, Erik Roos Lindgreen, Erik Roos Lindgreen, Roberta Salomone, Roberta Salomone, Tatiana Reyes, & Tatiana Reyes. (2020). A Critical Review of Academic Approaches, Methods and Tools to Assess Circular Economy at the Micro Level. *Sustainability*. <https://doi.org/10.3390/su12124973>
- European Commission. (2018). *A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment: updated bioeconomy strategy*. Publications Office of the European Union. <https://data.europa.eu/doi/10.2777/792130>
- European Commission. (2020). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: A new Circular Economy Action Plan For a cleaner and more competitive Europe*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN>
- European Commission. (2022). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A0142%3AFIN>
- European Commission. (2023). *Study on the critical raw materials for the EU 2023 – Final report*. <https://doi.org/10.2873/725585>
- EUROSTAT. (2022). *Statistical classification of economic activities in the European community Rev.2.1 (NACE 2.1)* [Data set]. https://showvoc.op.europa.eu/#/datasets/ESTAT_Statistical_Classification_of_Economic_Activities_in_the_European_Community_Rev._2.1._%28NACE_2.1%29/data
- Evans, J., & Bocken, N. (2014, April 28). *A tool for manufacturers to find opportunity in the circular economy – www.circulareconomytoolkit.org*.
- Fashion Positive. (2020). *Circular Materials Guidelines*. <https://fashionpositive.org/circular-materials/>
- Fleitas Girett, A., Wassenaar, T., & Pabon-Pereira, C. (2023). Assessing nutrient circularity capacity in South American metropolitan areas. *Resources, Conservation and Recycling*, 197, 107085. <https://doi.org/10.1016/j.resconrec.2023.107085>
- Frisvold, G. B., Moss, S. M., Hodgson, A., & Maxon, M. E. (2021). Understanding the U.S. Bioeconomy: A New Definition and Landscape. *Sustainability*, 13(4), Article 4. <https://doi.org/10.3390/su13041627>
- Garza-Reyes, J. A., Salomé Valls, A., Peter Nadeem, S., Anosike, A., & Kumar, V. (2019). A circularity measurement toolkit for manufacturing SMEs. *International Journal of Production Research*, 57(23), 7319–7343. <https://doi.org/10.1080/00207543.2018.1559961>

- Geissdoerfer, M., Savaget, P., Bocken, N., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2015.09.007>
- Gonçalves, M., Freire, F., & Garcia, R. (2021). Material flow analysis of forest biomass in Portugal to support a circular bioeconomy. *Resources, Conservation and Recycling*, 169, 105507. <https://doi.org/10.1016/j.resconrec.2021.105507>
- Graedel, T. E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F., & Sonnemann, G. (2011). What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology*, 15(3), 355–366. <https://doi.org/10.1111/j.1530-9290.2011.00342.x>
- Greenhalgh, T., & Peacock, R. (2005). Effectiveness and efficiency of search methods in systematic reviews of complex evidence: Audit of primary sources. *BMJ*, 331(7524), 1064–1065. <https://doi.org/10.1136/bmj.38636.593461.68>
- Gursel, I. V., Elbersen, B., Meesters, K., & van Leeuwen, M. (2022). Defining Circular Economy Principles for Biobased Products. *Sustainability*. <https://doi.org/10.3390/SU141912780>
- Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology*, 19(5), 765–777. <https://doi.org/10.1111/jiec.12244>
- Hackenhaar, I. C., Moraga, G., Thomassen, G., Taelman, S. E., Dewulf, J., & Bachmann, T. M. (2024). A comprehensive framework covering Life Cycle Sustainability Assessment, resource circularity and criticality. *Sustainable Production and Consumption*, 45, 509–524. <https://doi.org/10.1016/j.spc.2024.01.018>
- Harder, R., Giampietro, M., & Smukler, S. (2021). Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems. *Resources, Conservation and Recycling*, 172, 105693. <https://doi.org/10.1016/j.resconrec.2021.105693>
- Harris, S. E., Steve Harris, Michael Martin, Michael Martin, Michael Martin, Derek Diener, Derek Diener, & Derek Diener. (2020). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. *Sustainable Production and Consumption*. <https://doi.org/10.1016/j.spc.2020.09.018>
- Hatzfeld, T., Backes, J. G., Guenther, E., & Traverso, M. (2022). Modeling circularity as Functionality Over Use-Time to reflect on circularity indicator challenges and identify new indicators for the circular economy. *Journal of Cleaner Production*, 379, 134797. <https://doi.org/10.1016/j.jclepro.2022.134797>
- Heidi Simone Kristensen, Heidi Simone Kristensen, Mette Mosgaard, & Mette Mosgaard. (2020). A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2019.118531>
- Helbig, C., Wietschel, L., Thorenz, A., & Tuma, A. (2016). How to evaluate raw material vulnerability—An overview. *Resources Policy*, 48, 13–24. <https://doi.org/10.1016/j.resourpol.2016.02.003>
- Hendriks, Ch. F., Janssen, G. M. T., & Vogtländer, J. (2002). The Eco-Costs/Value-Ratio. In M. Anson, J. M. Ko, & E. S. S. Lam (Eds), *Advances in Building Technology* (pp. 1391–1398). Elsevier. <https://doi.org/10.1016/B978-008044100-9/50173-X>
- Hermann, B. G., Debeer, L., De Wilde, B., Blok, K., & Patel, M. K. (2011). To compost or not to compost: Carbon and energy footprints of biodegradable materials' waste treatment. *Polymer Degradation and Stability*, 96(6), 1159–1171. <https://doi.org/10.1016/j.polymdgradstab.2010.12.026>
- Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahí, M., Trasobares, A., & European Forest Institute. (2017). *Leading the way to a European circular bioeconomy strategy* (From Science to Policy) [From Science to Policy]. European Forest Institute. <https://doi.org/10.36333/fs05>

- Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., & De Meester, S. (2017). Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resources, Conservation and Recycling*, 120, 46–54. <https://doi.org/10.1016/j.resconrec.2017.01.013>
- Iglesias, H., Paredes Ortiz, A., Pereira, Á., Fernández-Gutiérrez, D., & Lara-Guillén, A. J. (2025). Measuring the Circularity of Bio-Based Fertilizers: Applying the BIORADAR Product Circularity Monitoring Framework. *Applied Sciences*, 15(14), 7701. <https://doi.org/10.3390/app15147701>
- ISO. (2017). *ISO 21930:2017. Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and service.*
- ISO. (2024a). *ISO 59004:2024. Circular economy — Vocabulary, principles and guidance for implementation.* <https://www.iso.org/standard/80648.html>
- ISO. (2024b). *ISO 59020:2024. Circular economy—Measuring and assessing circularity performance.* <https://www.iso.org/standard/80650.html>
- Jarre, M., Petit-Boix, A., Priefer, C., Meyer, R., & Leipold, S. (2020). Transforming the bio-based sector towards a circular economy—What can we learn from wood cascading? *FOREST POLICY AND ECONOMICS*, 110, 101872. <https://doi.org/10.1016/j.forpol.2019.01.017>
- Jerome, A., Helander, H., Ljunggren, M., & Janssen, M. (2022). Mapping and testing circular economy product-level indicators: A critical review. *Resources, Conservation and Recycling*, 178, 106080. <https://doi.org/10.1016/j.resconrec.2021.106080>
- Joanicjusz Nazarko, Joanicjusz Nazarko, Ewa Chodakowska, Ewa Chodakowska, Lukasz Nazarko, Łukasz Nazarko, & Lukasz Nazarko. (2022). Evaluating the Transition of the European Union Member States towards a Circular Economy. *Energies*. <https://doi.org/10.3390/en15113924>
- Joint Research Centre (European Commission), Talens Peiró, L., Blengini, G. A., Mathieux, F., & Nuss, P. (2018). *Towards recycling indicators based on EU flows and raw materials system analysis data: Supporting the EU 28 raw materials and circular economy policies through RMIS.* Publications Office of the European Union. <https://data.europa.eu/doi/10.2760/092885>
- Julian Kirchherr, Andrea Urbinati, & Kris Hartley. (2023). *Circular economy: A new research field?* <https://doi.org/10.1111/jiec.13426>
- Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., van Leeuwen, M., M'Barek, R., van Meijl, H., Piotrowski, S., Ronzon, T., Sauer, J., Verhoog, D., Verkerk, P. J., Vrachioli, M., Wesseler, J. H. H., & Zhu, B. X. (2021). Development of the Circular Bioeconomy: Drivers and Indicators. *Sustainability*, 13(1), Article 1. <https://doi.org/10.3390/su13010413>
- Keegan, D., Kretschmer, B., Elbersen, B., & Panoutsou, C. (2013). Cascading use: A systematic approach to biomass beyond the energy sector. *Biofuels, Bioproducts and Biorefining*, 7(2), 193–206. <https://doi.org/10.1002/bbb.1351>
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resources, Conservation and Recycling*, 194, 107001. <https://doi.org/10.1016/j.resconrec.2023.107001>
- Ko, J., Guedes, G. B., Badurdeen, F., Jawahir, I. S., Morris, K. C., Ferrero, V., Hapuwatte, B., Bradley, R., & Raihanian, A. (2024). A critical analysis of circular product attributes and limitations of product circularity assessment methods. *Resources, Conservation & Recycling Advances*, 23, 200219. <https://doi.org/10.1016/j.rcradv.2024.200219>
- Kristensen, H. S., & Mosgaard, M. A. (2020). A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? *Journal of Cleaner Production*, 243, 118531. <https://doi.org/10.1016/j.jclepro.2019.118531>

- Kusumo, F., Mahlia, T. M. I., Pradhan, S., Ong, H. C., Silitonga, A. S., Fattah, I. M. R., Nghiem, L. D., & Mofijur, M. (2022). A framework to assess indicators of the circular economy in biological systems. *Environmental Technology & Innovation*, 28, 102945. <https://doi.org/10.1016/j.eti.2022.102945>
- Ladu, L., & Morone, P. (2021). Holistic approach in the evaluation of the sustainability of bio-based products: An Integrated Assessment Tool. *Sustainable Production and Consumption*, 28, 911-924e6. <https://doi.org/10.1016/j.spc.2021.07.006>
- Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology*, 21(3), Article 3. <https://doi.org/10.1111/jiec.12552>
- Lokesh, K., Matharu, A. S., Kookos, I. K., Ladakis, D., Koutinas, A., Morone, P., & Clark, J. (2020). Hybridised sustainability metrics for use in life cycle assessment of bio-based products: Resource efficiency and circularity. *Green Chemistry*, 22(3), Article 3. <https://doi.org/10.1039/C9GC02992C>
- Mancini, E., & Raggi, A. (2021). A review of circularity and sustainability in anaerobic digestion processes. *Journal of Environmental Management*, 291, 112695. <https://doi.org/10.1016/j.jenvman.2021.112695>
- Mantau, U. (2015). Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. *Biomass and Bioenergy*, 79, 28–38. <https://doi.org/10.1016/j.biombioe.2014.08.013>
- Matos, J., Martins, C., Simões, C. L., & Simoes, R. (2023). Comparative analysis of micro level indicators for evaluating the progress towards a circular economy. *Sustainable Production and Consumption*, 39, 521–533. <https://doi.org/10.1016/j.spc.2023.06.002>
- Meath, C., Karlovšek, J., Navarrete, C., Eales, M., & Hastings, P. (2022). Co-designing a multi-level platform for industry level transition to circular economy principles: A case study of the infrastructure CoLab. *Journal of Cleaner Production*, 347. Scopus. <https://doi.org/10.1016/j.jclepro.2022.131080>
- Mesa, J. A., Sierra-Fontalvo, L., Ortegon, K., & Gonzalez-Quiroga, A. (2024). Advancing circular bioeconomy: A critical review and assessment of indicators. *Sustainable Production and Consumption*, 46, 324–342. <https://doi.org/10.1016/j.spc.2024.03.006>
- Mesa, J., Esparragoza, I., & Maury, H. (2018). Developing a set of sustainability indicators for product families based on the circular economy model. *Journal of Cleaner Production*, 196, 1429–1442. <https://doi.org/10.1016/j.jclepro.2018.06.131>
- Metic, J., McAloone, T. C., & Pigosso, D. C. A. (2021). A LOOK INTO CIRCULAR ECONOMY RESEARCH: EXPLORING THE BIO AND TECHNO CYCLES AND THE NEED FOR DUAL CIRCULARITY. *Proceedings of the Design Society*, 1, 121–130. <https://doi.org/10.1017/pds.2021.13>
- Mohamed Sultan, A. A., Lou, E., & Mativenga, P. T. (2017). What should be recycled: An integrated model for product recycling desirability. *Journal of Cleaner Production*, 154, 51–60. <https://doi.org/10.1016/j.jclepro.2017.03.201>
- Monia Niero, Monia Niero, Pradip P. Kalbar, & Pradip P. Kalbar. (2019). Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resources Conservation and Recycling*. <https://doi.org/10.1016/j.resconrec.2018.10.002>
- Moraga, G., Huysveld, S., De Meester, S., & Dewulf, J. (2021). Development of circularity indicators based on the in-use occupation of materials. *Journal of Cleaner Production*, 279, 123889. <https://doi.org/10.1016/j.jclepro.2020.123889>
- Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., de Meester, S., & Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, 146, 452–461. <https://doi.org/10.1016/j.resconrec.2019.03.045>
- Muscat, A., de Olde, E. M., Ripoll-Bosch, R., Van Zanten, H. H. E., Metze, T. A. P., Termeer, C. J. A. M., van Ittersum, M. K., & de Boer, I. J. M. (2021). Principles, drivers and opportunities of a circular bioeconomy. *Nature Food*, 2(8), 561–566. <https://doi.org/10.1038/s43016-021-00340-7>
- Muska, A., Popluga, D., & Pilvere, I. (2022). Assessment of the Concentration and Structure of the Bioeconomy: The Regional Approach. *Emerging Science Journal*, 7(1), Article 1. <https://doi.org/10.28991/ESJ-2023-07-01-05>

- Navare, K., Muys, B., Vrancken, K. C., & Van Acker, K. (2021). Circular economy monitoring – How to make it apt for biological cycles? *Resources, Conservation and Recycling*, *170*, 105563. <https://doi.org/10.1016/j.resconrec.2021.105563>
- Nelen, D., Manshoven, S., Peeters, J. R., Vanegas, P., D’Haese, N., & Vrancken, K. (2014). A multidimensional indicator set to assess the benefits of WEEE material recycling. *Journal of Cleaner Production*, *83*, 305–316. <https://doi.org/10.1016/j.jclepro.2014.06.094>
- Nobre, G. C., & Tavares, E. (2021). The quest for a circular economy final definition: A scientific perspective. *Journal of Cleaner Production*, *314*, 127973. <https://doi.org/10.1016/j.jclepro.2021.127973>
- OECD. (2024). *Monitoring Progress towards a Resource-Efficient and Circular Economy*. Organisation for Economic Co-operation and Development. https://www.oecd-ilibrary.org/environment/monitoring-progress-towards-a-resource-efficient-and-circular-economy_3b644b83-en
- Olsson, O., Roos, A., Guisson, R., Bruce, L., Lamers, P., Hektor, B., Thrän, D., Hartley, D., Ponitka, J., & Hildebrandt, J. (2018). Time to tear down the pyramids? A critique of cascading hierarchies as a policy tool. *WIREs Energy and Environment*, *7*(2), Article 2. <https://doi.org/10.1002/wene.279>
- Paletto, A., Becagli, C., Geri, F., Sacchelli, S., & De Meo, I. (2022). Use of Participatory Processes in Wood Residue Management from a Circular Bioeconomy Perspective: An Approach Adopted in Italy. *Energies*, *15*(3), Article 3. <https://doi.org/10.3390/en15031011>
- Parchomenko, A., Nelen, D., Gillabel, J., & Rechberger, H. (2019). Measuring the circular economy—A Multiple Correspondence Analysis of 63 metrics. *Journal of Cleaner Production*, *210*, 200–216. <https://doi.org/10.1016/j.jclepro.2018.10.357>
- Park, J. Y., & Chertow, M. R. (2014). Establishing and testing the “reuse potential” indicator for managing wastes as resources. *Journal of Environmental Management*, *137*, 45–53. <https://doi.org/10.1016/j.jenvman.2013.11.053>
- Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, *129*, 81–92. <https://doi.org/10.1016/j.resconrec.2017.10.019>
- Pieratti, E., Paletto, A., De Meo, I., Fagarazzi, C., & Rillo Migliorini, M. G. (2019). Assessing the forest-wood chain at local level: A Multi-Criteria Decision Analysis (MCDA) based on the circular bioeconomy principles. *ANNALS OF FOREST RESEARCH*, *62*(1), 123–138. <https://doi.org/10.15287/afr.2018.1238>
- Preisner, M., Smol, M., Horttanainen, M., Deviatkin, I., Havukainen, J., Klavins, M., Ozola-Davidane, R., Kruopienė, J., Szatkowska, B., Appels, L., Houtmeyers, S., & Roosalu, K. (2022). Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector. *Journal of Environmental Management*, *304*, 114261. <https://doi.org/10.1016/j.jenvman.2021.114261>
- Ramos Huarachi, D. A., Hluszko, C., Ulloa, M. I. C., Moretti, V., Ramos Quispe, J. A., Puglieri, F. N., & Francisco, A. C. de. (2023). Life Cycle Thinking for a Circular Bioeconomy: Current Development, Challenges, and Future Perspectives. *Sustainability*, *15*(11), Article 11. <https://doi.org/10.3390/su15118543>
- Razza, F., Briani, C., Breton, T., & Marazza, D. (2020). Metrics for quantifying the circularity of bioplastics: The case of bio-based and biodegradable mulch films. *Resources, Conservation and Recycling*, *159*, 104753. <https://doi.org/10.1016/j.resconrec.2020.104753>
- Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 Text with EEA Relevance. (2024). <http://data.europa.eu/eli/reg/2024/1252/oj/eng>
- Rocchi, L., Paolotti, L., Cortina, C., Fagioli, F. F., & Boggia, A. (2021). Measuring circularity: An application of modified Material Circularity Indicator to agricultural systems. *Agricultural and Food Economics*, *9*(1), 9. <https://doi.org/10.1186/s40100-021-00182-8>
- Rohit Panchal, Rohit Panchal, Anju Singh, Anju Singh, Hema Diwan, & Hema Diwan. (2021). Does circular economy performance lead to sustainable development? - A systematic literature review. *Journal of Environmental Management*. <https://doi.org/10.1016/j.jenvman.2021.112811>

- Rosenboom, J.-G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials*, 7(2), 117–137. <https://doi.org/10.1038/s41578-021-00407-8>
- Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production*, 207, 542–559. <https://doi.org/10.1016/j.jclepro.2018.10.014>
- Sazdovski, I., Hauschild, M. Z., Arfelis, S., Bala, A., & Fullana-i-Palmer, P. (2024). Short Communication: Biogenic carbon in fast-moving products: A deception or real contribution to circularity? *Environmental Advances*, 15, 100461. <https://doi.org/10.1016/j.envadv.2023.100461>
- Schrijvers, D., Hool, A., Blengini, G. A., Chen, W.-Q., Dewulf, J., Eggert, R., van Ellen, L., Gauss, R., Goddin, J., Habib, K., Hagelüken, C., Hirohata, A., Hofmann-Antenbrink, M., Kosmol, J., Le Gleuher, M., Grohol, M., Ku, A., Lee, M.-H., Liu, G., ... Wäger, P. A. (2020). A review of methods and data to determine raw material criticality. *Resources, Conservation and Recycling*, 155, 104617. <https://doi.org/10.1016/j.resconrec.2019.104617>
- Shaddel, S., Bakhtiary-Davijany, H., Kabbe, C., Dadgar, F., & Østerhus, S. W. (2019). Sustainable Sewage Sludge Management: From Current Practices to Emerging Nutrient Recovery Technologies. *Sustainability*, 11(12), Article 12. <https://doi.org/10.3390/su11123435>
- Simone Bastianoni, Giulia Goffetti, Elena Neri, Nicoletta Patrizi, Anna Ruini, Fabio Sporchia, & Federico Maria Pulselli. (2023). *LCA based circularity indices of systems at different scales: A holistic approach*. <https://doi.org/10.1016/j.scitotenv.2023.165245>
- Siregar, M., Raihan, R., & Cahyono, C. (2023). Application of circular economy in manufacturing industry in Indonesia. *AMCA Journal of Community Development*, 3(1), Article 1. <https://doi.org/10.51773/ajcd.v3i1.211>
- Sirkin, T., & Houten, M. ten. (1994). The cascade chain: A theory and tool for achieving resource sustainability with applications for product design. *Resources, Conservation and Recycling*, 10(3), 213–276. [https://doi.org/10.1016/0921-3449\(94\)90016-7](https://doi.org/10.1016/0921-3449(94)90016-7)
- Stegmann, P., Gerritse, T., Shen, L., Londo, M., Puente, Á., & Junginger, M. (2023). The global warming potential and the material utility of PET and bio-based PEF bottles over multiple recycling trips. *Journal of Cleaner Production*, 395, 136426. <https://doi.org/10.1016/j.jclepro.2023.136426>
- Stegmann, P., Londo, M., & Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation & Recycling: X*, 6, 100029. <https://doi.org/10.1016/j.rcrx.2019.100029>
- Steinmann, Z. J. N., Huijbregts, M. A. J., & Reijnders, L. (2019). How to define the quality of materials in a circular economy? *Resources, Conservation and Recycling*, 141, 362–363. <https://doi.org/10.1016/j.resconrec.2018.10.040>
- Stumpf, L., Schöggel, J.-P., & Baumgartner, R. J. (2021). Climbing up the circularity ladder? – A mixed-methods analysis of circular economy in business practice. *Journal of Cleaner Production*, 316, 128158. <https://doi.org/10.1016/j.jclepro.2021.128158>
- Tadesse, S. T., Oenema, O., van Beek, C., & Ocho, F. L. (2019). Nitrogen allocation and recycling in peri-urban mixed crop–livestock farms in Ethiopia. *Nutrient Cycling in Agroecosystems*, 115(2), 281–294. <https://doi.org/10.1007/s10705-018-9957-z>
- Toni, M. (2023). Conceptualization Of Circular Economy And Sustainability At The Business Level. Circular Economy And Sustainable Development. *INTERNATIONAL JOURNAL OF EMPIRICAL RESEARCH METHODS*, 1(2), 81–89. <https://doi.org/10.59762/ijerm205275791220231205140635>
- UN Environmental Programme. (2018). *Re-defining Value – The Manufacturing Revolution*. <https://www.resourcepanel.org/reports/re-defining-value-manufacturing-revolution>
- Upadhayay, S., Alqassimi, O., Khashadourian, E., Sherm, A., & Prajapati, D. (2024). Development in the Circular Economy Concept: Systematic Review in Context of an Umbrella Framework. *Sustainability*. <https://doi.org/10.3390/SU16041500>

- van Zanten, H. H. E., Simon, W., van Selm, B., Wacker, J., Maindl, T. I., Frehner, A., Hijbeek, R., van Ittersum, M. K., & Herrero, M. (2023). Circularity in Europe strengthens the sustainability of the global food system. *Nature Food*, 4(4), 320–330. <https://doi.org/10.1038/s43016-023-00734-9>
- Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. *Resources, Conservation and Recycling*, 135, 323–334. <https://doi.org/10.1016/j.resconrec.2017.06.022>
- Verstraeten-Jochems, J., Keijzer, E., van Harmelen, T., Kootstra, L., Kuindersma, P., & Koch, R. (2018). IMPACT: A Tool for R&D Management of Circular Economy Innovations. *Procedia CIRP*, 69, 769–774. <https://doi.org/10.1016/j.procir.2017.11.096>
- Vinod, A., Sanjay, M. R., Suchart, S., & Jyotishkumar, P. (2020). Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites. *Journal of Cleaner Production*, 258, 120978. <https://doi.org/10.1016/j.jclepro.2020.120978>
- Vom Berg, C., Carus, M., Piltz, G., Dammer, L., Breitmayer, E., & Essel, R. (2023). The Biomass Utilization Factor (BUF). *Industrial Biotechnology*, 19(2), 49–61. <https://doi.org/10.1089/ind.2023.29308.cvb>
- Vulsteke, K., Huysveld, S., Thomassen, G., Beylot, A., Rechberger, H., & Dewulf, J. (2024). What is the meaning of value in a circular economy? A conceptual framework. *Resources, Conservation and Recycling*, 207, 107687. <https://doi.org/10.1016/j.resconrec.2024.107687>
- Vural Gursel, I., Elbersen, B., & Meesters, K. P. H. (2023). Monitoring circular biobased economy – Systematic review of circularity indicators at the micro level. *Resources, Conservation and Recycling*, 197, 107104. <https://doi.org/10.1016/j.resconrec.2023.107104>
- Vural Gursel, I., Elbersen, B., Meesters, K. P. H., & van Leeuwen, M. (2022). Defining Circular Economy Principles for Biobased Products. *Sustainability*, 14(19), Article 19. <https://doi.org/10.3390/su141912780>
- Wang, P., & Kara, S. (2019). Material Criticality and Circular Economy: Necessity of Manufacturing Oriented Strategies. *Procedia CIRP*, 80, 667–672. <https://doi.org/10.1016/j.procir.2019.01.056>
- WBCSD, W. B. C. for S. D. (2023, May 30). *Circular Transition Indicators v4.0*. <https://www.wbcsd.org/resources/circular-transition-indicators-v4/>
- Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering*, 1–10. <https://doi.org/10.1145/2601248.2601268>
- World Economic Forum. (2023, July 7). *What is 'bio-based' construction and how could it help cities get to net zero?* World Economic Forum. <https://www.weforum.org/agenda/2023/07/how-nature-can-help-build-the-cities-of-the-future-and-contribute-to-net-zero-in-the-process/>
- Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P.-S. (2023). Circular economy strategies for combating climate change and other environmental issues. *Environmental Chemistry Letters*, 21(1), 55–80. <https://doi.org/10.1007/s10311-022-01499-6>



Deliverable D4.1. Critical evaluation of circularity assessment methods & indicators

Annex

August 2024

Cristian Pérez Hernández, Pieter Nachtergaele



This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101135071.

Document Information

Work package and deliverable number	WP4, Deliverable D4.1
Authors	Cristian Pérez Hernández, Pieter Nachtergaele
Involved organisations	UGENT
Reviewers	ESCIB Consortium
Document date/version	Final version

Project Information

Project acronym	ESCIB
Project title:	Developing environmental sustainability & circularity assessment methodologies for industrial bio-based systems
Project number:	101135071
Coordinator	WIP Renewable Energies
Project website	www.escib.eu
Start date:	1 January 2024
Duration:	48 months

Dissemination level of this document

- | | |
|-------------------------------------|-----------|
| <input checked="" type="checkbox"/> | Public |
| <input type="checkbox"/> | Sensitive |

Disclaimer



The ESCIB project has received funding from the European Union's Horizon Europe Framework Programme under grant agreement No.101135071.

The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

ACKNOWLEDGMENT & DISCLAIMER

The ESCIB project has received funding from the European Union's Horizon Europe Framework Programme under grant agreement No.101135071.

The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Reproduction is authorised provided the source is acknowledged.

List of contents

1	Key Characteristics assessment tables	6
2	Key Characteristics assessment figures	33

List of tables

Table 1.	Full list of CAIs studied with the references and acronym.	6
Table 2.	Characterisation of the full list of CAIs according to applications, specificity, implementation level, complexity and dimensionality. CAI rows that are not included in the short list are coloured in grey.	12
Table 3.	Characterisation of the full list of CAIs according to the flows and functional value measurement. CAI rows that are not included in the short list are coloured in grey.	16
Table 4.	Characterisation of the full list of CAIs according to sustainability, criticality and energy and utilities considerations. CAI rows that are not included in the short list are coloured in grey.	19
Table 5.	Characterisation of the full list of CAIs according to the flow(s) they cover in the bio-based systems flowchart. CAI rows that are not included in the short list are coloured in grey.	23
Table 6.	Characterisation of the full list of CAIs according to the CE Strategies coverage. X: Coverage, P: Partial coverage. CAI rows that are not included in the short list are coloured in grey.	26
Table 7.	Characterisation of the full list of CAIs according to the CE Principles coverage. X: Coverage, P: Partial coverage. CAI rows that are not included in the short list are coloured in grey.	30

List of figures

Figure 1.	Classification of CAIs by complexity.	33
Figure 2.	Classification of CAIs by implementation level.	33
Figure 3.	Classification of CAIs by dimensionality.	33
Figure 4.	Classification of CAIs by flows measured.	34
Figure 5.	Classification of CAIs by value reference.	34
Figure 6.	Classification of CAIs by the sustainability dimension coverage.	35
Figure 7.	Classification of CAIs by sustainability dimensions addressed.	35
Figure 8.	Classification of CAIs by the inclusion of energy, utilities and other auxiliaries.	35
Figure 9.	Classification of CAIs by criticality coverage.	36
Figure 10.	Classification of CAIs by the addressing of biotic and abiotic material.	36
Figure 11.	Classification of CAIs by coverage of the bio-based systems flowchart regions.	36
Figure 12.	Classification of CAIs by the flow cluster from the bio-based systems flowchart.	37
Figure 13.	Classification of CAIs by CE Strategies coverage.	37

Glossary

BBPS	Bio-based Product Systems
CAI	Circularity Assessment Indicator
CBE	Circular Bioeconomy
CE	Circular Economy
CEP	Circular Economy Principle
CES	Circular Economy Strategy
CPA	European Statistical Classification of Products by Activity
CRM	Critical Raw Material
EC	European Commission
EMF	Ellen MacArthur Foundation
EOL	End-of-life
EOU	End-of-use
LCA	Life Cycle Assessment
UN	United Nations

1 Key Characteristics assessment tables

Table 1. Full list of CAIs studied with the references and acronym.

CAI (Acronym)	CAI (Name)	Source	Output type	Short description
%CI	% Circular inflow	WBCSD, 2022	Quantitative	Measures the proportion of materials entering a system that are non-virgin or renewable and sustainably managed.
%CO	% Circular outflow	WBCSD, 2022	Quantitative	Assesses the share of output materials from a system that are recovered and reused.
%CRI	% Critical inflow	WBCSD, 2022	Quantitative	Indicates the percentage of input materials that are classified as critical, based on own or public lists of criticality materials.
%RT	% Recovery type	WBCSD, 2022	Quantitative	Presents a breakdown of the proportion of recovered outflow materials by recovery method.
BCI	Biorefinery Complexity Index	IEA Energy, 2014	Semi-quantitative	Assesses the complexity of biorefinery systems by evaluating platforms, feedstocks, products, and processes using TRL levels.
BCS100	Biogenic Carbon Stored Over a Period of 100 years	Corona et al., 2022	Quantitative	Quantifies the biogenic carbon stored in products over a 100-year horizon, indicating long-term carbon retention.
BUE	Biomass Utilisation Efficiency	Nova Institute, 2015	Quantitative	Measures how efficiently biomass is used within a production process, specifically focusing on the share of initial biomass that ends up in the final product.
BUE-E	Energetic Biomass Utilisation Efficiency	Nova Institute, 2015	Quantitative	Evaluates the efficiency of biomass use specifically for energy applications, focusing on the share of energy in terms of Highest Heating Value (HHV) that ends up in the final product in a manufacturing process or chemical reaction
BUF	Biomass Utilisation Factor	Vom Berg et al., 2023	Quantitative	Quantifies biomass use across multiple cascading stages, tracking its allocation to products, energy, and waste streams.
BUI	Bioresource Utilisation Index	Vamza et al., 2021	Quantitative	Assesses the efficiency of bioresource utilisation by weighting product and by-product outputs according to a value hierarchy.
C-BCS	Circular Biogenic Carbon Storage	Corona et al., 2022	Quantitative	Measures the share of biogenic carbon that follows a circular pathway through recycling, reuse, and/or long-term storage processes.
CC	Circularity Calculator	IDEAL & CO Explore, 2021	Quantitative	Online tool for designers to visualise circularity via flows of reuse, remanufacture, and recycling, informing product design.
CD	Circularity degree	Haas et al., 2015	Quantitative	Evaluates the proportion of recycled material in output flows, offering a direct measure of material recirculation.

CAI (Acronym)	CAI (Name)	Source	Output type	Short description
CEE-C	Circular economy efficiency for compost	Preisner et al., 2022	Quantitative	Evaluates the efficiency of composting systems within a circular economy context, considering nutrient recovery.
CEI	Circular Economy Index	Di Maio and Rem, 2015	Quantitative	Compares the market value of recycled materials to the value of materials entering a recycling facility to assess value recovery.
CEIP	Circular Economy Indicator Prototype	Cayzer et al., 2017	Semi-quantitative	Points-based Excel tool that scores circularity of products via a questionnaire encompassing different parts of its lifecycle, rated from 'Poor' to 'Very Good'.
CET	Circular Economy Toolkit	Evans and Bocken, 2014	Semi-quantitative	Checklist-based tool assessing product circularity through questionnaire scores (1–3) across lifecycle phases.
CF	Cascade Factor	Mantau, 2015	Quantitative	Set of indicators that quantify how often primary bio-based resources are reused, recycled, or recovered before disposal.
CI	Circularity Index	Cullen, 2017	Quantitative	Designed to measure the degree of circularity by evaluating both the quantity and quality of materials within an economy. It accounts for material stock dynamics, dissipative losses, and the energy required to restore materials to their original state.
CIC	Circularity indicator of a component	Cobo et al., 2018	Quantitative	Measures the proportion of a component recovered and reintegrated into new production cycles relative to waste generated.
CM	Combination Matrix	Figge et al., 2018	Quantitative	Evaluates resource recirculation and product longevity by mapping multiple use cycles and their duration on a two-dimensional matrix.
CMP	Circular Material Productivity	WBCSD, 2022	Quantitative	Measures a product's or company's efficiency in decoupling financial performance from the consumption of linear resources, assessing how effectively revenue can be generated while minimising the use of virgin, non-renewable materials.
CMT	Circularity Measurement Toolkit	Garza-Reyes et al., 2019	Semi-quantitative	Questionnaire-based toolkit for SMEs that categorises circularity into nine distinct levels, ranging from organisations with no CE practices (Linear) to those actively participating in developing new CE technologies and regulations (Circular Developer).
CR	Collection Rate	Graedel et al., 2011	Quantitative	Measures the proportion of discarded materials or products that are collected for reuse, recycling, or other recovery.
CST	Length of material use (as carbon sequestered time)	Stegmann et al., 2023	Quantitative	Calculates how long biogenic carbon remains stored within products before release to the atmosphere.
CUSI	Cascade Use Set of Indicators	Hildebrandt et al., 2017	Quantitative	Evaluates cascading use of biomass through sequential applications before energy recovery or disposal.
D	Displaced Production from recycling or reuse	Zink et al., 2015	Quantitative	Estimates avoided production impacts by substituting virgin production with recycled or reused materials.

CAI (Acronym)	CAI (Name)	Source	Output type	Short description
eDIM	Ease of Disassembly	Vanegas et al., 2018	Quantitative	Evaluates the effort required to fully or partially disassemble a product by quantifying the time necessary for various disassembly tasks.
EOL-RIR	End-of-Life Recycling Input Rate	JRC, 2018	Quantitative	Measures the proportion of recycled material derived from EOL products that is utilised as input in the production of new products, originally at the macro level.
EOL-RR	End-of-Life Recycling Rate	Graedel et al., 2011	Quantitative	Indicates the percentage of material recovered from EOU products that is successfully recycled and incorporated as a functional component in secondary products.
ER	Economic recircularity	Briassoulis et al., 2020	Quantitative	Relates economic value retained in circular systems to total economic input, linking circularity and profitability.
FCR	Circular Materials Guidelines Feedstock Content Requirements	Fashionpositive, 2020	Semi-quantitative	Quantifies the minimum required recycled or renewable content in materials to meet circular sourcing standards.
FRS	Final Retention in Society	Moraga et al., 2021	Quantitative	Measures the percentage of a primary raw material that remains in society after a specified time horizon.
HSI	Hybridised Sustainability Indicators	Lokesh et al., 2020	Semi-quantitative	Combines indicators from green chemistry and circularity to assess resource efficiency, renewability, and energy use.
INC	Input nutrient circularity	Harder et al., 2021	Quantitative	Quantifies the share of input nutrients derived from recovered sources.
LI	Longevity Indicator	Kusumo et al., 2022	Quantitative	Estimates product lifetime performance by comparing actual and expected duration of use.
MCI	Material Circularity Indicator (2019)	Ellen MacArthur Foundation, 2019	Quantitative	Calculates the degree of material circularity in a product by assessing the share of virgin versus recycled inputs, product utility, and recovery at end-of-life. It integrates material flow efficiency and product lifespan into a single, dimensionless score between 0 (linear) and 1 (fully circular).
MCI (mod. Razza)	Material Circularity Indicator (mod. Razza)	Razza et al., 2020	Quantitative	Adaptation of the 2015 MCI to bio-based materials, including biogenic carbon storage and renewability considerations.
MCI (mod. Rocchi)	Material Circularity Indicator (mod. Rocchi)	Rocchi et al., 2021	Quantitative	Adaptation of the 2019 MCI by incorporating product functionality and recovery efficiency in the circularity score.
MI	Material Intensity	Stegmann et al., 2023	Quantitative	Quantifies the mass of materials needed per functional output, providing insight into material efficiency and the potential for reducing resource inputs.
MRS	Material Reutilization Score	CradleToGate, 2016	Quantitative	Quantifies the share of materials eligible for safe reuse or recycling according to Cradle-to-Cradle principles, indicating overall material recovery potential.

CAI (Acronym)	CAI (Name)	Source	Output type	Short description
NF-EOL-RR	Nonfunctional End-of-life Recycling Rate	Graedel et al., 2011	Quantitative	Measures the share of recycled material that loses its original properties upon recycling, and therefore does not provide its original functionality in subsequent cycles.
NRI	Nutrient recovery Indicator	Shaddel et al., 2019	Quantitative	Quantifies the proportion of nutrients (e.g., N, P) recovered and reintegrated into reintroduced into productive use, particularly in fertilisers or soil improvement products.
N-RI	Nitrogen Recycling Index	Tadesse et al., 2019	Quantitative	Measures the proportion of nitrogen recovered from waste streams and reintroduced into productive use.
NTUM	Number of Times of Use of a Material	Matsuno et al., 2006	Quantitative	Estimates how many times a material is reused or recycled before final disposal.
ONC	Output nutrient circularity	Harder et al., 2021	Quantitative	Calculates the share of nutrients leaving a process that are recovered from process outputs and reintroduced into productive applications, particularly in fertilisers or soil enhancement products.
PCI	Product Circularity Indicator	Bracquené et al., 2020	Quantitative	A modified version of the 2015 MCI developed for product-level applications; it retains the core structure of the MCI but expands it by integrating product functionality, lifetime, and value retention parameters.
PLCM	Product-level Circularity Metric	Linder et al., 2017	Quantitative	Quantifies the degree of circularity of a product based on the economic value of its recirculated components. It integrates both closed- and open-loop recirculation.
QC	Circularity of Material Quality	Steinmann et al., 2019	Quantitative	Measures the quality of recycled materials relative to those produced from primary inputs. It accounts for the additional energy required to achieve equivalent quality and functionality.
RDI	Recycling Desirability Index	Mohamed Sultan et al., 2022	Semi-quantitative	Measures the desirability of recycling a product or component. It encompasses three standardised dimensions: product complexity, recycling technology readiness level (TRL), and simplicity of material separation.
R-FWSC-Paletto	R-principle indicators for forest-wood supply chains (Paletto)	Paletto et al., 2022	Semi-quantitative	Measures the application of R-principles (Reduce, Reuse, Recycle, Recover) within forest-wood value chains to assess circular resource management.
R-FWSC-Pieratti	R-principle indicators for forest-wood supply chains (Pieratti)	Pieratti et al., 2019	Semi-quantitative	Similar to R-FWSC-Paletto, it evaluates how forest-wood systems implement R-strategies, focusing on reuse, recycling, and recovery to enhance resource efficiency.
RI-C	(Recycling Index Set) Closure of material cycles	Nelen et al, 2014	Quantitative	Measures how effectively material cycles are closed through recycling, indicating the share of recovered materials reintroduced into production processes.

CAI (Acronym)	CAI (Name)	Source	Output type	Short description
RIR	Recycling Input Rate	Graedel et al., 2011	Quantitative	Measures the proportion of recycled materials used as input in production compared to total input.
R-IR	Recycled Input Rate	Van Ewijk et al., 2017	Quantitative	Similarly to RIR, it measures the share of secondary raw materials entering production processes.
RIS	Recycling Index set of indicators	Nelen et al., 2014	Quantitative	A set of indicators designed to evaluate different aspects of recycling performance, including material cycle closure, recovery of scarce materials, and weight-based recovery efficiency.
RI-S	(Recycling Index Set) Recovery of scarce materials	Nelen et al, 2014	Quantitative	Measures the recovery of scarce or critical materials from waste streams.
RI-W	(Recycling Index Set) Weight recovery of target materials	Nelen et al, 2014	Quantitative	Quantifies the weight of target materials recovered through recycling.
RPI	Reuse Potential Indicator for Secondary Materials	Park and Chertow, 2014	Quantitative	Estimates the potential for reuse of secondary materials based on their composition and quality.
RR	Recycling process efficiency rate	Graedel et al., 2011	Quantitative	Represents the percentage of material effectively recycled after accounting for losses during processing.
S4NR	Percentage of sludge that is treated for nutrient recovery	Fleitas Girett et al., 2023	Quantitative	Measures the fraction of wastewater sludge processed for nutrient recovery.
SCI-C	Sustainable Circular Index - Circularity Indicators	Azevedo et al., 2017	Quantitative	Integrates circularity and sustainability dimensions by combining indicators on material recirculation, resource efficiency, and environmental performance. It provides a composite measure.
SIAT	Sustainability Integrated Assessment Tool	Ladu and Morone, 2021	Semi-quantitative	Integrates circularity and sustainability indicators into a decision-support framework. It enables comparative assessments of technologies and systems by evaluating material efficiency, resource recovery, and socio-environmental performance.
SICE-LFIPF	Sustainability Indicators in CE - Linear Flow Index for Product Families	Mesa et al., 2018	Quantitative	Measures linear material flows within product families to identify potential circularity improvements.
SICE-PRecI	Sustainability Indicators in CE - Potential Recycle Index	Mesa et al., 2018	Quantitative	Quantifies the proportion of materials that could potentially be recycled based on product design aspects.
SICE-PReuI	Sustainability Indicators in CE - Potential Reuse Index	Mesa et al., 2018	Quantitative	Quantifies the proportion of materials that could potentially be reused based on product design aspects.
TESA	TESA Indicators	Briassoulis et al., 2021	Semi-quantitative	Set of indicators encompassing a group of criteria designed to evaluate the feasibility and viability of recycling for post-consumer bio-based plastics.

CAI (Acronym)	CAI (Name)	Source	Output type	Short description
TNP-BF	Technological nutrient performance for biofertilizer	Preisner et al., 2022	Quantitative	Measures the amount of biofertilizer generated relative to the volume of biological waste treated during an EOL treatment process, such as anaerobic digestion.
TNP-BG	Technological nutrient performance for Biogas	Mancini and Raggi, 2021	Quantitative	Measures the volume of biogas produced during the anaerobic digestion treatment of any biological waste relative to the total volume processed.
TRP	Total Restored Products	Pauliuk et al., 2018	Quantitative	Quantifies the number or share of products restored to functional use via reuse, repair, refurbishment, or remanufacturing.
TRR	Total recovery rate	Gonçalves et al., 2021	Quantitative	Calculates the overall proportion of materials or components recovered across all lifecycle stages.
UOR	In-use occupation ratio	Moraga et al., 2021	Quantitative	Quantifies the percentage of a material's utilisation (measured as mass multiplied by time of use) relative to the maximum theoretical utilisation within a defined time horizon.
VRE	Value-Based Resource Efficiency	Di Maio et al., 2017	Quantitative	Relates the economic value retained after resource recovery to the value of total resource input, emphasising value preservation.

Table 2. Characterisation of the full list of CAIs according to applications, specificity, implementation level, complexity and dimensionality. CAI rows that are not included in the short list are coloured in grey.

CAI (Acronym)	Application of the indicator(s)	Implementation level	Dimensionality	System-specific?	Complexity
%CI	Applied to a BBS	Micro (Product/company level)	Adimensional	No	Single indicator
%CO	Applied to a BBS	Micro (Product/company level)	Adimensional	No	Single indicator
%CRI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
%RT	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
BCI	Applied to a BBS (Specific)	Micro (Product/company level)	Adimensional	No	Single indicator
BCS100	Applied to a BBS (Specific)	Micro (Product/company level)	Dimensional	No	Single indicator
BUE	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
BUE-E	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
BUF	Just formulated	Meso-level indicator applicable to the micro level	Adimensional	No	Single indicator
BUI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
C-BCS	Applied to a BBS (Specific)	Micro (Product/company level)	Dimensional	No	Single indicator
CC	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Tool
CD	Just formulated	Macro-level indicator applicable to the micro level	Adimensional	No	Single indicator
CEE-C	Just formulated	Micro (Product/company level)	Adimensional	Biofertilizer	Single indicator
CEI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
CEIP	Just formulated	Micro (Product/company level)	Adimensional	No	Set of indicators
CET	Just formulated	Micro (Product/company level)	Adimensional	No	Tool
CF	Just formulated	Macro-level indicator applicable to the micro level	Adimensional	No	Set of indicators
CI	Just formulated	Micro (Product/company level)	Adimensional	No	Set of indicators
CIC	Applied to a BBS	Micro (Product/company level)	Adimensional	No	Single indicator
CM	Just formulated	Micro (Product/company level)	Dimensional	No	Set of indicators

CAI (Acronym)	Application of the indicator(s)	Implementation level	Dimensionality	System-specific?	Complexity
CMP	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
CMT	Just formulated	Micro (Product/company level)	Adimensional	No	Tool
CR	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator
CST	Applied to a BBS	Micro (Product/company level)	Dimensional	No	Single indicator
CUSI	Just formulated	Micro (Product/company level)	Dimensional	No	Set of indicators
D	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
eDIM	Just formulated	Micro (Product/company level)	Dimensional	No	Single indicator
EOL-RIR	Just formulated	Macro-level indicator applicable to the micro level	Adimensional	No	Single indicator
EOL-RR	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator
ER	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
FCR	Applied to a BBS	Micro (Product/company level)	Adimensional	Textiles (apparel)	Set of indicators
FRS	Applied to a BBS	Micro (Product/company level)	Adimensional	No	Single indicator
HSI	Just formulated	Micro (Product/company level)	Adimensional	No	Set of indicators
INC	Just formulated	Micro (Product/company level)	Adimensional	Agriculture (PP)	Single indicator
LI	Just formulated	Micro (Product/company level)	Dimensional	No	Single indicator
MCI	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator
MCI (mod. Razza)	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
MCI (mod. Rocchi)	Just formulated	Micro (Product/company level)	Adimensional	Animal-based production	Single indicator
MI	Applied to a BBS	Micro (Product/company level)	Adimensional	No	Single indicator
MRS	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator
NF-EOL-RR	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
NRI	Applied to a BBS	Micro (Product/company level)	Adimensional	Biofertilizer	Single indicator
N-RI	Applied to a BBS (Specific)	Meso-level indicator applicable to the micro level	Adimensional	Biofertilizer	Single indicator
NTUM	Just formulated	Micro (Product/company level)	Dimensional	No	Tool

CAI (Acronym)	Application of the indicator(s)	Implementation level	Dimensionality	System-specific?	Complexity
ONC	Just formulated	Micro (Product/company level)	Adimensional	Agriculture (PP)	Single indicator
PCI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
PLCM	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
QC	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
RDI	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Set of indicators
R-FWSC-Paletto	Applied to a BBS (Specific)	Meso-level indicator applicable to the micro level	Dimensional	Forest-wood supply chains	Set of indicators
R-FWSC-Pieratti	Applied to a BBS (Specific)	Meso-level indicator applicable to the micro level	Dimensional	Forest-wood supply chains	Set of indicators
RI-C	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
RIR	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator
R-IR	Applied to a BBS	Macro-level indicator applicable to the micro level	Adimensional	No	Single indicator
RIS	Just formulated	Micro (Product/company level)	Adimensional	No	Set of indicators
RI-S	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
RI-W	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
RPI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
RR	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator
S4NR	Applied to a BBS	Macro-level indicator applicable to the micro level	Adimensional	Biofertilizer	Single indicator
SCI-C	Just formulated	Micro (Product/company level)	Adimensional	No	Tool
SIAT	Just formulated	Micro (Product/company level)	Adimensional	No	Set of indicators
SICE-LFIPF	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
SICE-PRecI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
SICE-PReuI	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
TESA	Just formulated	Micro (Product/company level)	Adimensional	No	Set of indicators
TNP-BF	Just formulated	Micro (Product/company level)	Dimensional	Biofertilizer	Single indicator

CAI (Acronym)	Application of the indicator(s)	Implementation level	Dimensionality	System-specific?	Complexity
TNP-BG	Just formulated	Micro (Product/company level)	Dimensional	Biofertilizer	Single indicator
TRP	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
TRR	Applied to a BBS	Macro-level indicator applicable to the micro level	Adimensional	No	Single indicator
UOR	Just formulated	Micro (Product/company level)	Adimensional	No	Single indicator
VRE	Applied to a non-BBS	Micro (Product/company level)	Adimensional	No	Single indicator

Table 3. Characterisation of the full list of CAIs according to the flows and functional value measurement. CAI rows that are not included in the short list are coloured in grey.

CAI (Acronym)	Flows measured	Intrinsic properties (value reference)	Is time dimension covered?	How is the time dimension covered?
%CI	Material	Material flow	Not covered	
%CO	Material	Material flow	Not covered	
%CRI	Material	Material properties	Not covered	
%RT	Material	Material flow	Not covered	
BCI	No flows measured	Material properties	Not covered	
BCS100	Material	Material flow	Covered	The use time of the product is included. There is also the time horizon of 100 years included to account for biogenic carbon to be accounted as "permanently" stored
BUE	Material	Material flow	Not covered	
BUE-E	Energy	Material properties	Not covered	
BUF	Material	Function	Not covered	
BUI	Material	Function	Not covered	
C-BCS	Material	Material flow	Covered	The use time of the product is included
CC	Multiple	Function	Not covered	
CD	Material	Material flow	Not covered	
CEE-C	Material	Material flow	Not covered	
CEI	Money	Economic value	Not covered	
CEIP	Material	Material properties	Covered	Via the "Product Lifetime Extension" section
CET	No flows measured	Multiple	Covered	The lifetime (from short to long, qualitative assessment) is requested. It's a very narrow concept subject to different interpretations.
CF	Material	Material flow	Not covered	
CI	Multiple	Multiple	Not covered	
CIC	Material	Material flow	Not covered	
CM	Multiple	Lifetime	Not covered	
CMP	Money	Economic value	Not covered	

CMT	No flows measured	Multiple	Not covered	
CR	Material	Material flow	Not covered	
CST	Material	Material flow	Covered	The indicator displays the retention (in terms of time/recycling cycles) of the carbon content of the product.
CUSI	Multiple	Multiple	Not covered	
D	Material	Material flow	Not covered	
eDIM	Time	Time (other than use time)	Not covered	
EOL-RIR	Material	Material flow	Not covered	
EOL-RR	Material	Material flow	Not covered	
ER	Money	Economic value	Not covered	
FCR	No flows measured	Material properties	Not covered	
FRS	Material	Material flow	Covered	Explicitly covered. It is the main purpose of the indicator.
HSI	Multiple	Multiple	Not covered	
INC	Material	Material flow	Not covered	
LI	Time	Lifetime	Not covered	
MCI	Material	Material flow	Covered	Included in the Utility Factor (X). Lifetime of a product and intensity of use.
MCI (mod. Razza)	Material	Material flow	Covered	Included in the Utility Factor (X). Lifetime of a product and intensity of use.
MCI (mod. Rocchi)	Material	Material flow	Not covered	
MI	Material	Material flow	Not covered	
MRS	Material	Material flow	Not covered	
NF-EOL-RR	Material	Material flow	Not covered	
NRI	Material	Material flow	Not covered	
N-RI	Material	Material flow	Not covered	
NTUM	Material	Material flow	Not covered	
ONC	Material	Material flow	Not covered	
PCI	Material	Material flow	Covered	Lifetime extension through refurbishing and recycling is directly addressed as a main indicator
PLCM	Money	Economic value	Not covered	

QC	Energy	Material properties	Not covered	
RDI	Component	Material properties	Not covered	
R-FWSC-Paletto	Multiple	Multiple	Covered	The use time of the product is included
R-FWSC-Pieratti	Multiple	Multiple	Covered	The use time of the product is included
RI-C	Money	Economic value	Not covered	
RIR	Material	Material flow	Not covered	
R-IR	Material	Material flow	Not covered	
RIS	Multiple	Multiple	Not covered	
RI-S	Material	Material properties	Not covered	
RI-W	Material	Material flow	Not covered	
RPI	Material	Material properties	Not covered	
RR	Material	Material flow	Not covered	
S4NR	Material	Material flow	Not covered	
SCI-C	Material	Multiple	Covered	Included in the Utility Factor (X). Lifetime of a product and intensity of use.
SIAT	Multiple	Multiple	Not covered	
SICE-LFIPF	Material	Material flow	Not covered	
SICE-PRecI	Material	Material flow	Not covered	
SICE-PReul	Material	Material flow	Not covered	
TESA	Multiple	Material properties	Not covered	
TNP-BF	Material	Material properties	Not covered	
TNP-BG	Material	Material properties	Not covered	
TRP	Material	Material flow	Not covered	
TRR	Material	Material flow	Not covered	
UOR	Multiple	Function	Covered	Explicitly covered. It is the main purpose of the indicator.
VRE	Money	Economic value	Not covered	

Table 4. Characterisation of the full list of CAIs according to sustainability, criticality and energy and utilities considerations. CAI rows that are not included in the short list are coloured in grey.

CAI (Acronym)	Link to SDs:	Link to SDs: Environment	Link to SDs: Economy	Link to SDs: Social	Is criticality explicitly addressed?	How is criticality addressed?	Energy needs/auxiliaries
%CI	No				No		Not considered
%CO	No				No		Not considered
%CRI	No				Yes	Open to choose a reference for criticality (e.g EC guidelines.)	Not considered
%RT	No				No		Not considered
BCI	No				No		Not considered
BCS100	No				No		Not considered
BUE	No				No		Not considered
BUE-E	No				No		Not considered
BUF	No				No		Not considered
BUI	No				No		Not considered
C-BCS	No				No		Not considered
CC	No				No		Not considered
CD	No				No		Not considered
CEE-C	No				No		Not considered
CEI	Yes		Direct		Partially	Via price (GVA method)	Indirectly considered
CEIP	No				No		Considered - All
CET	No				Yes	"Use of scarce materials" is considered in the questionnaire.	Considered - Energy
CF	No				No		Not considered
CI	No				No		Considered - Energy
CIC	No				No		Not considered

CAI (Acronym)	Link to SDs:	Link to SDs: Environment	Link to SDs: Economy	Link to SDs: Social	Is criticality explicitly addressed?	How is criticality addressed?	Energy needs/auxiliaries
CM	No				No		Not considered
CMP	No				No		Not considered
CMT	Yes	Direct	Direct	Direct	No		Considered - All
CR	No				No		Not considered
CST	No				No		Not considered
CUSI	No				No		Not considered
D	No				No		Not considered
eDIM	No				No		Not considered
EOL-RIR	No				No		Not considered
EOL-RR	No				No		Not considered
ER	Yes		Direct		Partially	Economic importance	Not considered
FCR	Yes	Direct			No		Not considered
FRS	No				No		Not considered
HSI	Yes	Direct			No		Considered - All
INC	No				No		Not considered
LI	No				No		Not considered
MCI	No				No		Not considered
MCI (mod. Razza)	No				No		Not considered
MCI (mod. Rocchi)	No				No		Not considered
MI	No				No		Not considered
MRS	No				No		Not considered
NF-EOL-RR	No				No		Not considered
NRI	No				No		Not considered

CAI (Acronym)	Link to SDs:	Link to SDs: Environment	Link to SDs: Economy	Link to SDs: Social	Is criticality explicitly addressed?	How is criticality addressed?	Energy needs/auxiliaries
N-RI	No				No		Not considered
NTUM	No				No		Not considered
ONC	No				No		Not considered
PCI	No				No		Not considered
PLCM	No				Partially	Economic importance	Indirectly considered
QC	Yes	Indirect			No		Considered - Energy
RDI	Yes	Indirect		Indirect	No		Not considered
R-FWSC-Paletto	Yes	Direct	Direct		No		Not considered
R-FWSC-Pieratti	Yes	Direct	Direct		No		Not considered
RI-C	No				No		Not considered
RIR	No				No		Not considered
R-IR	No				No		Not considered
RIS	Yes	Direct			Yes	Via the RI-S Indicator: According to EC's (2010) Criticality definition	Not considered
RI-S	No				Yes		Not considered
RI-W	No				No		Not considered
RPI	No				No		Indirectly considered
RR	No				No		Not considered
S4NR	No				No		Not considered
SCI-C	No				No		Not considered
SIAT	Yes	Direct			No		Considered - Energy
SICE-LFIPF	No				No		Considered - Auxiliaries
SICE-PRecI	No				No		Not considered

CAI (Acronym)	Link to SDs:	Link to SDs: Environment	Link to SDs: Economy	Link to SDs: Social	Is criticality explicitly addressed?	How is criticality addressed?	Energy needs/auxiliaries
SICE-PReuI	No				No		Not considered
TESA	Yes	Direct			No		Considered - All
TNP-BF	No				No		Not considered
TNP-BG	No				No		Not considered
TRP	No				No		Not considered
TRR	No				No		Not considered
UOR	No				No		Not considered
VRE	Yes		Direct		Partially	Economic importance	Indirectly considered

Table 5. Characterisation of the full list of CAIs according to the flow(s) they cover in the bio-based systems flowchart. CAI rows that are not included in the short list are coloured in grey.

CAI (Acronym)	Flow “From”	Flow “To”	Flow Perspective
%CI	Material Recovery	Value Chain 1 (Use)	Recirculation
%CO	Value Chain 1 (Use)	OL+CL+Return To Biosphere	Recirculation
%CRI	Biosphere	Value Chain 1 (Manufacturing)	Inflow
%RT	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
BCI	Value Chain 1 (Manufacturing)	Value Chain 1 (Use)	Inflow
BCS100	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
BUE	Value Chain 1 (Manufacturing)	Value Chain 1 (Use)	Inflow
BUE-E	Value Chain 1 (Manufacturing)	Value Chain 1 (Use)	Inflow
BUF	Value Chain 1 (Manufacturing)	Open Loop Value Chains	Recirculation
BUI	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
C-BCS	Material Recovery	Open + Closed Loop Recirculation	Recirculation
CC	Biosphere	All	Holistic
CD	Material Recovery	Value Chain 1 (Use)	Recirculation
CEE-C	End Of Use Stage (C&S)	End Of Use Stage (Eou Strategies)	Outflow
CEI	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
CEIP	Biosphere	All	Holistic
CET	Biosphere	All	Holistic
CF	Biosphere	Open + Closed Loop Recirculation	Recirculation
CI	Material Recovery	Value Chain 1 (Manufacturing)	Recirculation
CIC	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
CM	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
CMP	Biosphere	Value Chain 1 (Use)	Inflow
CMT	Biosphere	All	Holistic
CR	End Of Use Stage (C&S)	Material Recovery	Recirculation

CAI (Acronym)	Flow “From”	Flow “To”	Flow Perspective
CST	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
CUSI	Biosphere	Open + Closed Loop Recirculation	Recirculation
D	Material Recovery	Value Chain 1 (Manufacturing)	Recirculation
eDIM	End Of Use Stage (C&S)	Material Recovery	Recirculation
EOL-RIR	Material Recovery	Value Chain 1 (Manufacturing)	Recirculation
EOL-RR	Material Recovery	Value Chain 1 (Use)	Recirculation
ER	Biosphere	Value Chain 1 (Manufacturing)	Inflow
FCR	Biosphere	All	Holistic
FRS	Biosphere	End Of Use Stage (Eou Strategies)	Outflow
HSI	Biosphere	All	Holistic
INC	Biosphere	Value Chain 1 (Use)	Inflow
LI	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
MCI	Biosphere	All	Holistic
MCI (mod. Razza)	Biosphere	All	Holistic
MCI (mod. Rocchi)	Biosphere	All	Holistic
MI	Value Chain 1 (Use)	Closed Loop Recirculation	Recirculation
MRS	Value Chain 1 (Manufacturing)	Material Recovery & Return To Biosphere	Recirculation
NF-EOL-RR	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
NRI	Value Chain 1 (Use)	Biosphere	Outflow
N-RI	Material Recovery	Value Chain 1 (Manufacturing)	Recirculation
NTUM	Value Chain 1 (Use)	Open + Closed Loop Recirculation	Recirculation
ONC	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
PCI	Biosphere	All	Holistic
PLCM	Material Recovery	Value Chain 1 (Manufacturing)	Recirculation
QC	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow

CAI (Acronym)	Flow “From”	Flow “To”	Flow Perspective
RDI	End Of Use Stage (C&S)	Material Recovery	Recirculation
R-FWSC-Paletto	Value Chain 1 (Use)	OI+CI+Return To Biosphere	Recirculation
R-FWSC-Pieratti	Value Chain 1 (Use)	OI+CI+Return To Biosphere	Recirculation
RI-C	Material Recovery	Value Chain 1 (Use)	Recirculation
RIR	Material Recovery	Value Chain 1 (Use)	Recirculation
R-IR	Material Recovery	Value Chain 1 (Use)	Recirculation
RIS	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
RI-S	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
RI-W	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
RPI	End Of Use Stage (C&S)	Open + Closed Loop Recirculation	Recirculation
RR	End Of Use Stage (C&S)	Value Chain 1 (Manufacturing)	Outflow
S4NR	End Of Use Stage (Eou Strategies)	Material Recovery & Return To Biosphere	Outflow
SCI-C	Biosphere	All	Holistic
SIAT	Biosphere	All	Holistic
SICE-LFIPF	Biosphere	End Of Use Stage (Eou Strategies)	Outflow
SICE-PreCI	Value Chain 1 (Use)	Closed Loop Recirculation	Recirculation
SICE-PreUI	Value Chain 1 (Use)	Closed Loop Recirculation	Recirculation
TESA	Biosphere	All	Holistic
TNP-BF	End Of Use Stage (Eou Strategies)	Biosphere	Outflow
TNP-BG	End Of Use Stage (Eou Strategies)	Biosphere	Outflow
TRP	Value Chain 1 (Use)	Material Recovery	Recirculation
TRR	Value Chain 1 (Use)	Value Chain 1 (Manufacturing)	Recirculation
UOR	Biosphere	End Of Use Stage (C&S)	Inflow
VRE	Value Chain 1 (Manufacturing)	Value Chain 1 (Use)	Inflow

Table 6. Characterisation of the full list of CAIs according to the CE Strategies coverage. X: Coverage, P: Partial coverage. CAI rows that are not included in the short list are coloured in grey.

CAI (Acronym)	CE Strategy: Use of recirculated/renewable feedstock	CE Strategy: Resource efficiency in the value chain	CE Strategy: Lifetime Assessment	CE Strategy: Recycling	CE Strategy: Reuse (Maintenance, Refurbish, Remanufacture, etc.)	CE Strategy: Repurpose	CE Strategy: Waste management	CE Strategy: Maintaining function or value	CE Strategy: Cascading in value	CE Strategy: Nutrient recovery
%CI	X									
%CO				X	X	X	X			X
%CRI										
%RT				X	X	P				X
BCI		X							X	
BCS100		X	X	X	X	X	P			
BUE	P	X								
BUE-E	P	X								
BUF	X	X		P	X	X	X	X	X	X
BUI		X		P	P	X	P	X	X	P
C-BCS		X	X	X	X	X				
CC	X	X		X	X	X	X	X		
CD	X									
CEE-C							X			X
CEI				X	P	P		X		
CEIP	X	X	X	X	X	X		X	X	
CET	X	X	X	X	X	P		X		P
CF	X	X		X	X	X		X	X	
CI	X	X		X	P	P		X		
CIC	X	X		X	X	X	X			
CM	X	X	X	X	X			X		

CAI (Acronym)	CE Strategy: Use of recirculated/renewable feedstock	CE Strategy: Resource efficiency in the value chain	CE Strategy: Lifetime Assessment	CE Strategy: Recycling	CE Strategy: Reuse (Maintenance, Refurbish, Remanufacture, etc.)	CE Strategy: Repurpose	CE Strategy: Waste management	CE Strategy: Maintaining function or value	CE Strategy: Cascading in value	CE Strategy: Nutrient recovery
CMP		X								
CMT	X	X		X	X	X			X	
CR				X	X	X				
CST	X	X	X	X		P		x		
CUSI	X	X		X	P	X	X	X	X	P
D	X	X		X	X					
eDIM				X	X	X	X			
EOL-RIR	X	X		X	X					
EOL-RR		X		X	P	P		X		
ER	X	X		X	X	P				
FCR	X			X	X	X				
FRS			X						P	
HSI	X	X								
INC	X	X					X			X
LI	X		X	X	X	P		X		P
MCI	X	X	X	X	X	X	X			X
MCI (mod. Razza)	X	X	X	X	X	X	X			X
MCI (mod. Rocchi)	P					X	P			X
MI	X	X		X		P		X		
MRS	X			X		P	X			P
NF-EOL-RR		X								
NRI		X		X	X	X	X			X

CAI (Acronym)	CE Strategy: Use of recirculated/renewable feedstock	CE Strategy: Resource efficiency in the value chain	CE Strategy: Lifetime Assessment	CE Strategy: Recycling	CE Strategy: Reuse (Maintenance, Refurbish, Remanufacture, etc.)	CE Strategy: Repurpose	CE Strategy: Waste management	CE Strategy: Maintaining function or value	CE Strategy: Cascading in value	CE Strategy: Nutrient recovery
N-RI	X	X		X		X				X
NTUM						X	X		X	
ONC	X	X					X			X
PCI	X	X	X	X	X	X				P
PLCM	X							X		
QC	X	X						X		
RDI				X	X	P				
R-FWSC-Paletto	X	X	X	X	X	X	X		X	
R-FWSC-Pieratti		X	X	X			X			
RI-C		X		X		X		X		
RIR				X						
R-IR	X	X		X	P	P				
RIS		X				X		X		
RI-S		X		X		P		X		
RI-W		X		X		P				
RPI		X		X	X	X		X	X	
RR				X	X	X				
S4NR							X			X
SCI-C	X	X	X	X	X	P				
SIAT	X	X	X	X	X	X	X			X
SICE-LFIPF	X	X		X	X	P				
SICE-PRecI				X				X		

CAI (Acronym)	CE Strategy: Use of recirculated/ renewable feedstock	CE Strategy: Resource efficiency in the value chain	CE Strategy: Lifetime Assessment	CE Strategy: Recycling	CE Strategy: Reuse (Maintenance, Refurbish, Remanufacture, etc.)	CE Strategy: Repurpose	CE Strategy: Waste management	CE Strategy: Maintaining function or value	CE Strategy: Cascading in value	CE Strategy: Nutrient recovery
SICE-Preul					x			x		
TESA	X	X		X				X		
TNP-BF							X			X
TNP-BG							X			
TRP				X	X	P				
TRR	X	X		X	P	P				
UOR		X	X	X	X	X			X	
VRE		X								

Table 7. Characterisation of the full list of CAIs according to the CE Principles coverage. X: Coverage, P: Partial coverage. CAI rows that are not included in the short list are coloured in grey.

CAI (Acronym)	CEP1. Minimizing virgin inputs to the economy	CEP2. Retaining products and materials in the economy (at the highest value)	CEP3. Minimizing outputs from the economy
%CI	X		
%CO		X	X
%CRI			
%RT		X	X
BCI		X	
BCS100		X	P
BUE	P		
BUE-E	P		
BUF	X	X	X
BUI		X	P
C-BCS		X	
CC	X	X	X
CD	X		
CEE-C			X
CEI		X	
CEIP	X	X	
CET	X	X	P
CF	X	X	
CI	X	X	
CIC	X	X	X
CM	X	X	
CMP			
CMT	X	X	
CR		X	

CAI (Acronym)	CEP1. Minimizing virgin inputs to the economy	CEP2. Retaining products and materials in the economy (at the highest value)	CEP3. Minimizing outputs from the economy
CST	X	X	
CUSI	X	X	X
D	X	X	
eDIM		X	X
EOL-RIR	X	X	
EOL-RR		X	
ER	X	X	
FCR	X	X	
FRS		X	
HSI	X		
INC	X		X
LI	X	X	P
MCI	X	X	X
MCI (mod. Razza)	X	X	X
MCI (mod. Rocchi)	P	X	X
MI	X	X	
MRS	X	X	X
NF-EOL-RR			
NRI		X	X
N-RI	X	X	X
NTUM		X	X
ONC	X		X
PCI	X	X	P
PLCM	X	X	

CAI (Acronym)	CEP1. Minimizing virgin inputs to the economy	CEP2. Retaining products and materials in the economy (at the highest value)	CEP3. Minimizing outputs from the economy
QC	X	X	
RDI		X	
R-FWSC-Paletto	X	X	X
R-FWSC-Pieratti		X	X
RI-C		X	
RIR		X	
R-IR	X	X	
RIS		X	
RI-S		X	
RI-W		X	
RPI		X	
RR		X	
S4NR			X
SCI-C	X	X	
SIAT	X	X	X
SICE-LFIPF	X	X	
SICE-PRecI		X	
SICE-PReuI		X	
TESA	X	X	
TNP-BF			X
TNP-BG			X
TRP		X	
TRR	X	X	
UOR		X	
VRE			

2 Key Characteristics assessment figures

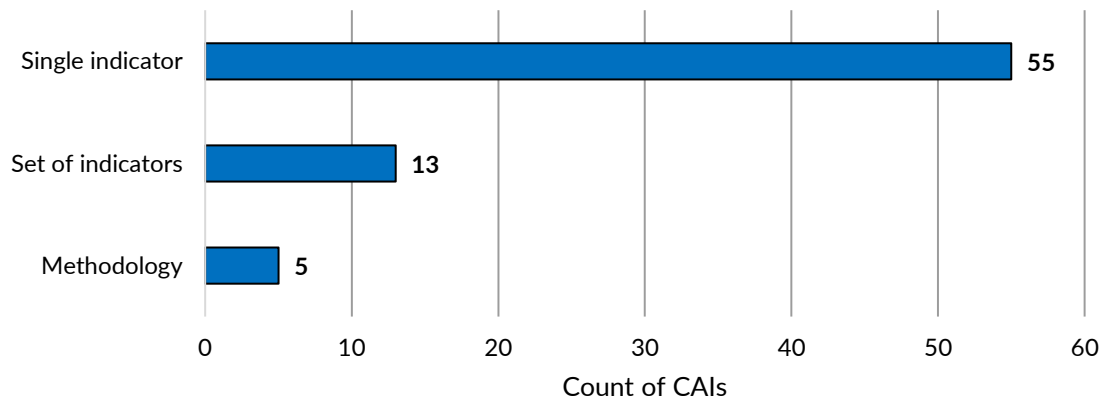


Figure 1. Classification of CAIs by complexity.

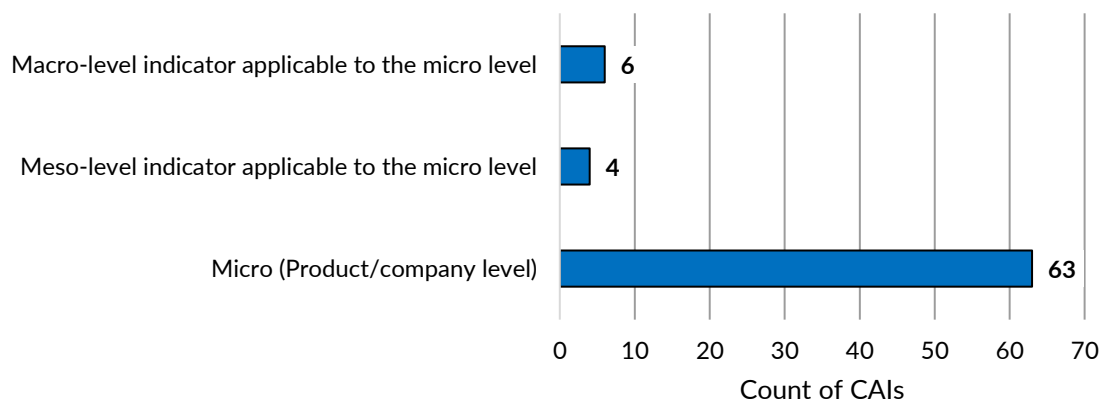


Figure 2. Classification of CAIs by implementation level.

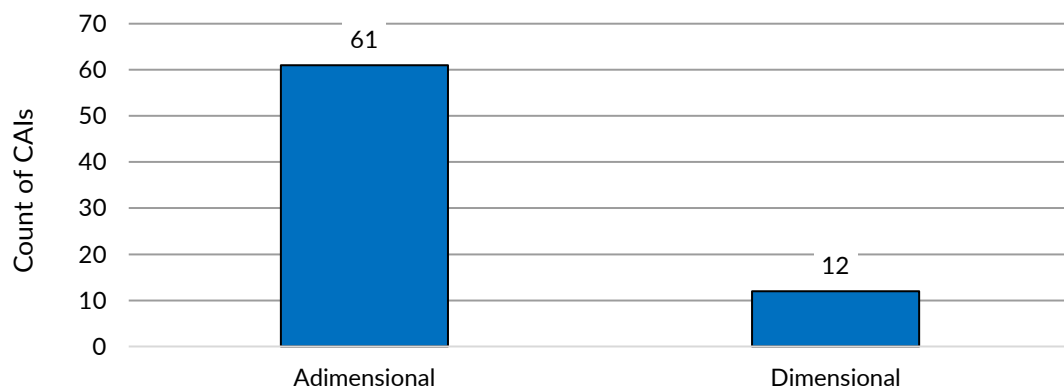


Figure 3. Classification of CAIs by dimensionality.

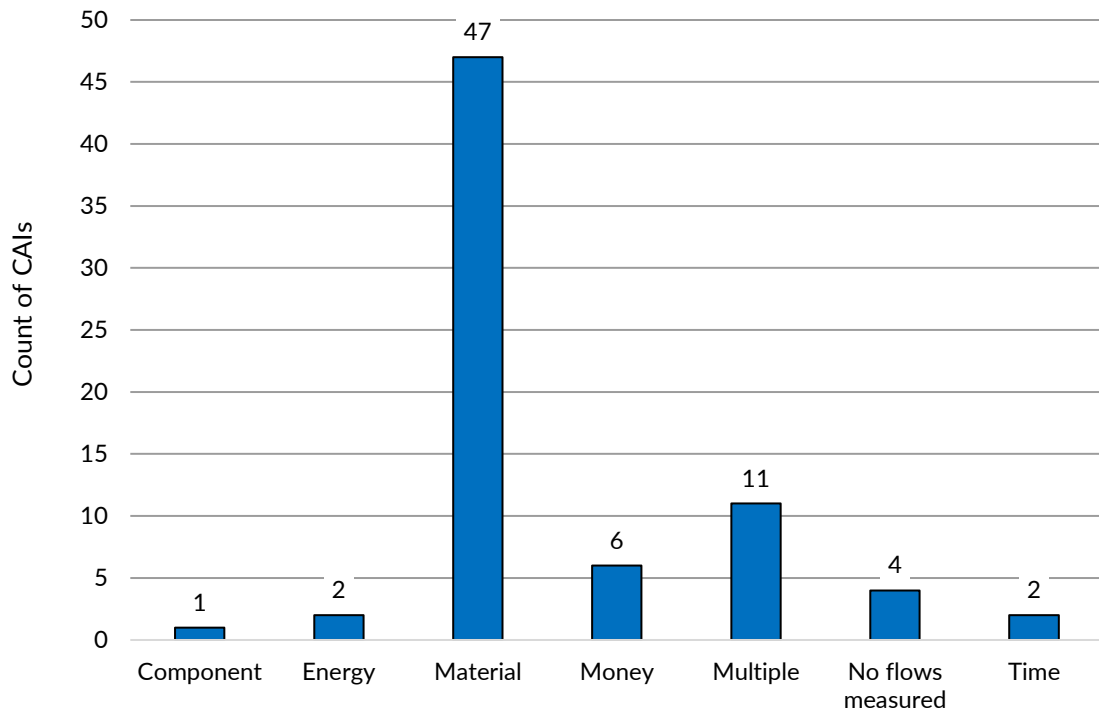


Figure 4. Classification of CAIs by flows measured.

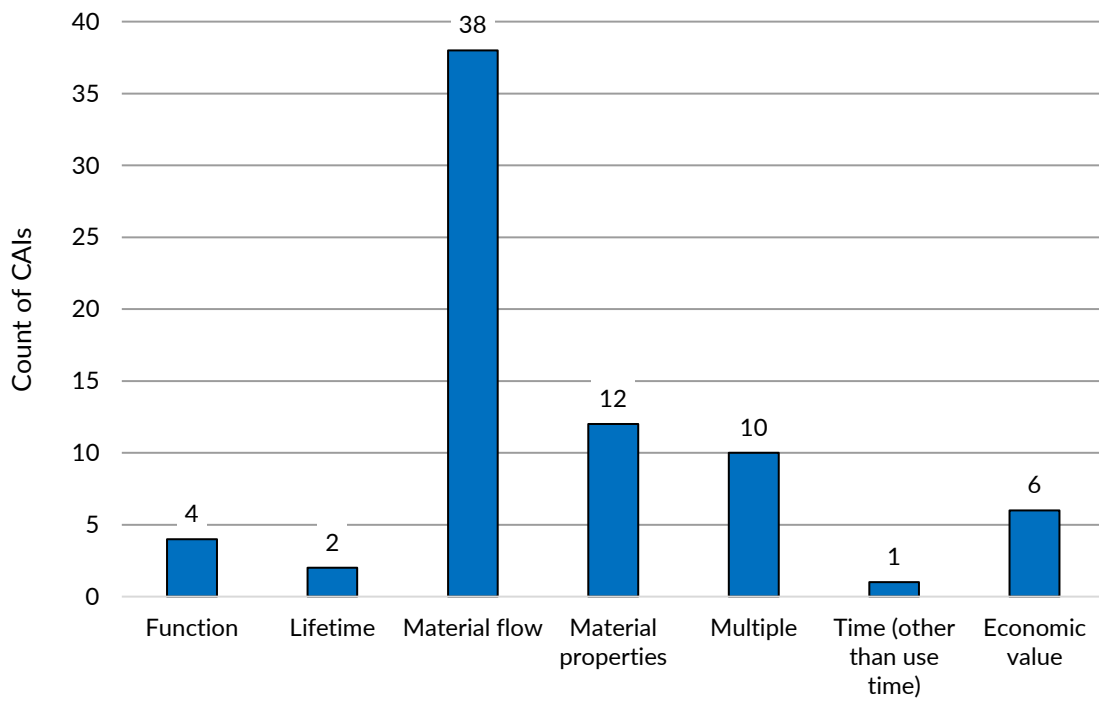


Figure 5. Classification of CAIs by value reference.

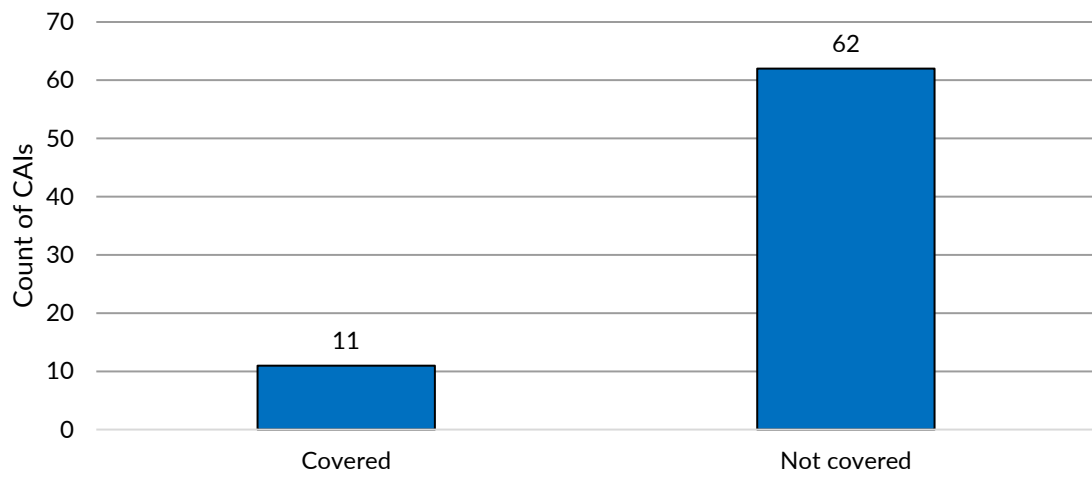


Figure 6. Classification of CAIs by the sustainability dimension coverage.

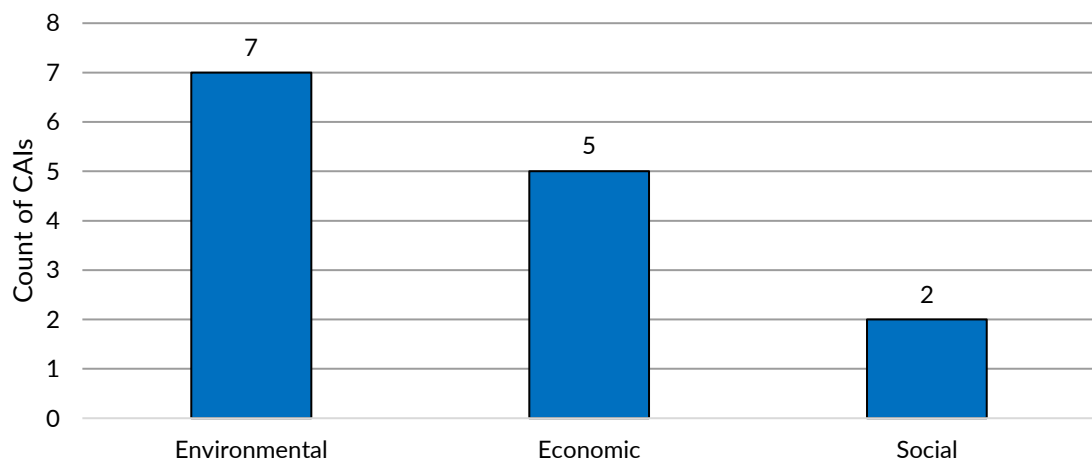


Figure 7. Classification of CAIs by sustainability dimensions addressed.

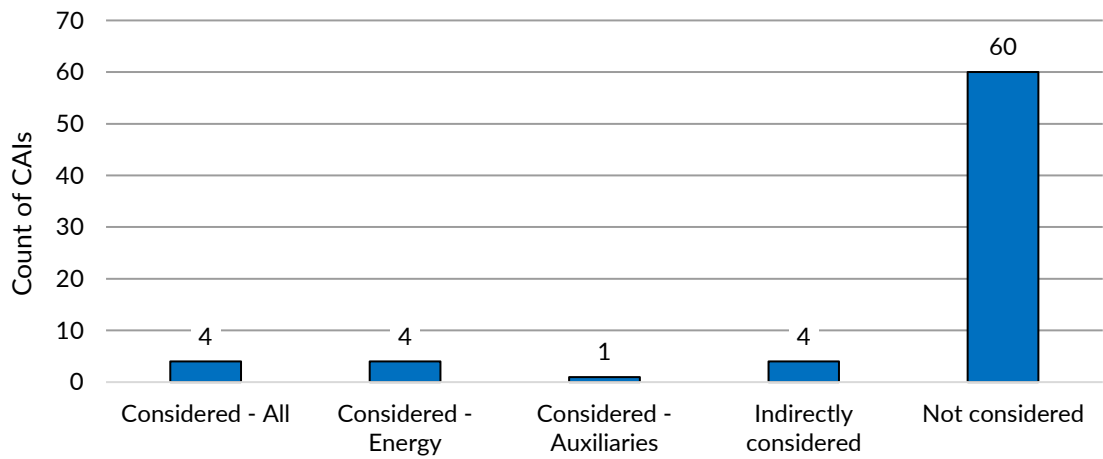


Figure 8. Classification of CAIs by the inclusion of energy, utilities and other auxiliaries.

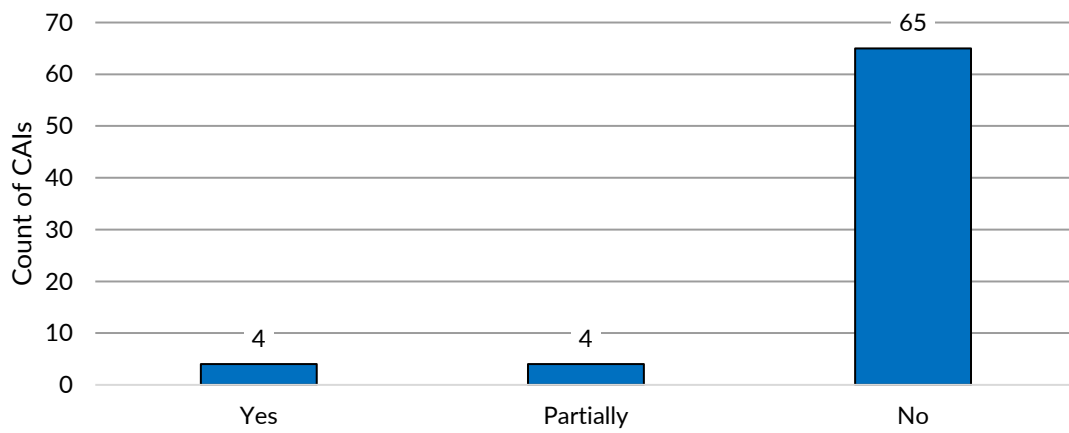


Figure 9. Classification of CAIs by criticality coverage

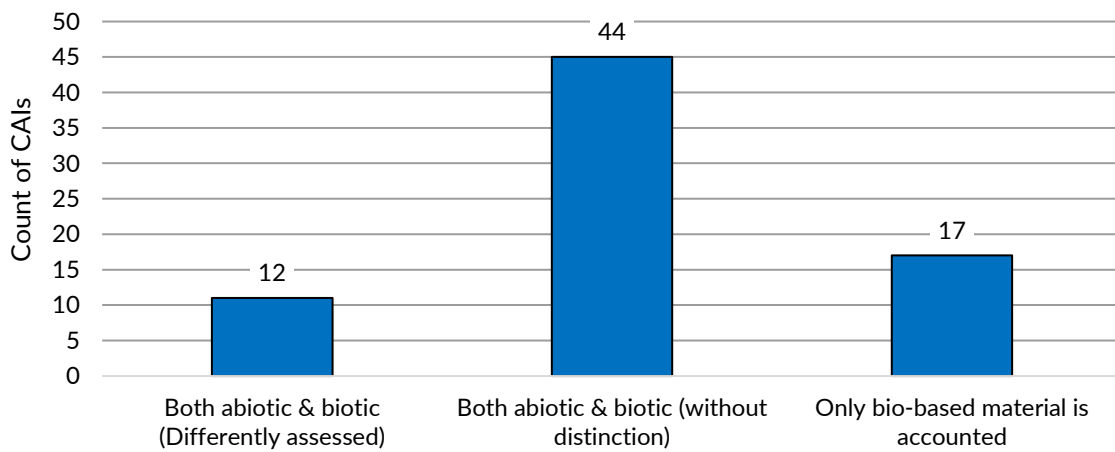


Figure 10. Classification of CAIs by the addressing of biotic and abiotic material

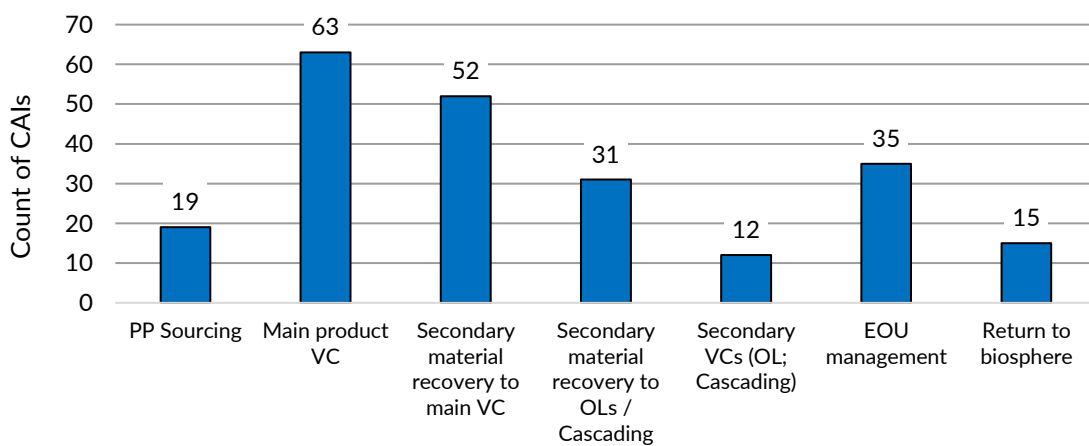


Figure 11. Classification of CAIs by coverage of the bio-based systems flowchart regions

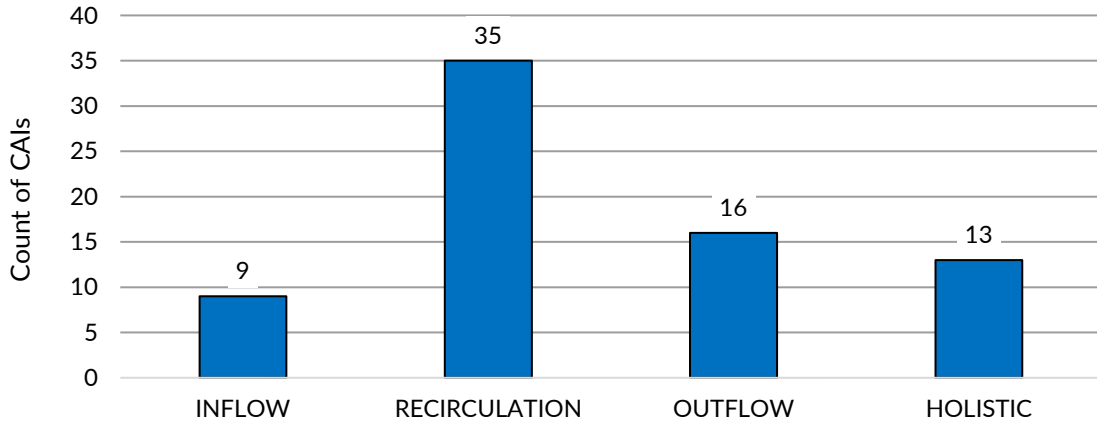


Figure 12. Classification of CAIs by the flow cluster from the bio-based systems flowchart.

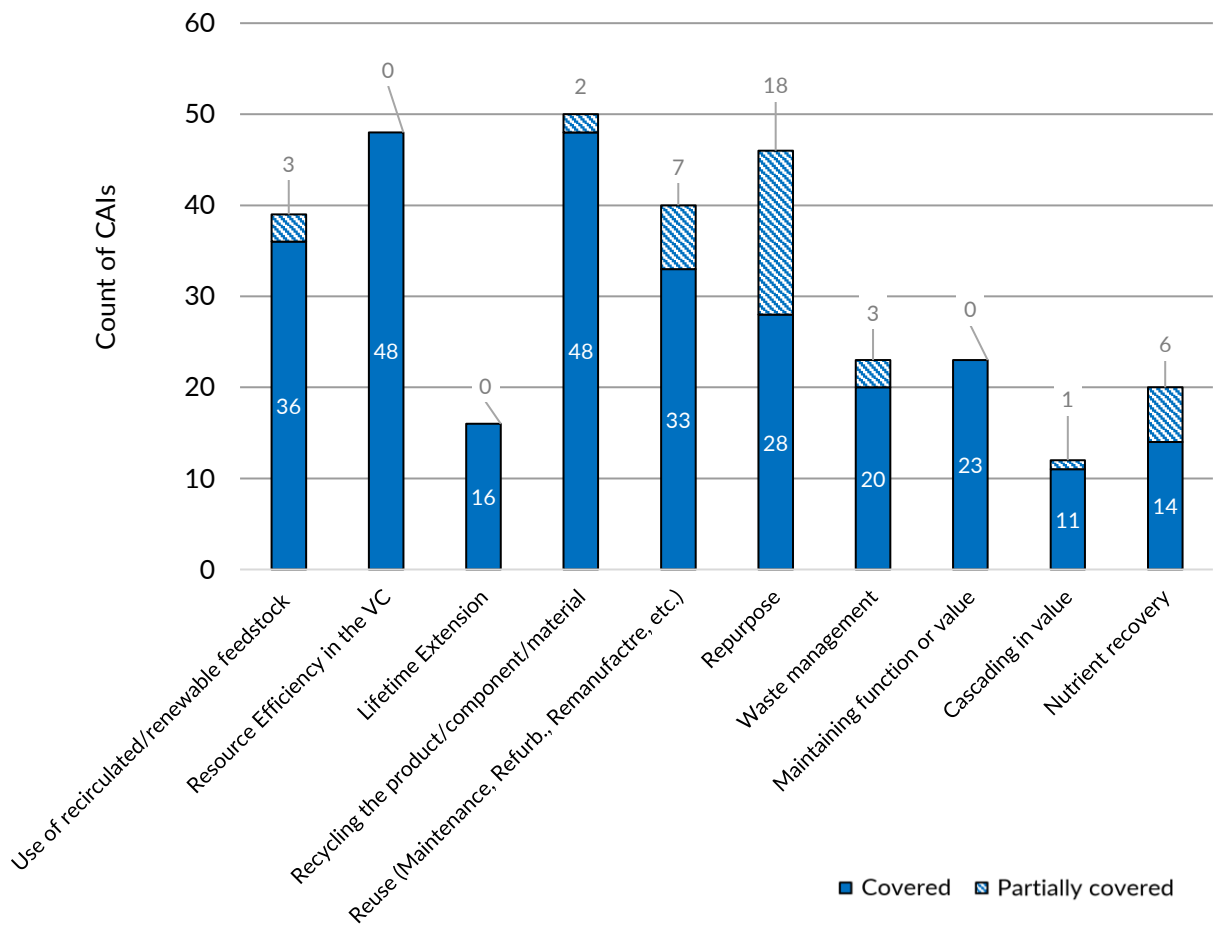


Figure 13. Classification of CAIs by CE Strategies coverage.