




Indicators for Measuring Circularity of Bio-based Products: A Systematic Review

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Abstract

Circular bioeconomy is emerging as an alternative framework to produce and consume bio-based resources while reducing damage to nature. But after a decade of development of circular economy (CE) indicators, bio-based products are still missing an appropriate body of product-level measurement tools. This review mapped the CE indicators that have been applied to bio-based fertilizers, packaging, and textiles, with the aim of supporting the further development of decision-relevant tools for product circularity (within the BIORADAR project context). Using a systematic literature review of English-language publications (2016-2025) complemented with widely adopted grey literature and standards, 162 scientific literature documents were retained, and complemented with 16 grey literature documents, resulting in 123 distinct indicators that were extracted, coded, and critically assessed. Although general-purpose and sector-applied indicators together form an extensive body of knowledge, the mapped tools remain uneven in robustness and practical applicability: they often rely on context-sensitive assumptions and data that are not consistently available across firms and regions, and they frequently aggregate multiple circularity features into composite scores that can obscure trade-offs. The indicator set also shows persistent gaps, including limited operationalization of the biological cycle, and weak coverage of key life-cycle stages beyond manufacturing. Overall the main challenge is less the absence of additional metrics than the lack of coordination and transparent, comparable calculation conventions; future work should prioritize a tiered, modular measurement architecture combining a standardized core indicator set with bio-based and sector-specific modules supported by clear data requirements and disclosure rules.

Keywords Circular Bioeconomy · Biocircularity · Circular Economy · Environmental Product Management · Fertilizers · Packaging · Textiles

1. Introduction

Businesses striving to measure the circularity of their products often find themselves navigating a labyrinth of metrics, with little guidance on what to prioritize. Most circular economy (CE) indicator frameworks have been developed for macro-level assessments —countries, regions, or cities (Howard et al., 2019) —and only a limited subset can be meaningfully translated to the product level. In bio-based industries, circularity at the product level is still frequently assumed rather than measured (Carus & Dammer, 2018; Iglesias et al., 2025;

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Khanna et al., 2024), leaving companies without operational tools to diagnose performance, set realistic targets, and track progress over time.

This measurement gap is becoming increasingly consequential. The European Union (EU) is calling for increased circularity through initiatives such as the Clean Industrial Deal (European Commission, 2025a) and the Competitiveness Compass (European Commission, 2025b), which outlines a plan to adopt a Circular Economy Act by the end of 2026. As a result, European manufacturing firms face growing pressure to substantiate circularity claims and report progress, yet the metric landscape remains fragmented and difficult to apply consistently at product level—particularly in the bio-based sector, where circularity is often presumed by default (Holden et al., 2023; Rojas-Serrano et al., 2024; Tan & Lamers, 2021).

This review adopts the perspective of the circular bioeconomy (CBE), defined as a model that promotes the resource-efficient valorization of biomass in integrated production chains while reusing residues and optimizing biomass value through cascading (Stegmann et al., 2020). The CBE is expected to grow significantly in the EU, from EUR 31 billion in 2022 to EUR 100 billion in 2030, a compound annual growth rate of 13.9%, creating 500,000 new jobs (The World Bank, 2022).

Both CE and CBE are highly technology dependent. Therefore, their measurement must rely on variables associated with manufacturing processes, while also acknowledging economic variables such as resource constraints and market dynamics. Regarding what to measure when talking about CBE, Khanna et al. (2024) note recurring emphases on “reducing the use of virgin materials, recycling and reusing materials, restoring, and regenerating natural systems, and converting the unavoidable wastes and other biological resources into bioenergy or bioproducts to substitute for fossil fuels”. In practice, however, product circularity management is often subsumed under broader environmental product management practices (e.g., the ISO 14000 family, Life Cycle Assessment, Environmental Product Declarations), even as efforts to integrate circularity into Life Cycle Assessment (LCA) frameworks continue to face conceptual and operational limitations (Cilleruelo Palomero et al., 2024; Peña et al., 2021; Rigamonti & Mancini, 2021; Samani, 2023).

Within the CBE, fertilizers, packaging and textiles have attracted particular attention due to their scale, their environmental impacts, and the uptake of bio-based materials as a mitigation strategy. In that regard, the European Commission, through its Horizon Europe program, funded the BIORADAR project, which aims to develop digital tools and indicators to monitor the sustainability and circularity performance of bio-based value chains specifically in these three sectors. The focus on them is justified by the size of their industries and the magnitude of their impacts: nitrogen fertilizers alone were responsible for an estimated 1.13 GtCO₂eq emissions in 2018—accounting for 10.6% of agricultural emissions and 2.1% of global greenhouse gas emissions (GHG) (Menegat et al., 2022). Moreover, it is estimated that 95% of phosphorus is lost due to inefficient utilization, exacerbating concerns over resource scarcity and import dependency (Walsh et al., 2023). Here, “fertilizers” refers to circular-produced fertilizers, i.e., fertilizers obtained through nutrient recovery or biomass-residue valorization routes, rather than implying that fertilizer use is inherently circular.

Packaging is estimated to account for one third of household waste, contributing significantly to the rise in municipal solid waste (Pongrácz, 2007), as well as to global warming and water pollution (Roberge, 2019), in part due to fossil-based manufacturing processes and current waste management and disposal limitations (Interreg Baltic Sea Region, 2024). Textiles also play a major role in environment degradation: in the EU, textile consumption ranks third in land and water use, and fifth in GHG and raw material consumption (Deckers et al., 2023).

The central research question guiding the present study is: What are the indicators currently available for bio-based industries to assess the circularity of their fertilizer, packaging and textile products? Numerous studies have mapped and analyzed CE indicators. (e.g., Parchomenko et al., 2019; Dos Santos Gonçalves & Campos, 2022; Munonye, 2025).

In contrast, the literature on bioeconomy indicators remains relatively scarce. (Vural Gursel et al., 2023; Mesa et al., 2024). While some sector-relevant advances do exist—such as nutrient-oriented indicators, including the Circularity Indicators of Nutrient proposed by Cobo et al. (2018)—their use has not yet translated into broadly adopted, sector-tailored indicator sets that are consistently applied across bio-based fertilizers, packaging, and textiles. Building on this gap, this article goes beyond mapping: it critically assesses the indicators currently used in these sectors, identifies key conceptual and operational limitations (e.g., what dimensions are systematically omitted or weakly operationalized), and proposes a research route that prioritizes the most pressing methodological and data challenges to address in order to move toward more robust, decision-relevant product-level circularity measurement for bio-based products.

2. Methods

2.1. Systematic literature review

This study systematically reviews the academic literature on product-level circularity indicators within the CBE, focusing on three key sectors: fertilizers, packaging, and textiles. It considers publications indexed in the Web of Science (WoS) and SCOPUS databases and follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). In addition, key circularity indicators originating from standardization bodies and institutional frameworks (ISO, CEN, WBCSD, EU, etc.) were included as complementary grey literature sources to contextualize indicator development.

The search was carried out across Title-Abstract-Keywords fields in SCOPUS and across Topic (Title, Abstract and keywords) in Web of Science using the following query:

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

Only articles published in English between 2016 and 2025 were considered, resulting in 3234 records. After removing 760 duplicates, 2474 records remained. These were screened based on title and abstract, applying three primary exclusion criteria (Table 1): (E2) the analytical level was not the product, or (E3) the study addressed sectors outside the scope of this review. Table 1 also includes some examples of how the exclusion criteria was identified in the wording of title and abstracts.

Table 1. Primary exclusion criteria applied at title/abstract screening.

Exclusion criterion	Operational definition	Typical signs in title/abstract
(E1) No CBE indicator addressed	The study does not introduce, calculate, apply or operationalize quantitative indicators/metrics intended to measure circularity (or circular performance).	Mentions of “indicator” unrelated to circularity metrics (e.g., bio-indicator, pH indicator, thermochromic indicator, etc.); purely qualitative assessment; technology/strategy discussion without measurement outputs.
(E2) Wrong analytical level	The assessment is conducted at macro (country/region/city), meso (supply chain/industrial symbiosis networks), or company/corporate level, rather than product level.	“National/regional circularity”, “global flows”, “company-level circularity”, “supply-chain circularity”.
(E3) Wrong sector	The product(s) assessed fall outside the review scope: fertilizers, packaging, textiles.	Sector keywords not aligned with scope.

To ensure consistency in identifying “indicator-based” evidence, we operationalized what qualifies as a CBE product-level indicator versus related-but-ineligible evidence types (Table 2).

Table 2. Operational definition of “CBE product-level indicators” used for inclusion/exclusion.

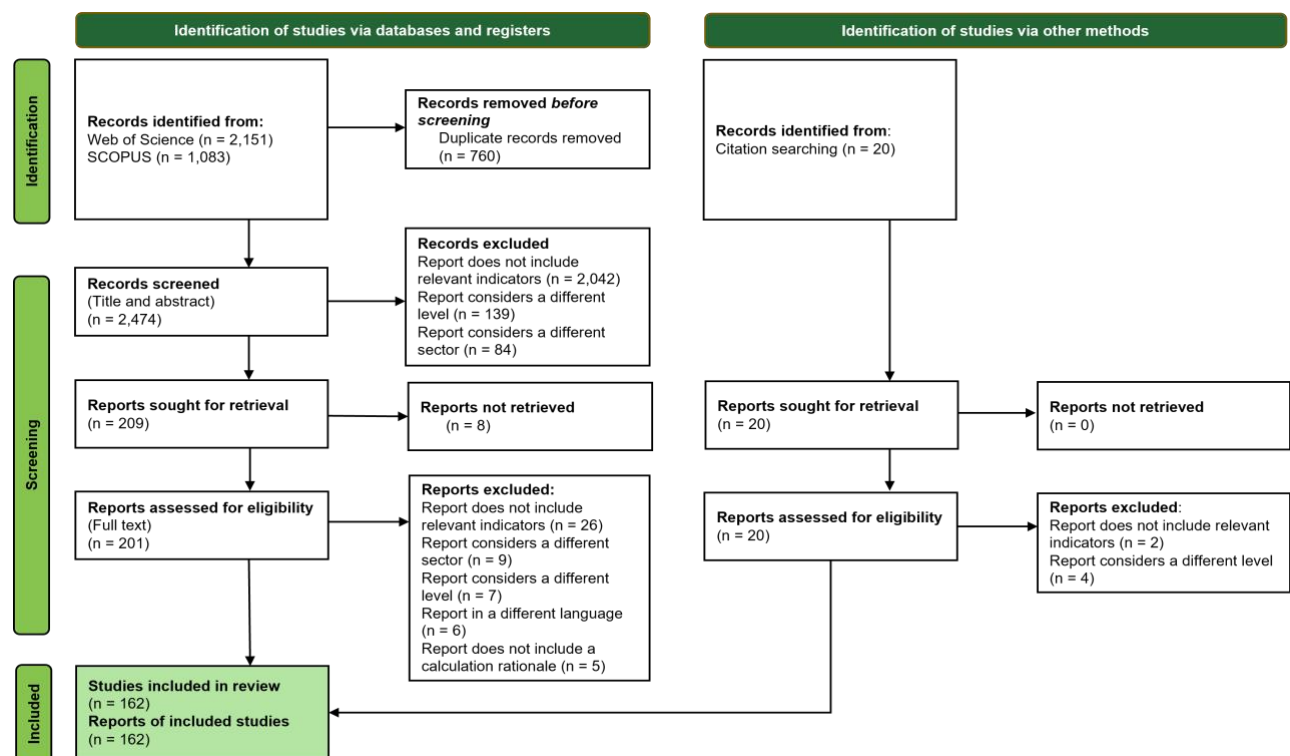
Considered a CBE product-level indicator (included)	Not considered a CBE product-level indicator (excluded under E1)
Quantitative indicators/metrics that measure circularity or circular performance at the product level, including: <ul style="list-style-type: none"> LCA-based indicators and footprint metrics only when explicitly used within a circularity assessment as proxies or inputs to compute circularity-related metrics (e.g., carbon, water, ecological footprints; LCA impact categories when used to compare circular vs. linear options). 	Evidence types that are not indicators, or are non-circular or non-quantitative, including: <ul style="list-style-type: none"> Surveys, interviews, questionnaires, qualitative scorecards/checklists (yes/no), participatory tools. GHG inventories or accounting exercises that report emissions without a circularity indicator/metric for a product. SWOT analyses and other qualitative strategic tools.

Table 2 (Cont.). Operational definition of “CBE product-level indicators” used for inclusion/exclusion.

Considered a CBE product-level indicator (included)	Not considered a CBE product-level indicator (excluded under E1)
<ul style="list-style-type: none"> Efficiency metrics linked to circular performance (e.g. resource/energy/water use efficiency, recovery yields) when tied to a product output. Circular vs. Business as Usual (BAU) comparisons that produce quantifiable outputs enabling circularity assessment at product level. Metrics explicitly structured around CE principles (design out waste, keep products/materials at highest value, regenerate nature) (Ellen MacArthur Foundation, n.d.) when operationalized as quantifiable metrics. Circularity indices/ratios. 	<ul style="list-style-type: none"> Ancillary methodologies (mass balances, neural networks, machine learning, modelling) unless they yield an explicit circularity metric/indicator. Classic project economic indicators (NPV, IRR, payback) when not integrated into a circularity metric. Circular business models/strategies/principles discussed only conceptually (no measurable indicator calculated or applied). Design parameters/variables (pH, concentration, material characteristics) and performance indicators (strength, permeability, resistance) reported as technical properties rather than circularity metrics. Test methods (e.g., MFR, calorimetry) and product specifications/thresholds (e.g. heavy metals limits). Goals/targets stated as aspirations (e.g., “30% reduction in GHG”) without indicator calculation.

Title and abstract screening was managed in Rayyan[®] (Ouzzani et al., 2016) to facilitate record handling and reviewer coordination; however, all inclusion and exclusion decisions were made manually by the authors based on the predefined eligibility criteria. This step resulted in 209 articles selected for full-text screening. Full texts were then assessed against the same three primary criteria applied at title/abstract stage (no CBE indicator reported, wrong analytical level, or wrong sector), and three additional full-text criteria: (i) no calculation rationale (i.e., indicators are mentioned but no calculation method is explained or referenced), (ii) wrong language (full text not available in English), and (iii) full text not available (e.g., access restrictions or irretrievable records).

A total of 148 articles met all inclusion criteria. At this stage, an additional fourteen articles were identified through citation searching, resulting in a final sample of 162 documents. The full selection process is detailed in Fig. 1.

**Figure 1.** PRISMA flow diagram.

To document inter-rater reliability (IRR), two reviewers independently applied the inclusion/exclusion criteria to an overlapping subset of records. Observed agreement was high (% alignment = 91.2%), but Cohen's kappa was $k = 0.472$, which is typically interpreted as moderate agreement (McHugh, 2012). Given the low inclusion prevalence in the review overall ($147/2474 = 5.94\%$), k can be deflated by prevalence effects (Gianinazzi et al., 2015; Wongpakaran et al., 2013); therefore, we also report prevalence-adjusted / kappa paradox-resistant coefficients. Using the observed agreement, the prevalence-adjusted bias-adjusted kappa (PABAK) (Gianinazzi et al., 2015) was 0.823, and Gwet's AC1 (Wongpakaran et al., 2013) was 0.894, both indicating substantial-to-almost perfect agreement (McHugh, 2012) and supporting the robustness of the screening decisions despite the skewed class distribution.

2.2. Grey literature

Given how circular economy metrics have evolved in practice, indicator development has not been driven exclusively by scientific literature. In parallel, companies and industry initiatives have developed and adopted proprietary or business-led metrics to support decision-making and reporting, often outside peer-reviewed outlets. Therefore, alongside the systematic literature review, we also retrieved a set of grey literature documents selected based on evidence of widespread use and influence. These documents were grouped into: (a) standards and technical specifications, (b) public and intergovernmental documents, and (c) industry- and business-led frameworks. These documents and the indicators they propose are analyzed separately, in section 4.4.

2.3. Indicator extraction and characterization protocol

Indicators were extracted manually from the final set of eligible full texts. For each article, we identified any quantitative metric explicitly proposed, calculated, referenced, or applied to represent circularity (or circular performance) at the product level, in line with the eligibility criteria. Each extracted indicator was then recorded in a structured spreadsheet. Because the review integrates two analytical levels —documents and indicators— we implemented a two-tier tagging scheme to support consistent assessment. First, each document was assigned one or more document-level tags describing its application domain and explicit reference to well-positioned indicators (e.g., fertilizer, packaging, textile, general; and LCA, Material Flow Analysis, Material Circularity Indicator, Material Reutilization Score, Emergy, Entropy). Second, each extracted indicator was assigned indicator-level tags reflecting (a) sector applicability (fertilizer, packaging, textile, general), and (b) the main dimensions included in its calculation rationale. These dimensions capture whether the indicator accounts for: recycled/reused input, efficiency, product lifetime, economic input, end-of-life processes, recyclability, energy, environmental impact, and benchmarking against a linear (BAU) option; as well as whether it leverages well-established frameworks (LCA-based or Material Circularity Indicator-based) and the type of value reported (relative vs. absolute). Operational definitions for each tag and dimension are provided in Table 3. Indicators retrieved from grey literature are classified using the same tagging criteria.

Table 3. Operational definitions of indicator tags and characterization dimensions.

Dimension	Variable	Rationale
Sector	General	Indicator is formulated to be applicable across product categories (i.e., not inherently tied to fertilizers, packaging or textiles) and can be computed without sector-specific parameters.
	Fertilizers	Indicator is explicitly designed for or applied to fertilizer products in the source study.
	Packaging	Indicator is explicitly designed for or applied to packaging products in the source study.
	Textiles	Indicator is explicitly designed for or applied to textile products in the source study.
Aspects included	Recycled/reused input	Indicator explicitly includes recycled/reused content (mass) as an input variable.
	Efficiency	Indicator includes an efficiency term (e.g., yield, recovery rate, conversion efficiency, resource-use efficiency) used in the computation.
	Product lifetime	Indicator includes lifetime/durability/service life (or expected use phase duration) as a variable or normalization factor.

Table 3 (cont.). Operational definitions of indicator tags and characterization dimensions.

Dimension	Variable	Rationale
Aspects included	Economic input	Indicator includes monetary variables (e.g., costs, prices, value, revenue) as part of the computation.
	End-of-life processes	Indicator explicitly accounts for one or more end-of-life pathways (e.g., recycling, composting, energy recovery, remanufacturing, landfill) within the calculation.
	Recyclability	Indicator includes recyclability (technical recyclability, design-for-recycling score, or a recyclability rate) as a parameter.
	Energy	Indicator includes energy use/consumption (directly or via energy intensity) as an input or component of the metric
	Environmental impact	Indicator includes environmental performance or impact information as part of its computation, such as LCA impact category results and footprint metrics (e.g., carbon, water), as well as direct environmental load/pressure metrics (e.g., water consumption, pollutant releases/effluents, emissions, waste generation) when used quantitatively within the indicator.
	Benchmark against the linear option	Indicator is computed relative to a linear/BAU reference, reporting deviation/improvement versus that baseline.
	Entropy	Indicator explicitly uses entropy/exergy/thermodynamic entropy terms within its computation.
Leverage of well-established frameworks	LCA-based	Indicator requires LCA inventory/impact results or is directly derived from LCA impact categories/footprints.
	MCI-based	Indicator uses the Material Circularity Indicator (MCI) value, its components, or a documented modification/extension of the MCI calculation.
Type of value	Relative value	Output is dimensionless or normalized (e.g., ratio, index, %, score).
	Absolute value	Output is in physical units (e.g., kg, MJ) or monetary units without normalization.

Tags were not mutually exclusive (an indicator could receive multiple tags). Sector tags reflect the context of application reported in the source (not necessarily exclusivity). Coding was binary (present/absent) based on whether the variable appeared explicitly in the indicator formula, required inputs, or calculation procedure.

2.4. Bibliometric analysis

To conduct the bibliometric analysis, the software VOSviewer® (version 1.6.20) was used to generate and visualize networks of keyword co-occurrence, and co-authorship. These analyses were used to characterize the thematic structure of the field and the main disciplinary and intellectual linkages within the scientific literature. In addition, raw metadata from both databases were used to examine (i) the cumulative number of publications over the study period and (ii) the frequency distribution of database-set categories and subject areas assigned to the retrieved records.

The bibliometric analysis comprised two complementary approaches. First, keyword co-occurrence analysis mapped the most recurrent terms and grouped them into clusters based on their tendency to appear together within the same publications. Second, co-authorship analysis quantified collaboration patterns among authors, where links represent shared authorship in at least one document.

The keywords co-occurrence and co-authorship charts were generated in VOSviewer using a map based bibliographic data. The co-occurrence analysis used keywords as the unit of analysis and full counting as the counting method. The minimum number of keyword occurrences was set to 21, resulting in 66 keywords. Generic terms that did not contribute to the characterization of the research field were excluded (e.g., “article”, “human”, “nonhuman”, “controlled study”, “procedures”, “animals”, “comparative study”, “priority journal”, “quantitative analysis”).

The co-authorship analysis used authors as the unit of analysis and full counting as the counting method. To reduce distortion from hyper-authored publications, documents with more than 25 authors were excluded. Authors were included if they appeared in at least five documents in the final sample, resulting in 62 authors.

Although WoS allows exporting the cited-reference data required for co-citation mapping, SCOPUS did not provide equivalent cited-reference export for our dataset; therefore, we did not perform co-citation analysis to preserve methodological consistency and comparability across databases.

3. Bibliometric Analysis

The results of the search provide valuable insight into the structure and evolution of the scientific landscape. Therefore, before identifying and analyzing the indicators found in the selected 162 documents, a bibliometric overview is presented to help position the reader within the field. The complete database of records included is available in the supplementary materials (Table S1).

3.1. Publication trends and database overview

A first relevant aspect concerns the temporal evolution of publications. As shown in Fig. 2, prior to 2016, scientific output on CBE indicators for fertilizers, packaging and textiles was virtually negligible. This inflection point may have been triggered by the Paris Agreement (UNFCCC, 2015) and the EU's first Circular Economy Action Plan (European Commission, 2015), increasing the number of studies in this field by 1,700% between 2016 and 2019. From that point onward, publication activity steadily increased, peaking in 2025. This trend reflects growing interest and effort within the scientific community to develop appropriate CBE metrics. It also underscores the relevance of conducting a review that synthesizes current knowledge and guides future methodological development.

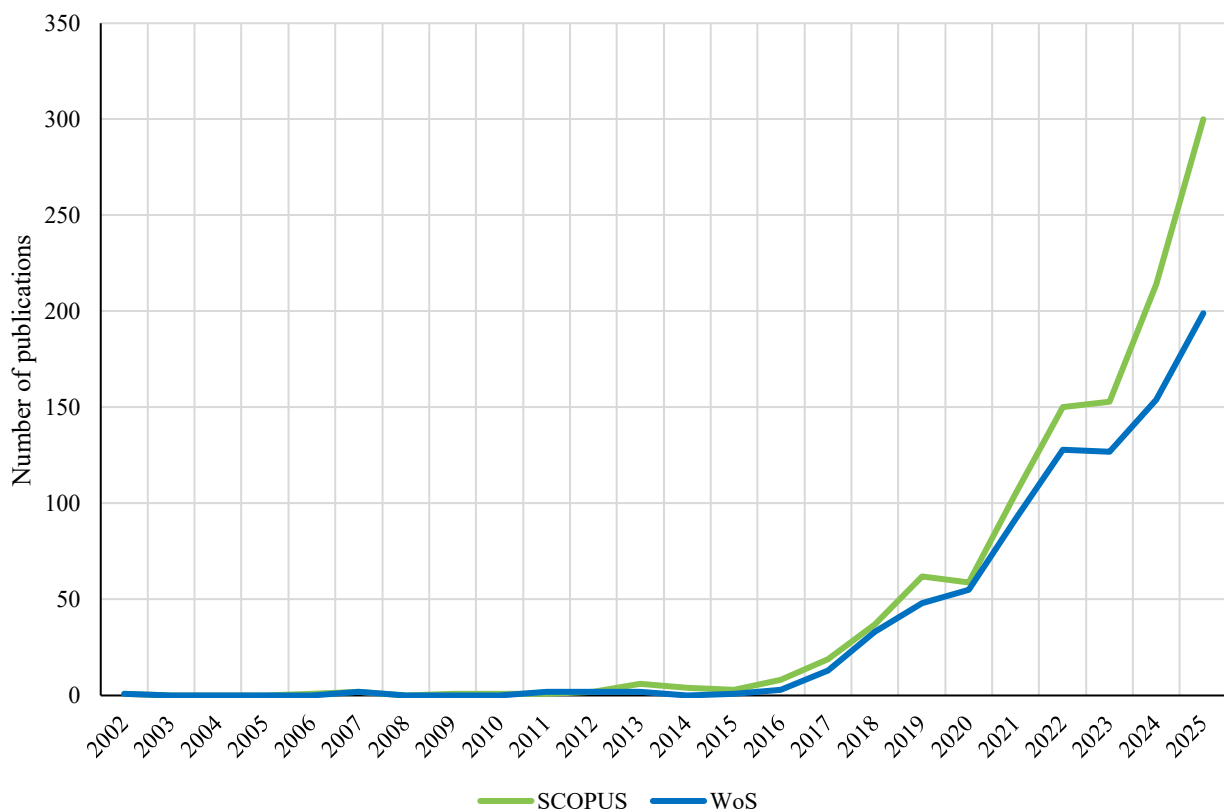


Figure 2. Evolution of publications obtained through search queries in the indexed databases.

It is also important to identify the disciplinary fields contributing to this body of literature. As illustrated in Fig. 3, the field is dominated by environmentally and technologically oriented scholarship: environmental science, sustainability and environmental engineering-related categories account for the majority of records (62% in WoS and half of SCOPUS records before the distribution becomes more dispersed across additional technical domains such as materials, chemistry, energy, and agri-biological sciences). This confirms a

predominantly technical framing of circularity, largely approached through physical flows, process performance, and environmental assessment. At the same time, SCOPUS shows a comparatively stronger presence of social sciences and business/management than WoS, yet these perspectives remain secondary relative to the environmental-engineering core, suggesting that organizational, managerial, and socio-economic dimensions are present but still not central in the retrieved literature.

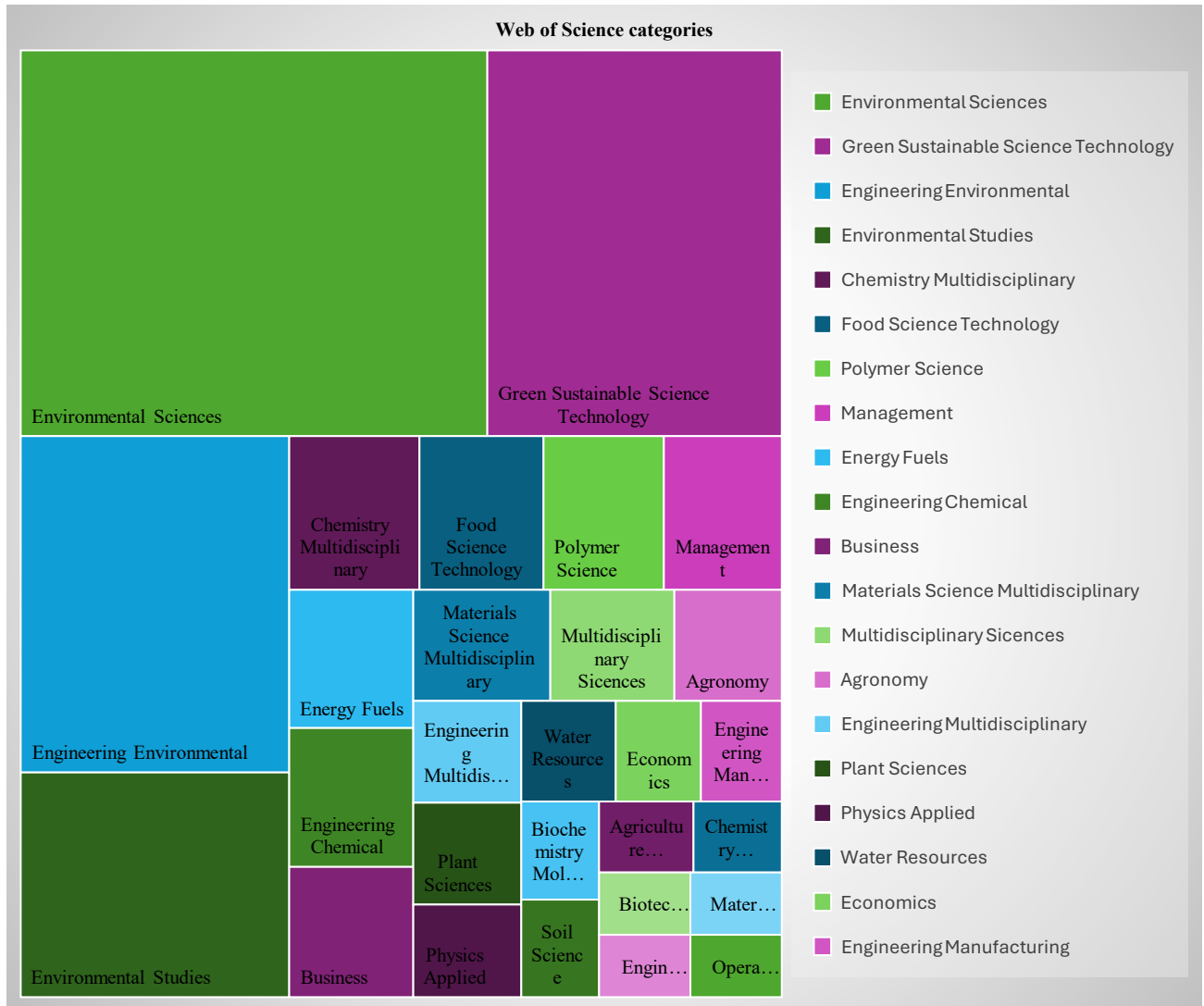


Figure 3. Disciplinary distribution of retrieved articles (Web of Science categories and SCOPUS subject areas).

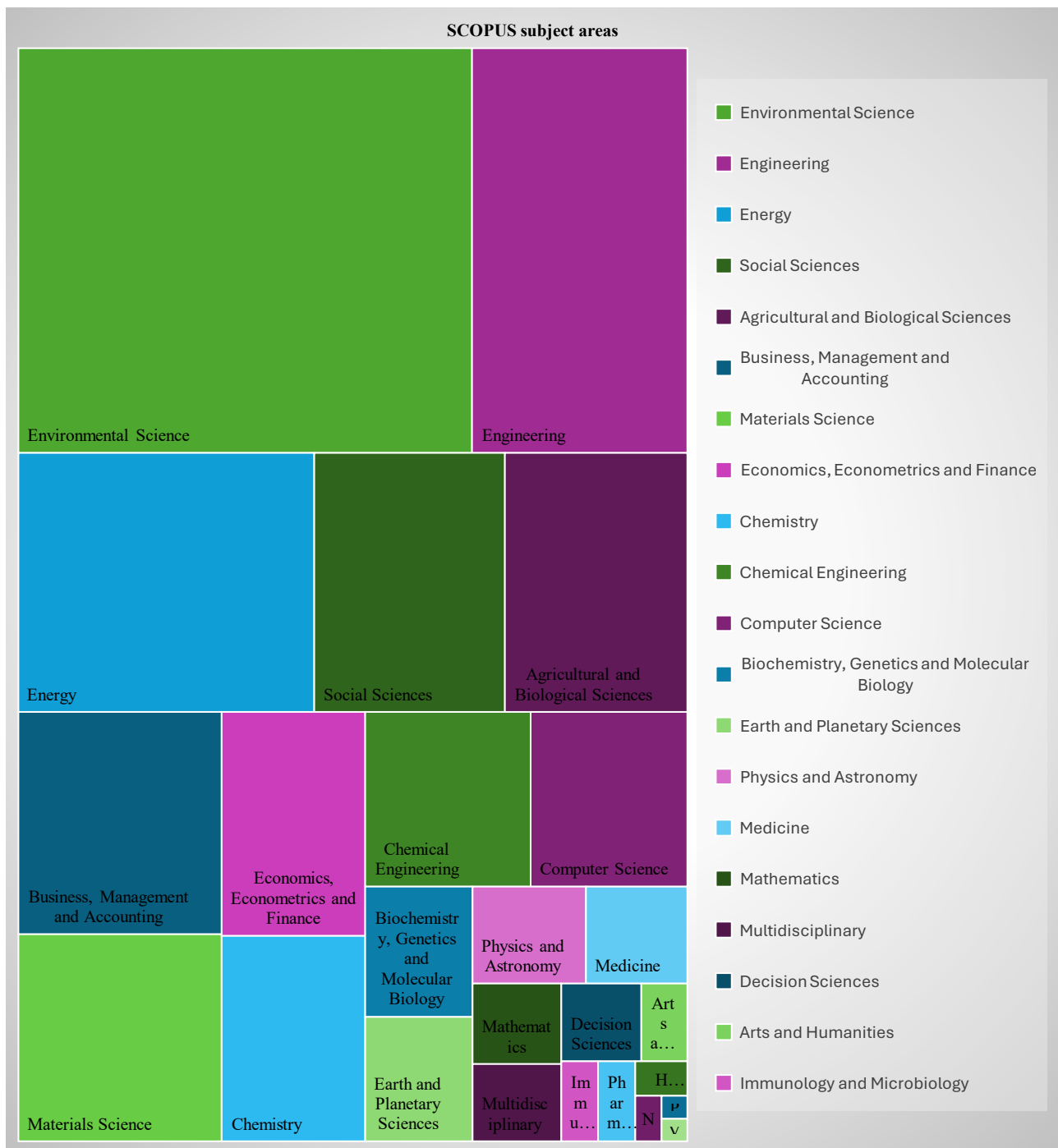


Figure 3 (cont.). Disciplinary distribution of retrieved articles (Web of Science categories and SCOPUS subject areas).

3.2. Keyword and cluster analysis

The keyword co-occurrence analysis provides a structured view of the thematic emphases and cross-links within the reviewed literature. Fig. 4 shows the co-occurrence network of the most frequent keywords (threshold: ≥ 21 occurrences), revealing four main clusters. The red cluster concentrates terms related to fertilizers and agricultural systems, closely connected to biomass and waste-treatment pathways, suggesting that a substantial share of the literature operationalizes circularity through nutrient and residue valorization contexts. The green cluster is organized around high-frequency umbrella terms (*circular economy*, *sustainability*, *recycling*, *waste*, and *economics*) and extends toward product-application terms such as *packaging*, *plastics*, *textiles*, as well as *supply chains* and *Europe*, indicating a comparatively stronger link to

product systems, market implementation, and policy-relevant contexts. The blue cluster is smaller and revolves around measurement and flow-accounting approaches. Finally, a minor purple cluster centered on *efficiency* appears weakly connected to the broader network, reflecting that efficiency is frequently mentioned but less consistently developed as a cohesive thematic strand in the keyword structure.

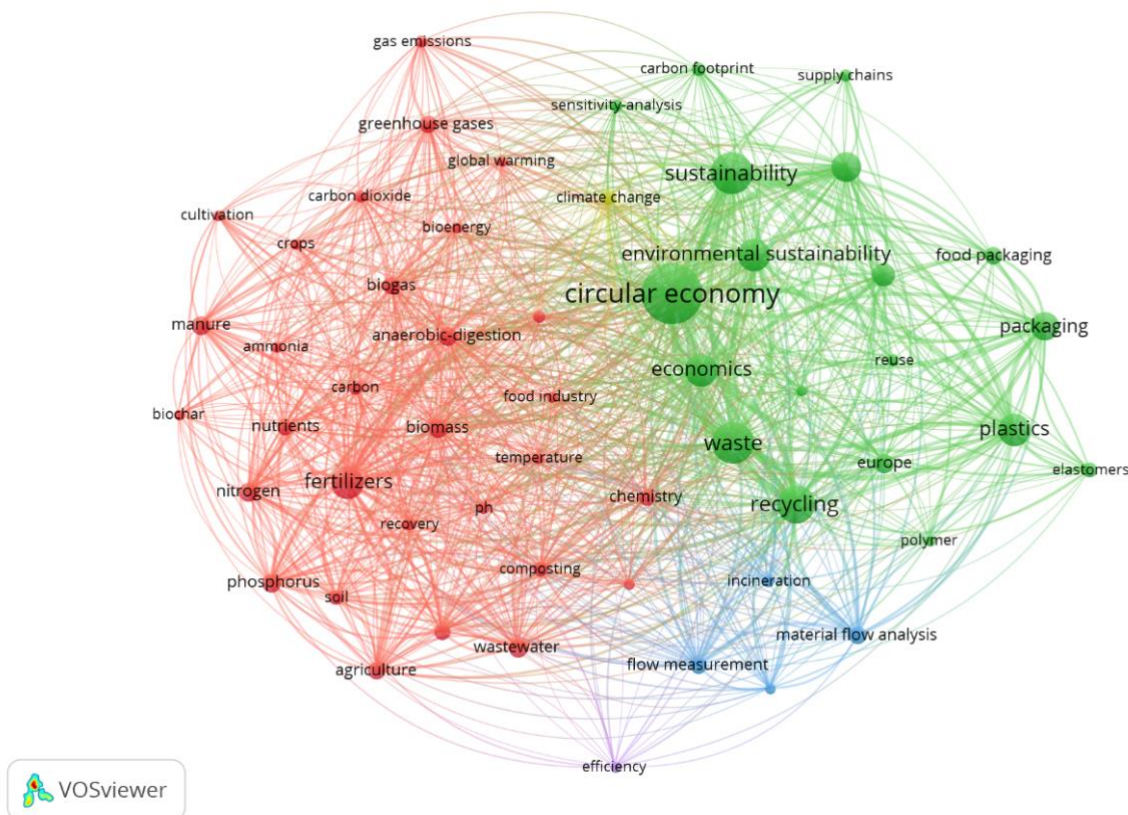


Figure 4. Keywords co-occurrence and cluster mapping.

To better understand how the three target sectors connect to the broader keyword landscape, Fig. 5 focuses on sector-centered co-occurrence patterns, highlighting the terms that most frequently appear alongside fertilizers, packaging, and textiles. This sector-oriented view helps distinguish between (i) concepts that are shared across sectors and therefore provide a common measurement vocabulary (e.g., *circular economy*, *sustainability*, *waste*, *recycling*), and (ii) terms that are more sector-specific and reflect different problem framings. In particular, fertilizers co-occurs predominantly with agricultural and residue-management terminology, indicating that circularity in this sector is frequently framed through nutrient recovery and biomass/waste valorization routes. In contrast, packaging is more closely associated with materials and product-system language (e.g., *plastics*, *polymers*, *reuse*, *supply chains*), suggesting a stronger emphasis on material loops, design choices, and value-chain implementation. *Textiles* appear less central in the high-frequency keyword space, and when present it tends to align with the broader sustainability/circular economy vocabulary rather than with a dense set of textile-specific co-occurring terms, pointing to a thinner thematic base for this sector within the retrieved literature.

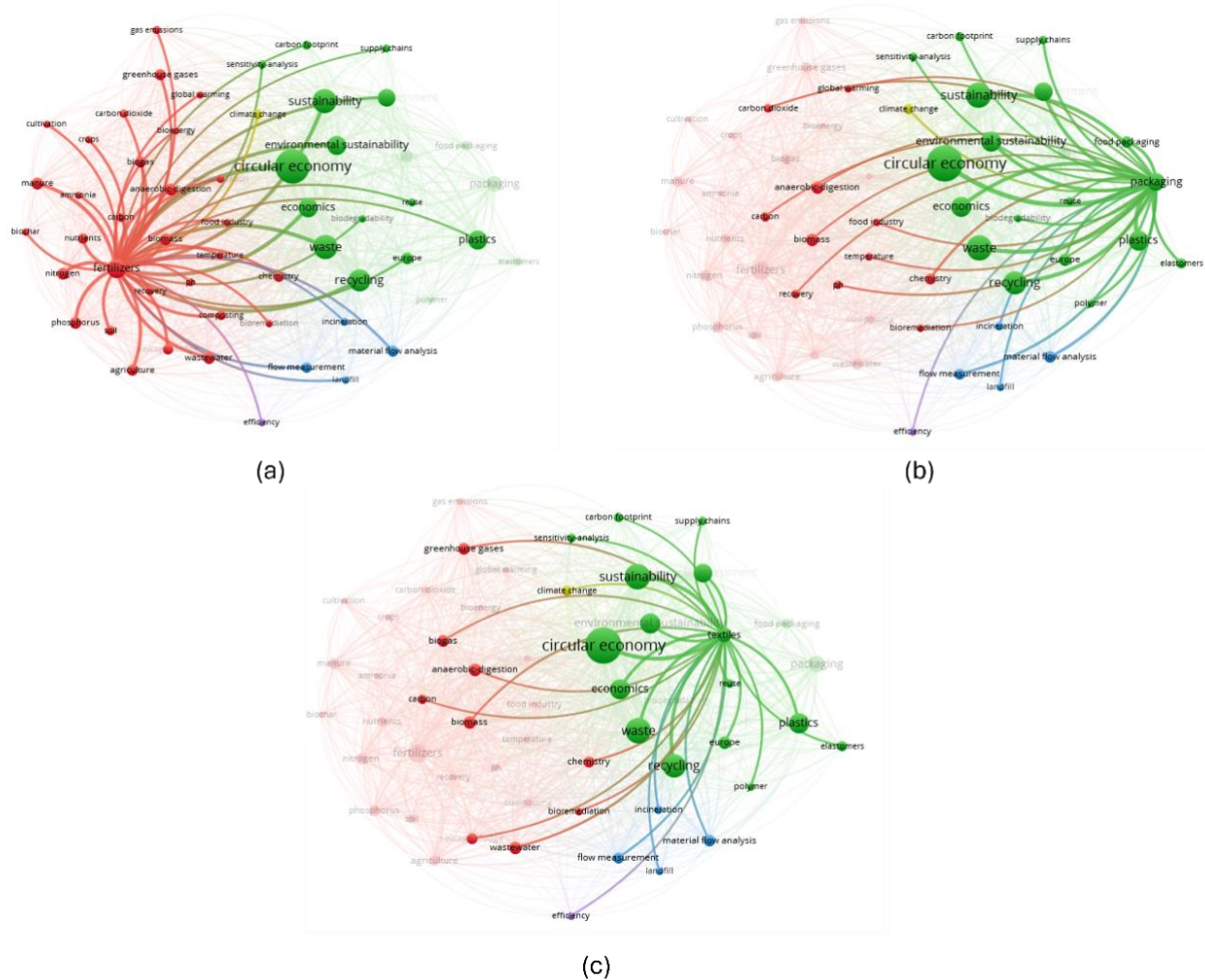


Figure 5. Keywords co-occurrence segmented by sectors: (a) fertilizers, (b) packaging, and (c) textiles.

Beyond the sector-specific neighborhoods, the combined Fig. 4-5 evidence also clarifies cluster interactions. The green “umbrella” cluster (organized around *circular economy*) acts as the main bridge linking the sector-focused strands: it connects the fertilizer/agro-residue cluster (red) to product/material-focused discussions (where packaging terms sit at the periphery of the green cluster). By comparison, the measurement/accounting cluster (blue), remains weakly integrated into the sector-specific neighborhoods, suggesting that accounting approaches form a methodological sub-stream that does not consistently translate into sector-applied, product-level indicator development.

These interaction patterns help explain several gaps that are relevant to product-level indicator development. First, the prominence of fertilizer-related keywords and their strong coupling with waste/agricultural terms suggests that bio-based circularity is often operationalized through nutrient and waste management, while other product-centric dimensions (e.g., product lifetime, end-of-life design choices, or cross-sector comparability) are less visible at the keyword level. Second, the comparatively marginal and weakly clustered presence of textiles indicates a potential evidence imbalance across sectors, which may constrain the availability of mature, sector-tailored indicator sets. Third, the limited connectivity between flow-accounting terms (blue cluster) and the sector-specific neighborhoods suggests a methodological gap: flow-based quantification seems not consistently integrated with circularity indicators in the three sectors examined.

3.3. Author collaboration and co-authorship networks

The co-authorship analysis provides a complementary view of how research on circularity indicators for bio-based products is organized in terms of collaboration. Fig. 6 visualizes the co-authorship network produced in VOSviewer, where nodes represent authors and links indicate at least one shared publication.

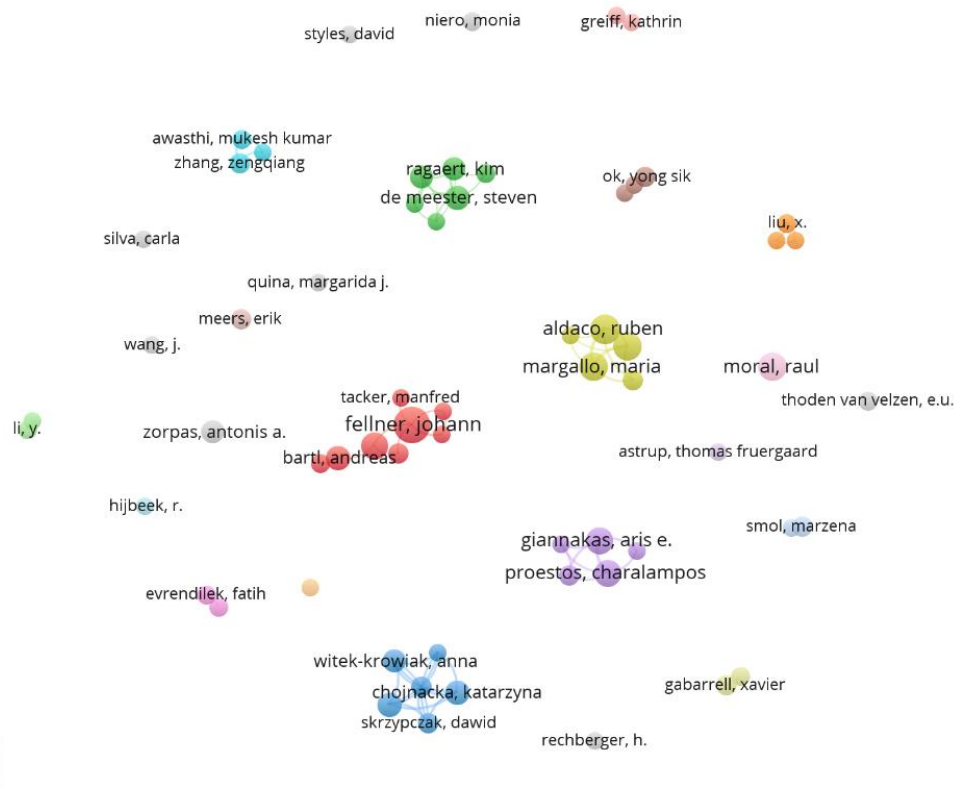


Figure 6. Co-authorship networks identified in the sample of scientific articles of the review.

The network reveals a highly fragmented collaboration structure, characterized by multiple small clusters and several authors positioned at the periphery with limited connections. This pattern suggests that the field is driven by relatively independent research groups, rather than by a single, highly interconnected community. In bibliometric terms, collaboration appears to be more strongly consolidated within teams than across teams, with limited cross-cluster co-authorship. Collaboration clusters formed by five or more authors are described below:

- The green cluster, centered around *De Meester, S.* and *Ragaert, K.* from Ghent University (The Netherlands), who specialize in plastic recycling.
- The red cluster, led by *Fellner, J.* and *Lederer, J.* from TU Wien (Austria), specializes in material flow analysis, waste management, and circular packaging recycling.
- The blue cluster, with *Chojnacka, K.* and *Izydorczyk, G.*, from Wrocław University of Science and Technology (Poland) and National Technical University of Athens (Greece), focuses on bio-based fertilizers, nutrient recovery, and lignocellulosic biomass valorization within circular bioeconomy frameworks.
- The yellow cluster, centered around *Aldaco, R.* and *Margallo, M.* from UNESCO Chair in Life Cycle and Climate Change at ESCI-UPF and University of Cantabria (Spain), who specialize in circularity indicators, life cycle assessment, and sustainability metrics for agri-food packaging systems.
- The fuchsia cluster, led by *Giannakas, A.E.* and *Proestos, C.*, from University of Patras and National and Kapodistrian University of Athens (Greece), who specialize in active food packaging innovation, sustainable packaging materials, and food waste reduction through circular material design.

Overall, the distribution of clusters indicates that packaging-related research is comparatively more consolidated, with several established collaboration groups spanning recycling, circular packaging design, and assessment-oriented work. By contrast, the fertilizer-related strand appears more limited in size and connectivity, reflecting a more emerging collaboration landscape around nutrient circularity and biomass valorization. Most notably, the network does not display a distinct, consolidated cluster centered on textiles, suggesting that collaboration in this sector is either less developed within the retrieved sample or dispersed across broader sustainability and materials-oriented communities rather than organized around a coherent author group.

The co-authorship network points to two practical gaps. First, the absence of a textile-focused collaboration core aligns with the weaker visibility of textile-related terms in the keyword structure, suggesting a thinner evidence base for sector-specific indicator maturation. Second, stronger cross-cluster collaboration could accelerate convergence on transparent calculation rationales and improve the transferability of indicators across fertilizers, packaging, and textiles.

4. Product-level bio-based circularity indicators

Measuring the circularity of bio-based products is not straightforward, as it involves combining different perspectives and data sources. This section explores how recent studies address this challenge: which sectors and indicators are most often examined, how circular metrics connect with LCA and economics, and which tools are currently used to monitor circularity. An inventory of these indicators is presented, grouped by key attributes to highlight both current strengths and remaining gaps in practice.

4.1. Sectoral representation and positioning of indicators

Upon analyzing the sectoral focus of the documents included, clear patterns emerge. As shown in Fig. 7(a), 40% of the documents address packaging, 39% address fertilizers, 17% address textiles, and 14% are general-purpose (sector-agnostic). Importantly, these percentages describe the share of documents addressing each sector, and they are not mutually exclusive: a single paper may cover more than one sector or may report very different numbers of indicators. For this reason, the sectoral distribution of documents should not be interpreted as directly proportional to the sectoral distribution of extracted indicators.

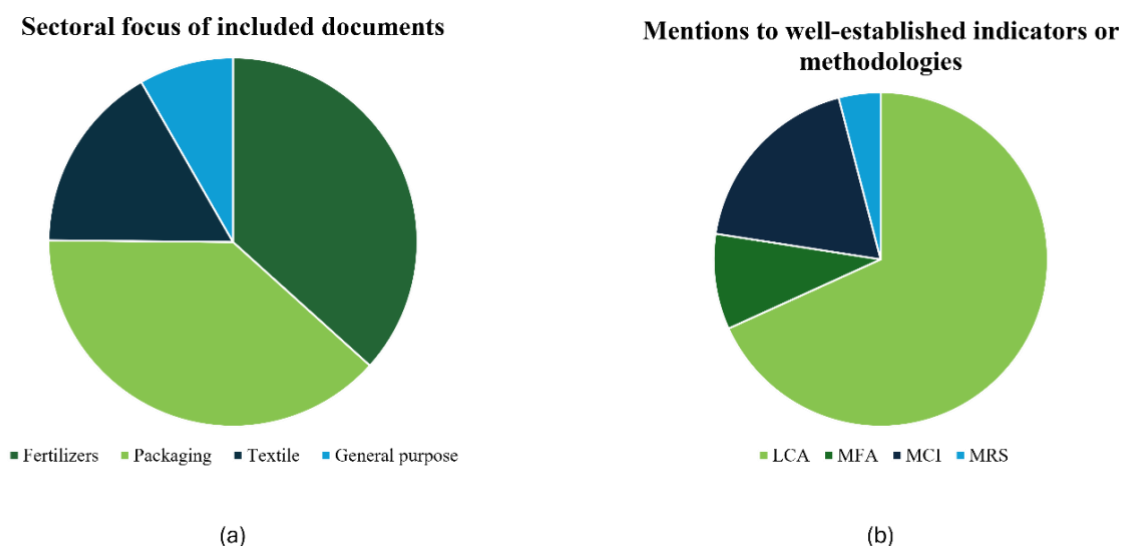


Figure 7. Weight of (a) sectors addressed in the included documents and (b) presence of well-established measurement methods.

Likewise, the review highlights the central role of widely recognized methods in circularity assessment. As shown in Fig. 7(b), 70% of the documents referred to LCA, either by using LCA results as a proxy for circular

performance or by leveraging LCI results and inventories as inputs for deriving circularity-related metrics. The Ellen MacArthur Foundation's MCI followed with 20%, often serving as a reference point for newer indicators. The Material Flow Analysis (MFA)—though more a methodological approach than an indicator—appeared in 10% as a complementary methodology, while the Cradle to Cradle's Material Reutilization Score (MRS) was cited in 4%.

4.2. Conceptual linkages: circular economy, LCA, and mainstream economic assessment

Given the prominence of LCA within the scientific landscape of circular economy measurement, Fig. 8 summarizes how three major assessment traditions relate to each other: circular economy, life cycle thinking (often operationalized through LCA), and mainstream economic assessment. Here, mainstream economic assessment refers to the conventional, widely used decision-making logic in firms and policy appraisal, which focuses on costs, revenues, market conditions, and profitability, and is commonly tracked using indicators such as return on investment (ROI), cost-benefit ratio (CBR), payback period, or earnings before interests, taxes, depreciation, and amortization (EBITDA). While essential for understanding feasibility and adoption dynamics, this approach often remains limited for circularity assessment because it primarily captures private costs/benefits and may overlook system-wide effects.

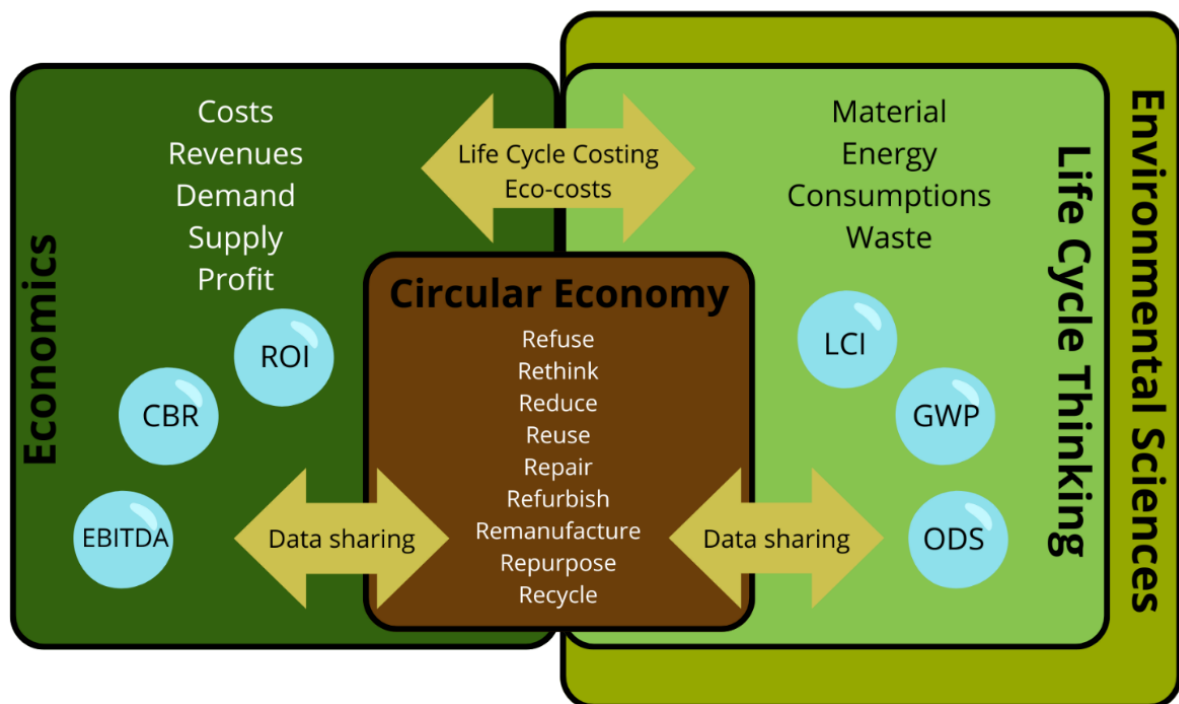


Figure 8. Diagram depicting the complementarity of life cycle thinking, circular economy, and mainstream economic assessment.

As depicted, life cycle thinking captures the aggregate environmental implications of products and systems across their full life cycles. By building life cycle inventories (LCI), LCA enables the quantification of impact categories such as Global Warming Potential (GWP) and Ozone Depletion Potential (ODP), among others. The intersection between these economic and environmental traditions is reflected in approaches such as life-cycle costing (LCC) and eco-costs metrics, which connect environmental pressures to economic valuation.

CE, in turn, interacts with both domains but addresses a different core question: how resources are kept in use, at what state, and with what degree of value retention.

When studying circularity of products, both economic data and LCA-derived insights are essential, as they jointly determine not only a product's environmental performance but also the feasibility and effectiveness of circular strategies. These two perspectives, while interconnected and often complementary, address different dimensions: LCA focuses on quantifying environmental impacts across the entire life cycle, whereas

economics assesses the financial viability, cost-benefit balance, and market implications of implementing circular strategies.

On the other hand, CE approaches emphasize resource loops, circular business models, and economic value creation. Consequently, neither LCA nor mainstream economic assessment capture all the strategic nuances relevant to CE, just as CE assessments do not necessarily account for the full spectrum of a product's environmental impacts or all its interactions with the economic system in which it is embedded.

This distinction is particularly relevant for circular bioeconomy (CBE) assessments. Beyond general CE logic, product circularity in bio-based systems must also reflect what is specific to biomass-based value creation: the valorization of biological resources, the handling of residues, and cascading uses over time. In other words, circularity for bio-based products cannot be reduced to “low impact” alone; it must also reflect whether the product system is designed to retain functionality and value through appropriate loops. To this end, the Resource State Framework proposed by Blomsma & Tennant (2020) helps to clarify the measurement of loops (product-, part-, or material-level cycling), avoiding conceptual ambiguity when comparing indicators across sectors and technologies.

In contrast to what is often assumed in technical CE evaluations, LCA, while valuable, is not sufficient to determine whether a product is truly circular. Low environmental impacts do not necessarily equate to high circularity, nor does higher circularity automatically imply lower impacts. Saidani et al. (2021) explicitly illustrate this relationship through a trade-off matrix between circularity and LCA-based environmental performance, distinguishing situations that range from win-win improvements to cases where gains in one dimension may come at the expense of the other. In practice, firms therefore face decisions that require balancing circularity ambitions with environmental outcomes, rather than optimizing a single metric. This is precisely why circularity assessments should not rely solely on LCA outputs but should be complemented with circularity-specific indicators that capture resource loops and value-retention mechanisms.

A comprehensive assessment of product circularity thus requires integrating multiple variables—each capturing a distinct dimension—so that, collectively, they provide a robust profile of both environmental performance and circularity.

4.3. Inventory of indicators identified in scientific literature

Currently, product-level circularity (and circularity-related assessment practices) for circular-produced bio-based fertilizers, packaging and textiles is reported in the scientific literature through the 88 quantitative indicators listed in Table 4, which consolidates the indicators identified in the literature review, referencing their original sources, and the reviewed articles in which they are mentioned.

Table 4. List of the circularity indicators identified in the documents included in the review.

#	Indicator	Symbol	Addressed in	Original source of indicator
1	Additives impact on sustainability of organic recycling	η_{add}	Briassoulis et al. (2021)	Briassoulis et al. (2021)
2	Atom Economy	AE	Hessel et al. (2021)	Hessel et al. (2021)
3	Bio-based fertilizers (BBFs) indicators	$I_{BBF(N/P)}$	Preisner et al. (2022)	Nika et al. (2020)
4	Biodegradable content	BC	Iglesias et al. (2025)	Iglesias et al. (2025)
5	Carbon Circularity Indicator	CI_C	Cobo et al. (2018)	Cobo et al. (2018)
6	Carbon Circularity Rate	CCR	Zhang et al. (2026)	Zhang et al. (2026)
7	Circo-economic indicator	MCIE	Tashkeel et al. (2021)	Tashkeel et al. (2021)
8	Circular Economy Index	CEI	Rossi et al. (2020)	Di Maio & Rem (2015)
9	Circular Economy Package	CEP	Pauer et al. (2019)	Pauer et al. (2019)
10	Circular Economy Performance Indicator	CEPI	Rossi et al. (2020)	Huysman et al. (2017)
11	Circular Index – CirculAbility model	CI	Latif et al. (2023), Iglesias et al. (2025)	Enel (2018)

Table 4 (cont.). List of the circularity indicators identified in the documents included in the review.

#	Indicator	Symbol	Addressed in	Original source of indicator
12	Circular Indicators for designing and selecting food packaging	CIDSFP	Schmidt Rivera et al. (2019)	Schmidt Rivera et al. (2019)
13	Circular Material Use Rate	CMU	Havrysh et al. (2023), Rodino et al. (2023), Gonçalves et al. (2024)	Eurostat (2024)
14	Circular Process Energy Intensity	CPEI	Hessel et al. (2021)	Hessel et al. (2021)
15	Circularity Index	CI	Rossi et al. (2020), Rasines et al. (2024)	Cullen (2017)
16	Circularity Index	CI	Y. Zhang et al. (2024)	Y. Zhang et al. (2024)
17	Circularity Index for Textiles	CI _T	De Oliveira Neto et al. (2022)	De Oliveira Neto et al. (2022)
18	Circularity Indicator for Resource Recovery at a WWTP	ICE _{RR+E,WWTP}	Preisner et al. (2022)	Preisner et al. (2022)
19	Circularity Indicator of Component i	CI _i	Cobo et al. (2018)	Cobo et al. (2018)
20	Circularity Indicators of N and P	CI _N / CI _P	Cobo et al. (2018), Cobo et al. (2019), (Lavallais & Dunn, 2023), Iglesias et al. (2025).	Cobo et al. (2018)
21	Collection Rate	CR	Gonçalves et al. (2024)	Gonçalves et al. (2024)
22	Cyclical Use Rate Indicator	PU _{cm1+2}	Tashkeel et al. (2021)	Kovanda (2014)
23	Ecological Sustainability Index	ESI	Khan et al. (2025)	Muthu et al. (2012)
24	EcoStrategic Index	ESI	Barahmand & Eikeland (2025)	Barahmand & Eikeland (2025)
25	Emergy	Em	Wang et al. (2019), Rodino et al. (2023)	Odum (1996)
26	Environmental Factor	EF	Hessel et al. (2021)	Hessel et al. (2021)
27	Green Aspiration Level	GAL	Hessel et al. (2021)	Roschangar et al. (2015)
28	Green Protein Food Index	GPF	Laso et al. (2018)	Laso et al. (2018)
29	Indicator of Circular Economy for Biofertilizer	I _{bf,ce}	Molina-Moreno et al. (2017)	Molina-Moreno et al. (2017)
30	In-use occupation of materials	Occ _U	Moraga et al. (2021)	Moraga et al. (2021)
31	Joint Entropy	H	Liu et al. (2021)	Liu et al. (2021)
32	Levelized Cost of Waste	LCOW	Bury et al. (2025)	Bury et al. (2025)
33	Littering Potential	LP	Anand et al. (2024)	Civancik-Uslu et al. (2019)
34	Longevity Factor	L	Tashkeel et al. (2021)	Franklin-Johnson et al. (2016)
35	Mass Intensity Total	MIT	Teixeira et al. (2025)	Saurat & Ritthoff (2013)
36	Material Circularity Indicator	MCI	32 articles referenced the Ellen MacArthur Foundation's MCI	Ellen MacArthur Foundation & ANSYS Granta (2019)
37	Material Durability Indicator	MDI	J. Mesa et al. (2020)	J. Mesa et al. (2020)
38	Material Reutilization Score	MRS	7 articles referenced the Cradle to Cradle's MRS	Cradle to Cradle Products Innovation Institute (2016)
39	Maximum Achievable Circularity	MAC	Latif et al. (2023)	C.-E. Nika et al. (2021)
40	MCI based on economic and residual value	-	Jiang et al. (2022)	Jiang et al. (2022)
41	MCI coupled with LCA	-	Rufi-Salis et al. (2021)	Rufi-Salis et al. (2021)
42	Modified MCI	mMCI	Escriba-Gelonch et al. (2023)	Escriba-Gelonch et al. (2023)

Table 4 (cont.). List of the circularity indicators identified in the documents included in the review.

#	Indicator	Symbol	Addressed in	Original source of indicator
43	Nitrogen Use Efficiency	NUE	Silva et al. (2021), Cowan et al. (2022), Piccoli et al. (2025)	Oenema (2015)
44	Nutrient Recycling Index	NRI	Møller et al. (2023)	Tadesse et al. (2019)
45	Nutrient Removal Efficiency Indicator	$I_{RE(N)} / I_{RE(P)}$	Preisner et al. (2022)	Council of the European Communities (1991)
46	Nutrient Slow-Release Indicator	NSRI	Iglesias et al. (2025)	Iglesias et al. (2025)
47	Organic Recycling Efficiency	η_{mr}	Briassoulis et al. (2021)	Briassoulis et al. (2021)
48	Packaging Index	PIX	Scagnetti et al. (2022)	Scagnetti et al. (2022)
49	Percentage Biodegradation	PB	Priya et al. (2025)	Priya et al. (2025)
50	Percentage Circularity	PC	Roos Lindgreen et al. (2021), Wiedemann et al. (2022)	World Business Council for Sustainable Development (2020)
51	Plastic Circularity Index	PCI	Ghosh et al. (2024)	Ghosh et al. (2024)
52	Process Excellence Index	PEI	Hessel et al. (2021)	Hessel et al. (2021)
53	Process Improvement	PI	Hessel et al. (2021)	Hessel et al. (2021)
54	Process Mass Intensity	PMI	Hessel et al. (2021)	Hessel et al. (2021)
55	Process Yield / Net Recovery	Y / R	Lase et al. (2022)	Lase et al. (2022)
56	Product Circularity Indicator	PCI	Sazdovski et al. (2024)	Bracquené et al. (2020)
57	Product Circularity Metric (UL 3600)	C_{prod}	Roos Lindgreen et al. (2021)	ULSE Inc (2024)
58	Product Index	PI	Latif et al. (2023)	C.-E. Nika et al. (2021)
59	Product Sustainability Index	PSI	A. Gonçalves et al. (2025)	A. Gonçalves et al. (2025)
60	Product-level Circularity	PLC	Betts et al. (2022)	Betts et al. (2022)
61	Product-level Circularity Metric	PLCM	Rossi et al. (2020)	Linder et al. (2017)
62	Quality Indicator	G	Lase et al. (2022)	Lase et al. (2022)
63	Quality Model for Recycled Plastics	QMRP	Golkaram et al. (2022)	Golkaram et al. (2022)
64	Quality of Recycling Framework	QRF	Roosen et al. (2023)	Roosen et al. (2023)
65	Recycled Input Rate	RIR	Gonçalves et al. (2024)	Van Ewijk et al. (2018)
66	Recycled Potential Performance	RPP	Gonçalves et al. (2024)	Gonçalves et al. (2024)
67	Recycling Effectiveness	RE	Roithner & Rechberger (2020)	Roithner & Rechberger (2020)
68	Recycling Rate	RR	Gonçalves et al. (2024)	Gonçalves et al. (2024)
69	Regenerative Capacity Index	RCI	Latif et al. (2023)	C.-E. Nika et al. (2021)
70	Relative Antibiotic-to-Phosphorus Ratio	RAP	Bolujoko et al. (2025)	Bolujoko et al. (2025)
71	Relative Green Process Improvement	RPI	Hessel et al. (2021)	Hessel et al. (2021)
72	Relative Process Complexity Improvement	RCI	Hessel et al. (2021)	Hessel et al. (2021)
73	Relative Process Greenness	RPG	Hessel et al. (2021)	Hessel et al. (2021)
74	Renewable Energy Use	$\eta_{Renergy}$	Briassoulis et al. (2021)	Briassoulis et al. (2021)
75	ResCom Circularity Calculator	ResCom	Roos Lindgreen et al. (2021)	IDEAL&CO (2016)
76	Residuals, solid waste	R_{sw}	Briassoulis et al. (2021)	Briassoulis et al. (2021)

Table 4 (cont.). List of the circularity indicators identified in the documents included in the review.

#	Indicator	Symbol	Addressed in	Original source of indicator
77	Resource Flow Indicators	RFI	Renfrew et al. (2024), Arias et al. (2025)	Renfrew et al. (2024)
78	Resource Pressure	RP	Lama et al. (2022)	Desing et al. (2021)
79	Sorting Efficiency	η_{sort}	Briassoulis et al. (2021)	Briassoulis et al. (2021)
80	Sorting Rate	SR	Gonçalves et al. (2024)	Gonçalves et al. (2024)
81	Statistical Entropy	H	Nimmegeers & Billen (2021)	Nimmegeers & Billen (2021)
82	Textile Sustainability Index	TSI	Khan et al. (2025)	Khan et al. (2025)
83	Total Energy Consumption Efficiency	η_{energy}	Briassoulis et al. (2021)	Briassoulis et al. (2021)
84	Total Water Consumption Efficiency	η_{water}	Briassoulis et al. (2021)	Briassoulis et al. (2021)
85	Value-based Resource Efficiency Indicator	VRE	Matos et al. (2024)	Di Maio et al. (2017)
86	Volume-Time-Output	VTO	Hessel et al. (2021)	Hessel et al. (2021)
87	Waste Index	WI	Latif et al. (2023)	C.-E. Nika et al. (2021)
88	Yarn Knittability	KA	Bukhonka & Kyzymchuk (2024)	Zinovjeva (2000)

4.4. Complementary evidence from grey literature and standardization bodies

Some of the product-level circularity indicators identified in scientific literature do not originate within academia (e.g., Enel's Circular Index, Eurostat's CMU, Ellen MacArthur Foundation's MCI, ULSE's Product Circularity Metric). Instead, they are often adopted, adapted, or operationalized from definitions developed by industry initiatives, governmental bodies, standardization organizations, and other specialized institutions with a direct role in shaping business reporting and policy implementation. For this reason, the present section complements the systematic literature review by expanding the evidence base with additional indicators that were not captured in the systematic search but are influential in practice.

Grey literature was therefore used as a complementary source for indicator identification and definition tracing, but it was not included in the systematic search corpus. The grey literature documents were selected purposively based on their widespread uptake and their institutional proximity to industry practice, prioritizing documents produced by organizations that are strongly connected to business reporting, standardization, or public governance of circular economy and bio-based value chains. Accordingly, the grey literature sources comprised:

- 1) Standards and technical specifications:
 - a) ISO 59004: Circular Economy. Vocabulary, principles and guidance for implementation (International Standardization Organization, 2024a).
 - b) ISO 59010: Circular Economy. Guidance on the transition of business models and value networks (International Standardization Organization, 2024b).
 - c) ISO 59020: Circular Economy. Measuring and assessing circularity performance (International Standardization Organization, 2024c).
 - d) ISO 59040: Circular Economy. Product Circularity Data Sheet (International Standardization Organization, 2025).
 - e) UNE-EN 16785-1: Bio-based products. Bio-based content. Part 1: Determination of the bio-based content using the radiocarbon analysis and elemental analysis (Asociación Española de Normalización, 2016).
 - f) UNE-EN 16785-2: Bio-based products. Bio-based content. Part 2: Determination of the bio-based content using the material balance method (Asociación Española de Normalización, 2018).

- 2) Public and intergovernmental documents:
 - a) EU's Joint Research Center Technical Report: Building a monitoring system for the EU bioeconomy (Giuntoli et al., 2020).
 - b) EU's Joint Research Center: Method for the assessment of circularity aspects and integration in or relation with the Methodology for the Ecodesign of Energy-related Products (MEErP) (Rodriguez Manotas et al., 2025).
 - c) European Commission staff working document: Measuring progress towards circular economy in the European Union – Key indicators for a revised monitoring framework (European Commission, 2023).
- 3) Industry and business-led frameworks:
 - a) CEFLEX's Designing for a Circular Economy (CEFLEX, 2025).
 - b) Ellen MacArthur Foundation's Material Circularity Indicator methodology (Ellen MacArthur Foundation & ANSYS Granta, 2019).
 - c) Enel's CirculAbility model (Enel, 2018).
 - d) Euratex's Circular textiles. Prospering in the circular economy (Euratex, 2020).
 - e) Plastics Europe's The circular economy for plastics. A European analysis (Plastics Europe, 2024).
 - f) Textile Exchange's Fiber and materials matrix. Methodology (Textile Exchange, 2025).
 - g) World Business Council for Sustainable Development's (WBCSD) Circular Transition Indicators v4.0 (World Business Council for Sustainable Development, 2023).

For a clearer interpretation of the indicator approaches reported in the grey literature, indicator lists are presented by source rather than merged into a single consolidated table, in order to preserve each document's original definitions and scope.

ISO 59004 and 59010 provide the conceptual and strategic foundation for circularity without listing specific quantitative metrics. They focus on principles and managerial guidance for the transition. For performance measurement, both standards refer to ISO 59020, which specifies the quantitative indicators and calculation formulas. The indicators contained in ISO 59020 are listed in Table 5.

Table 5. List of the circularity indicators contained in the standard ISO 59020.

Indicator category	Indicator	Symbol
Resource inflows	Average reuse content of an inflow	%REUI(X)
	Average recycled content of an inflow	%RECI(X)
	Average renewable content of an inflow	PRENI(X)
Resource outflows	Average lifetime of product or material relative to industry average	RLP(X)
	Per cent actual reused products and components derived from outflow	PREUO(X)
	Per cent actual recycled material derived from outflow	PRECO(X)
	Per cent actual recirculation of outflow in the biological cycle	PRENO(X)
	Per cent designed reusability rate of the outflow	PDFRM
	Per cent designed recyclability rate of the outflow	PDRMO(X)
Energy	Average per cent of energy consumed is renewable energy	PECONRE(X)
	Per cent energy recovered from residual, non-renewable and non-recoverable resource outflows	PRNRENE
	Energy intensity	IEI
Water	Per cent water withdrawal from inflow circular sources	PCWW
	Per cent water discharged in accordance with quality requirements	PCDW
	Ratio (on-site or internal) water reuse or recirculation	RWRR
	Per cent of nutrient-extracted water discharged	WE
	Percentage of extracted surplus materials	PESMAT
Economic	Water intensity	IWI
	Material productivity	MP
	Resource Intensity Index	RII
	Value per mass	IVPUM
	Resource productivity	IRP

ISO 59040, which standardizes the Product Circularity Data Sheet (PCDS), defines a structured set of standardized disclosure statements—primarily in a binary (true/false) format—to support interoperability and transparency. Although the approach is statement-based, it can incorporate quantitative information through predefined percentage ranges. ISO 59040 refers to ISO 59020 for the underlying measurement and calculation methodologies. To avoid redundancy, Table 6 reports the PCDS disclosure structure without repeating the underlying indicators already listed in Table 5.

Table 6. Outline of items for the disclosure of product circularity per the ISO 59040 standard.

Category	Module	Obligation
PCDS template	PCDS template issuer	Mandatory
	PCDS template verifier	Mandatory
	PCDS template version	Mandatory
	Persistent identifier page	Optional
Company and product information	Product identification	Mandatory
	Supplier identification	Mandatory
	Production site information	Optional
	PCDS issuance	Mandatory
	PCDS revision	Mandatory
Material inputs	Product composition	Mandatory
	Hazardous substances and substances of concern	Mandatory
	Reused content	Mandatory
	Recycled materials	Mandatory
	Renewable materials	Mandatory
Circular production	Renewable energy	Optional
	Water reuse or recirculation	Optional
Durability and extended lifetime	Reliability	Optional
	Maintenance and repair	Optional
	Upgradability	Optional
	Demounting	Optional
	Disassembly	Optional
	Reuse	Optional
	Refurbishing	Optional
Circularity at end of product use period	Product portion released into the environment during its use	Mandatory
	Dismantling	Optional
	Remanufacturing	Optional
	Recycling	Mandatory
	Composting and biodegradability	Mandatory
Circularity benefits	Environmental benefits	Optional

On the other hand, UNE-EN 16785-1 and UNE-EN 16785-2 focus on scientific and technical determination methods rather than high-level strategic management. UNE-EN 16785-1 relies on laboratory testing, whereas UNE-EN 16785-2 is based on a material-balance approach. Together, these standards operationalize two key technical indicators: bio-based content (m_B), and bio-based carbon content (x_B). Bio-based content represents the fraction of a product's total mass derived from biomass, while bio-based carbon content quantifies the share of carbon in the product that originates from biological sources.

Regarding public and intergovernmental documents, Giuntoli et al. (2020) outlines how the European Union can monitor the bioeconomy at regional, national, and supranational levels. Rather than operationalizing specific quantitative indicators, they provide a conceptual basis for what to measure and why. Similarly, the European Commission (2023) identifies strategic monitoring areas for circular economy policy and proposes

headline indicators for the macroeconomic level. Although these are not product-level metrics, the underlying monitoring areas remain relevant for framing measurement priorities across levels; for completeness, the dimensions are listed below:

- 1) Production and consumption: (a) material consumption; (b) green public procurement; (c) waste generation.
- 2) Waste management: (a) overall recycling rates; (b) recycling rates for specific waste streams.
- 3) Secondary raw materials: (a) contribution of recycled materials to raw materials demand; (b) trade in recyclable raw materials.
- 4) Competitiveness and innovation: (a) private investment, jobs and gross added value related to circular economy sectors; (b) innovation.
- 5) Global sustainability and resilience: (a) global sustainability from circular economy; (b) resilience from circular economy.

At the product-policy interface, Rodriguez Manotas et al. (2025) propose a methodological bridge to integrate circularity into eco-design for products in the European market. Their contribution is primarily conceptual, highlighting circularity aspects that can be embedded across design stages —without specifying quantitative indicators.

Lastly, industry and business-led frameworks were reviewed to conceptualize how circularity is operationalized in practice, although their scope is not indicator-based. For example, CEFLEX (2025) presents circular economy design guidelines for flexible packaging; Euratex (2020) outlines a strategic roadmap and actions to foster circularity and sustainable growth in the European textile and apparel industry; and Plastics Europe (2024) provides an overview of the European plastics market and its waste-management pathways.

Textile Exchange (2025), in turn, presents the “Fiber and Materials Matrix” (FMM), a tool intended to assess sustainability performance of textile raw materials. The FMM comprises 76 items, of which 72 are survey-based qualitative questions and four correspond to LCA impact categories.

Table 7 reports on the Circularity Transition Indicators (CTI) developed by the World Business Council for Sustainable Development (WBCSD). The CTI are a widely used, business-oriented framework designed to support corporate measurement and reporting of circularity by quantifying key aspects such as circular inflows/outflows and value retention. Because this framework is frequently referenced in practice but was not captured in its entirety through the systematic search corpus, its indicators are presented here as complementary evidence.

Table 7. List of the circularity indicators contained in the WBCSD’s Circularity Transition Indicators framework.

Indicator	Symbol	Source
Actual lifetime	AL	WBCSD (2023)
Circular material productivity	CMP	WBCSD (2023)
CTI revenue	CTIr	WBCSD (2023)
GHG impact	GHGi	WBCSD (2023)
Nature impact	NI	WBCSD (2023)
Onsite water circulation	OWC	WBCSD (2023)
% Critical material	%CM	WBCSD (2023)
% Material circularity	%MC	WBCSD (2023)
% Recovery type	%RT	WBCSD (2023)
% Renewable energy	%RE	WBCSD (2023)
% Water circularity	%WC	WBCSD (2023)

Across the grey literature sources reviewed, only two documents were specifically designed for bio-based products (UNE-EN 16785-1 and UNE-EN 16785-2), operationalizing bio-based content and bio-based carbon content. All other grey literature frameworks and standards identified are general circularity indicator sets, developed to be applicable across product types and sectors rather than tailored to bio-based value chains.

Nevertheless, these general indicators are commonly applied in bio-based contexts in practice, often serving as default measurement tools in the absence of standardized sector-specific product-level circularity metrics.

Altogether, 35 indicators were identified from grey literature documents, which added to those sourced from the systematic literature review, totaled 123 CBE metrics. These indicators are characterized and assessed in the following sections.

4.5. Characterization by attributes

To better understand the landscape of product circularity indicators applied to bio-based fertilizers, packaging, and textiles, three dimensions were evaluated for each of them: aspects included, leverage of well-established frameworks, and type of value. Table 8 describes variables included in each of the dimensions, following the rationale described in Table 3. The complete indicator-by-indicator characterization is provided in the Supplementary Material (Table S2).

Table 8. Characterization of the product-level circularity indicators identified through systematic literature review (SLR) and complementary grey literature.

Dimension	Variable	Weight SLR	Weight grey literature
Sector	General	43%	100%
	Fertilizers	26%	0%
	Packaging	28%	0%
	Textiles	9%	0%
Aspects included	Recycled/reused input	33%	14%
	Efficiency	38%	29%
	Product lifetime	15%	6%
	Economic input	16%	17%
	End-of-life processes	22%	23%
	Recyclability	20%	26%
	Energy	13%	11%
	Environmental impact	18%	23%
	Benchmark against the linear option	8%	6%
	Entropy	5%	0%
Leverage of well-established frameworks	LCA-based	8%	0%
	MCI-based	8%	0%
Type of value	Relative value	89%	94%
	Absolute value	11%	6%

As observed, Table 8 summarizes the main dimensions currently operationalized in circularity indicators applied to bio-based products, and it helps clarify how sectoral focus at the document level differs from the sectoral orientation of the extracted indicators. In the reviewed corpus, fertilizers and packaging dominate the documents (39% and 40%, respectively), followed by textiles (17%) and general-scope papers (14%). However, the indicators themselves are more frequently general-purpose (43%) than sector-tailored (fertilizers 26%, packaging 28%, textiles 9%). Importantly, these percentages describe characteristic prevalence (non-mutually exclusive), and they should not be read as a one-to-one correspondence between “share of papers” and “share of indicators”.

Despite being a widespread practice, relying on general-purpose indicators can overlook features that are unique to particular product types. Examples include nutrient recovery and nutrient-soil dynamics for fertilizers; multiple-use applications and product-to-packaging ratios for packaging; and strategies such as reuse, refurbishing, repair, or circular business models (CBM) for textiles.

Regarding the aspects considered, the most common feature in scientific literature is the explicit inclusion of efficiency (38%) followed by recycled inputs (33%). While recycled-input emphasis aligns with the circular

principle of extending material life beyond its first use, it also risks narrowing circularity to recycling alone. For bio-based products—which can originate from either recirculated biomass or virgin organic feedstocks—acknowledging the distinction between biogenic origin, renewability, and recirculation in the biological cycle is essential to reflect the full breadth of circular strategies. Yet explicit operationalization of the biological cycle remains comparatively rare, appearing mainly through a small set of indicators such as biodegradable content (Iglesias et al., 2025), percentage biodegradation (Priya et al., 2025), product circularity metric (ULSE Inc, 2024), ISO 59020's disclosure on actual recirculation of outflows in the biological cycle, and the UNE-EN 16785 indicators on bio-based content and bio-based carbon content. Product lifetime (15%) remains relatively underrepresented and appears mainly in packing and textiles.

Several additional contrasts emerge when comparing the SLR with grey literature. Grey literature sources are entirely general purpose (100% general) and are not designed specifically for bio-based value chains or for the three focal sectors, even though they are frequently applied in practice. Both groups emphasize efficiency and end-of-life processes (SLR 22%; grey 23%), but the SLR places more weight on recycled input (33% vs. 14%), whereas grey literature emphasizes recyclability (26% vs. 20%) and, in practice, tends to foreground “actual recycling/recirculation” considerations more explicitly. Environmental impacts appear in both (SLR 18%; grey 23%), but it tends to enter the scientific literature primarily through LCA-derived aggregation, whereas grey literature more often reflects direct pressure/load metrics such as water consumption and pollution-related disclosures. Benchmarking against a linear option remains limited in both groups, suggesting that explicit counterfactual framing is still not a dominant design choice in indicator construction.

Finally, the two bodies of evidence differ in how they package information for decision-making. Scientific publications tend to aggregate circularity features into single scores or indices, which can be attractive for communication and comparison but may compress distinct mechanisms into one number. Standards and grey literature frameworks, by contrast, more often prefer a set of complementary indicators—a dashboard logic that preserves detail and traceability across dimensions. This aligns with the strong prevalence of relative outputs in both sources (SLR 89%; grey 94%), which are easier to communicate to non-experts than absolute outputs. At the same time, the growing use of relative, index-like indicators increases the importance of transparent calculation rationales and clear disclosure of what is (and is not) captured, to reduce ambiguity and mitigate greenwashing risks.

4.6. Critical assessment of mapped indicators

Overall, the findings highlight a systematic neglect of the CE's biological cycle (Ellen MacArthur Foundation, 2021) within the mapped indicators. Biodegradability and bio-based specific operationalization is the exception rather than the rule: only a small subset of indicators explicitly captures biological-cycle features, notably biodegradable content, product circularity metric, and percentage biodegradation reported in the scientific literature, together with the UNE-EN 16785 indicators on bio-based content and bio-based carbon content. This limited coverage is noteworthy given the existence of standards and regulations addressing biodegradability/compostability (European Committee for Standardization, 2001; International Standardization Organization, 2021), and because “bio-based” does not automatically imply biodegradability or safe biological recirculation. As a result, product circularity assessment for bio-based products can become disproportionately focused on technical-cycle recirculation while overlooking biological end-of-life pathways that may be central for decision-making in the circular bioeconomy.

Across the reviewed studies, the robustness of an indicator is strongly shaped by how explicitly its calculation boundary conditions, required data points, and data sources are defined. When indicators depend on detailed life-cycle inventory information, reproducibility becomes contingent to access disaggregated process data that many firms may not routinely collect or disclose.

Several indicators function as composite measures that aggregate multiple dimensions into a single value. While this supports reporting and high-level benchmarking, it can dilute key specificities, mask hotspots, and create false reassurance if used as a standalone decision rule. A more decision-useful approach is to pair any aggregated score with complementary “diagnostic” indicators targeted to known gaps, and to report sensitivity to key assumptions (i.e., system boundaries, allocation rules, and end-of-life scenarios).

Practical applicability is often limited less by the formula itself and more by data availability and contextual dependence. Several indicators are sensitive to manufacturing configuration and to the local/regional installed circular capacity of the value chain, which reduces cross-case comparability unless assumptions and data

provenance are clearly documented. The problem of data availability is in fact a complex one, as it creates a “chicken-and-egg” dilemma in indicator design. On the one hand, restricting indicators to variables that firms already measure can improve immediate usability, but it risks reinforcing the status quo and narrowing what circularity becomes in practice. On the other hand, designing indicators around variables that are not yet routinely measured may better reflect what should matter for circularity, but it can limit adoption until data infrastructures and reporting practices mature. A pragmatic way forward is therefore to define a tiered approach, starting with a feasible core set of indicators while explicitly signaling higher-ambition metrics that require improved data collection over time.

Fertilizer-oriented indicators tend to emphasize process yields (e.g., nutrient recovery efficiency), while downstream agronomic performance and post-application dynamics remain weakly captured; even when use-phase proxies are proposed, data scarcity can hinder their calculation. Critical aspects such as soil-nutrient interactions, impacts on crop productivity, long-term soil health, and contributions to environmental regeneration—whether through carbon sequestration, biodiversity support, or reduced nutrient leaching—are largely excluded from the analysis. The emphasis on process yields reveals an overwhelming focus on the manufacturing phase, despite the fact that the use phase is arguably where the most significant environmental and agronomic impacts of fertilizer occur (Cardenas et al., 2019; Karimi et al., 2023; Kuusemets et al., 2025; Menegat et al., 2022).

Packaging indicators are comparatively more mature, but they often remain narrowly tied to recycling performance, leaving multi-loop effectiveness and displacement of primary raw materials under-characterized.

Textile indicators show additional fragmentation: although fiber manufacturing was considered under a series of different approaches, assessments may exclude use-phase circularity practices (repair, reuse, service models) as “not applicable” to materials, yet these practices are central to circularity at the product-system level.

A recurring methodological risk is that some circularity results can be misleading in “extreme cases”, where one dominant flow (e.g., water as a renewable input) overshadows other circular features such as recycled content, shifting interpretations unless normalization choices are made explicit and complementary indicators are reported. Likewise, communicating results without reference points can inflate interpretive ambiguity; previous studies have identified that, where feasible, reporting relative performance against a linear baseline improves decision relevance (Iglesias & Paredes Ortiz, 2025).

More broadly, most indicators identified are not specifically designed for bio-based products, often neglecting characteristics unique to these materials, such as biodegradability, compostability, or interactions with biological systems, thereby leaving important dimensions of biocircularity unaddressed.

It is important to acknowledge the lack of economic-focused indicators accounting for labor- and innovation-related variables. This may be a result of focusing on the product level, as economic and social factors are more associated with the firm level. However, since CE practices are often labor-intensive (Llorente-González & Vence, 2020), those dynamics are not negligible as they have an influence on the feasibility of a society-wide transition toward the CE.

Likewise, when the identified indicators are examined against the CBE conceptual framework, several significant gaps become evident. As mentioned above, the main one is the lack of consideration of biological origin and renewability of the raw materials, which are two of the six attributes identified by Holden et al. (2023) and also mentioned by Khanna et al. (2024). The attribute of circular business ecosystem does not match the product-level, as it is more interested on how firms interact with one another to fulfill manufacturing and logistic needs. The identified indicators also fall short on accounting for the design for extended life, and the avoidance of end-of-life failure, which complete the six attributes that Holden et al. (2023) identified as paramount for measuring biocircularity. By contrast, the aspect most consistently captured by the identified indicators is the conversion of waste streams into bioproducts as a substitution route for fossil-based materials (Khanna et al., 2024). This reinforces the extended practice of framing the CE mainly as waste management oriented toward the recovery of key materials.

Taken together, the mapped indicators are more mature for quantifying “waste-to-resource substitution” and process-level loop closure than for capturing core biocircularity attributes (e.g., biological origin, renewability, extended-life design, and avoidance of end-of-life failure) and their interactions across the life cycle. This creates a practical risk of optimizing what is easiest to quantify (e.g., recycling yields) rather than what is most strategic for CBE outcomes. A priority research route is therefore to (i) standardize and scale biological-cycle metrics beyond the current limited set, (ii) strengthen indicators that bridge manufacturing to

use and end-of-life realities with explicit data requirements, and (iii) promote indicator “packs” (dashboards) that make trade-offs transparent instead of collapsing them into single scores.

5. Conclusions and future work

Despite more than a decade of circular economy indicator development, product-level metrics that are truly decision-relevant for bio-based fertilizers, packaging, and textiles remain fragmented and uneven in scope. This review contributes by mapping and critically assessing the indicators currently used in scientific literature, and by contrasting them with complementary grey-literature frameworks increasingly shaping practice. Overall, the evidence suggests that the current toolbox captures some circularity mechanisms reasonably well (especially process-level loop closure and waste-to-resource substitution), but it still underrepresents key biocircularity attributes and life-cycle interactions that are decisive for bio-based product design and evaluation.

Importantly, the main limitation identified is not the absence of yet another indicator, but the lack of coordination across disciplinary and sectoral strands. The bibliometric evidence shows a predominantly technical framing and a fragmented collaboration structure, which increases the risk that indicators evolve as discipline-specific tools with limited convergence across sectors and limited transferability across cases. As a result, the field risks optimizing what is easiest to quantify rather than what is strategically relevant for CBE outcomes. A central, actionable research problem is therefore to build convergence on a shared measurement architecture: common definitions, compatible datasets, and transparent calculation conventions that enable comparability without erasing sector-specific needs.

Future measurement framework development also requires greater conceptual clarity on what “circularity” means for bio-based products. In this review, circularity and sustainability were treated as related but non-equivalent dimensions: LCA-based results are essential for environmental performance, but circularity metrics must additionally capture how resources and functions are retained through loops (product, component, and material cycling), including biomass valorization, cascading use, and end-of-life pathways. A “truly circular” bio-based product can thus be defined as one that (i) preserves value and functionality through appropriate loops, (ii) uses renewable biogenic resources responsibly and transparently, and (iii) ensures safe and effective recirculation routes without shifting burdens across the life cycle.

Rather than continuing the pursuit of a “perfect” standalone indicator, the evidence supports a shift toward circularity monitoring frameworks that combine: (i) a small, standardized core of indicators for reporting and comparability, and (ii) sector- and material-specific modules that capture the mechanisms that actually drive circularity in each product system. This dual design directly addresses the tension between product-management (which needs diagnostic, design-oriented data granularity) and corporate reporting (which favors standardization, aggregation, and comparability). In practice, frameworks should discourage single-score decision making unless aggregation is accompanied by clear disclosure of assumptions, boundary conditions, and complementary diagnostic indicators that reveal trade-offs and bottlenecks.

A feasible research route follows an explicit priority order. First, consolidate conceptual foundations (system boundaries, loop typologies, and minimum disclosure rules) so that indicators become interpretable across studies. Second, define a shared minimum dataset—aligned with emerging standardization and product data-sharing practices—to reduce reproducibility barriers and clarify data provenance. Third, expand bio-based specific coverage beyond today’s limited biological-cycle operationalization, while specifying data requirements that make calculation auditable. Finally, validate indicator “packs” through real-world case studies across fertilizers, packaging, and textiles to test sensitivity, comparability, and decision usefulness under realistic data constraints.

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Data availability Supplementary material containing the sample of 162 included articles (Table S1), and the characterization of product-level bio-based circularity indicators based on attributes (Table S2) is available in the online version of this article at <https://circulareconomyjournal.org/ojs/JoCE/article/view/36/170>

Declarations

Competing Interests The authors declare no competing interests.

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