Journal of Sustainability (2026) 2:1, 1-25
https://doi.org/10.55845/jos-2026-2190

RESEARCH ARTICLE

Building a Product-level Bio-based Circularity Monitoring Framework

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Received: 14. November 2025 / Accepted: 3. March 2026 / Published: 13. March 2026

Abstract
Despite the proliferation of circular economy (CE) indicators and the lack of harmonised measurement conventions, bio-based industries still lack tailored, product-level metrics to guide their circular transition. Three sectors are particularly relevant due to their environmental impacts: fertilisers, packaging, and textiles. This article builds upon indicator mappings by critically assessing how existing indicators account for relevant CE principles and activities, and by developing complementary indicators to address identified gaps. The goal is to propose a product-level circularity monitoring and benchmarking framework tailored for bio-based fertilisers, packaging, and textiles. Following the design research method, existing metrics were characterised, those covering the largest number of CE practices were selected, and complementary indicators were developed to extend the information provided by the original metrics. The framework bridges recurring gaps by incorporating the ratio of biodegradable or compostable materials used in manufacturing, the consumption of virgin materials in packaging manufacturing and textile fibre treatment, and the speed of fertiliser nutrient release. The proposed framework was ultimately feasibility-tested through sectoral applications and industry engagement, demonstrating data availability for computation, interpretive usefulness, and managerial relevance for eco-innovative firms under the tested conditions. Results should be interpreted as comparative screening and monitoring outputs, rather than certification-like estimates.

Keywords Circular Bioeconomy · Indicators · Fertilisers · Packaging · Textiles

1. Introduction

While the circular economy is gaining traction, several industries still lack specific indicators to guide their circular transition. That is the case of bio-based industries; these industries have often assumed that using biological materials inherently ensures circularity. However, as the circularity landscape becomes increasingly specialised, more sophisticated tools are required to support the circular transition.

In this context, the Horizon Europe project BIORADAR (www.bioradar.org) was initiated to develop a digital tool to monitor and benchmark circularity and sustainability performance in three bio-based value chains (fertilisers, packaging materials, and textiles) where firms face concrete dilemmas about which product characteristics to prioritise and how to track progress over time. This article consolidates BIORADAR's product-level circularity monitoring work by showcasing its results and disclosing its methodologies.

We situate this contribution within the circular bioeconomy (CBE), understood here as an economic model that "focuses on the sustainable, resource-efficient valorisation of biomass in integrated, multi-output production chains while also making use of residues and wastes and optimising the value of biomass over time

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via cascading" (Stegmann et al., 2020). We adopt this definition because it explicitly links circularity strategies to biomass-based value chains and therefore highlights what product-level monitoring must be able to capture: not only renewable sourcing, but also the role of residues, cascading pathways, and bio-based specificities that shape whether materials and nutrients effectively cycle back into productive use.

Despite growing recognition of CBE as a pathway to increase circularity within bio-based industries, indicator development has progressed unevenly across scales. Advances at the macroeconomic level have not fully translated into micro-level tools that firms can apply to products and processes (Howard et al., 2019). Macro indicator sets rely primarily on aggregated flows and national accounts; they rarely provide the product granularity and actionable levers that companies need (e.g., procurement shares of renewable/recycled inputs, process yields and losses, recovery performance, or purity/quality degradation across end-of-life routes). A persistent gap therefore remains: operational, product-level indicators that are comparable yet decision-relevant for firms implementing circular transition strategies.

At the same time, the circularity landscape is becoming increasingly specialised. Bio circularity criteria and conceptual frameworks are emerging, but their translation into consistent, operational monitoring remains constrained. For example, Holden et al. (2023) propose a bio circularity framework and note that measurement conventions and the datasets required for operational monitoring remain limited, underscoring the need for practical assessment approaches These operationalization challenges are especially visible in sectors where bio-based specificities and end-of-life pathways introduce additional complexity —such as fertilizers (nutrient cycling and use-phase functionality), packaging (sorting/recycling losses and quality preservation), and textiles (multi-material systems and trade-offs across recycling routes)— while sectoral tools continue to emerge with heterogeneous scopes and assumptions. (Deckers et al., 2023; Menegat et al., 2022; Pongrácz, 2007; Roberge, 2019; Walsh et al., 2023).

Recent reviews further motivate the need for implementable approaches. Mesa et al. (2024) identified the following key gaps regarding CBE indicators: lack of established guidelines for identifying and implementing CBE indicators —leading to incomplete characterisation and limited decision use; and the comparatively limited use of CBE indicators in industrial practice, particularly a notable research gap in bio-based products. Complementarily, Pérez-Hernández et al. (2025) report "a predominant emphasis on academic implications with limited industrial implementation; insufficient consideration of resource renewability and return to the biosphere; and an unclear distinction between circularity and sustainability aspects". Together, these critiques point to a practical research need: product-level monitoring approaches that are (i) transparent and replicable in how indicators are selected, (ii) remain implementable within routine company data, and (iii) cover bio circularity-relevant mechanisms without collapsing them into overly broad claims.

To address this need, we build on BIORADAR deliverables D2.1 – D2.2 (Cámara et al., 2024; Iglesias & Paredes Ortiz, 2025), which identified and mapped circular economy (CE) indicators applied to the three target groups. We then translate this fragmented indicator landscape into a streamlined monitoring framework using a theory-informed selection logic. Specifically, we derive indicator attributes from core CE constructs (narrowing, slowing, and closing loops) and from the requirement to represent both technical and biological cycling in bio-based systems. This yields a set of attributes that prioritise: (I) the quality of resource inputs (renewable/recycled versus virgin), (II) retention and quality preservation across processing and end-of-life pathways (including purity losses), (III) relevant use-phase functionality for bio-based products (e.g., nutrient-release behaviour in fertilisers), and (IV) contextualization of resource pressure where thresholds matter (e.g., boundary-informed perspectives). Instead of assuming that a single universal indicator can adequately represent circularity across heterogeneous value chains —a goal that can dilute mechanism-specific trade-offs and obscure what is being improved (Figueirinhas et al., 2026)— we adopt a tiered measurement logic: a small, interpretable set designed for routine industrial monitoring, complemented by sector-specific indicators that capture the dominant circularity mechanisms and data realities of each sector. To make the translation from diagnosis to design explicit, we map recurring measurement gaps to recognised circular principles (such as cascading use, nutrient cycling, preservation of material quality, and biological versus technical loops) and show how these principles informed indicator design choices and the final monitoring set.

This study, therefore, asks: How can a transparent and replicable product-level circular bioeconomy monitoring framework be constructed from a fragmented indicator landscape, while remaining implementable by firms and comparable across sectors?

Our contributions are threefold:

1. A transparent screening and selection protocol to build streamlined indicator sets from heterogeneous candidate metrics, explicitly balancing completeness with feasibility.
2. An operational specification of the BIORADAR product-level monitoring framework, combining cross-cutting and sector-specific indicators tailored to bio-based fertilisers, packaging materials, and textiles, and complemented where necessary by newly developed indicators to cover recurring gaps.
3. A cross-sector feasibility and interpretive validation through three sectoral applications using real manufacturing contexts, demonstrating data availability and the decision relevance of the resulting circularity signals.

To the best of the authors' knowledge, it constitutes the first set of indicators specifically tailored for monitoring the circularity of bio-based products in the fertiliser, packaging, and textile industries, and it also includes testing by industry actors.

2. Theoretical Framing

This research is situated within ongoing developments in CE and, more specifically, CBE, with a focus on how conceptual principles are translated into implementable product-level metrics for monitoring and decision support.

The CE has been conceptually established for several decades, with Stahel & Reday-Mulvey (1981) considered pioneers for introducing the concept of a "closed-loop economy", and Pearce & Turner (1989) being the first to coin the term circular economy. Yet, Bezama (2023) highlighted that CE remains an ongoing methodological challenge, as it has not been sufficiently defined, despite Kirchherr et al. (2017) having summarised 114 definitions. Similarly, Tan & Lamers (2021) discussed multiple definitions of the CBE, reflecting the diversity of conceptual approaches within the field. The main challenge, therefore, appears to lie not in the lack of definitions but in the absence of consensus among them. Likewise, Rojas-Serrano et al. (2024) analysed the interactions and relationships among sustainability, CE, and the bioeconomy — areas where consensus also remains limited.

2.1. Conceptual lens guiding BIORADAR

For this study, we adopt the CBE definition proposed by Stegmann et al. (introduced in the previous section) as the conceptual lens guiding BIORADAR. This framing is particularly suitable for product-level monitoring because it explicitly connects circularity strategies to bio-based value chains, emphasises resource-efficient biomass valorisation in integrated, multi-output chains, promotes the use of residues and wastes, and foregrounds value optimisation over time through cascading (Stegmann et al., 2020). In other words, Stegmann's lens links the CE logics of retaining value to the bioeconomy-specific question of where biomass is most valuable, and how value can be preserved as biomass moves through successive uses.

A central implication of Stegmann et al.'s CBE framing is that circularity in bio-based systems must reflect both technical and biological cycling pathways and must treat cascading and value retention as core mechanisms rather than optional add-ons. The bio-based value pyramid (Figure 1), often used to illustrate cascading priorities, highlights the ambition to retain the highest possible value of biomass (e.g., from pharmaceuticals and fine chemicals to food and feed, to materials and polymers, and finally to energy uses). While BIORADAR is not a full value-chain optimisation model, this pyramid reinforces a measurement implication: product-level metrics should not only track "closing loops", but also whether loops preserve function and quality in ways that support higher-value pathways.

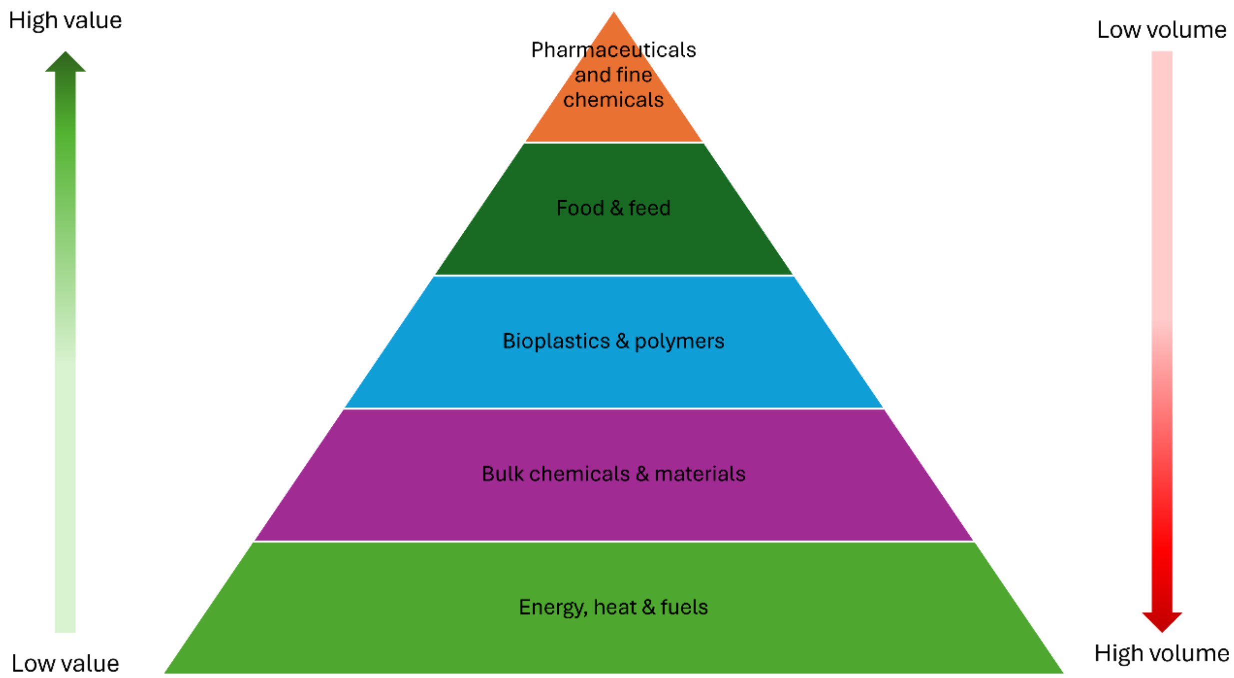

Figure 1. Bio-based value pyramid. Figure adapted from Stegmann et al. (2020) licensed under Creative Commons CC BY 4.0.

2.2. From CE/CBE constructs to indicator attributes

Building on the conceptual lens defined above, BIORADAR translates CE/CBE theory into a small set of measurable constructs that guide indicator screening, selection and later gap analysis. This translation is necessary because CE/CBE constructs are often formulated at a level of abstraction that is not directly operationalizable for firms, whereas BIORADAR aims to support product-level monitoring with data typically available in industrial settings.

Recent syntheses help specify which constructs matter most for circularity assessment in bio-based product systems. Pérez-Hernández et al. (2025) propose six key elements for a more comprehensive circularity assessment: renewable inputs, circular inputs, circular outputs, cascading of outputs, R-strategy performance, and value retention. Complementing this, Vural Gursel et al. (2023) identify micro-level measurement gaps that are particularly salient for bio-based product monitoring, including functional use of resources, preservation of recycled material quality, closing of nutrient cycles, shares of renewable resources, cascading use, and organic recycling routes. Together, these two perspectives provide a theoretically grounded yet practice-oriented basis for defining the indicator attributes BIORADAR prioritises.

Figure 2 summarises how these constructs were translated into BIORADAR screening attributes (tags) used to characterise candidate indicators. Rather than imposing a one-to-one correspondence, the mapping clarifies the operational pathway from theory to measurement: high-level constructs related to inputs (renewability and secondary materials) motivate the inclusion of sourcing-related attributes, constructs related to loop closure motivate end-of-use/end-of-life attributes (including technical and organic cycling routes), and constructs related to value retention over time motivate lifetime-related attributes. Importantly, the figure also makes explicit where theory is richer than what generic indicators typically capture at the product level (particularly around nutrient-cycle closure, cascading use, and quality preservation), thereby motivating BIORADAR's later emphasis on complementary, sector-sensitive indicators. In this way, the framework makes transparent the trade-off any streamlined indicator set must manage: representing core circularity mechanisms while remaining feasible with industry-available data and interpretable for decision-making.

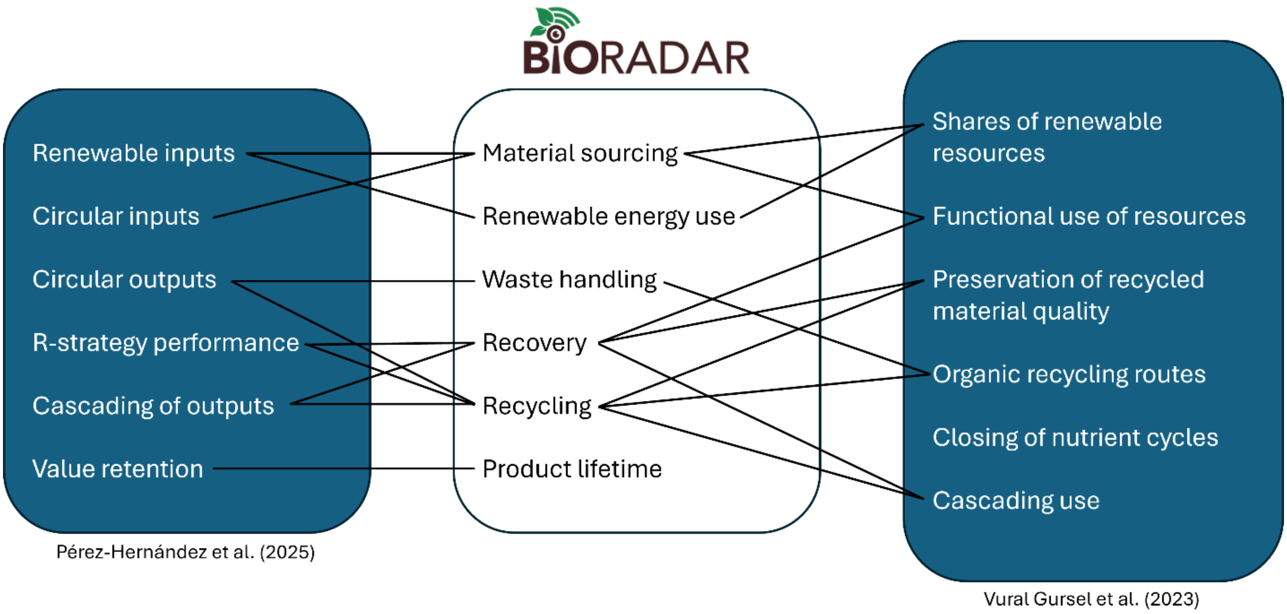

Figure 2. Linkages between conceptual frameworks and BIORADAR indicator attribute selection.

2.3. Divergence, convergence, and why macro indicators are insufficient for firms

The CE/CBE measurement field is currently evolving through two parallel dynamics. Divergence is visible in the proliferation of sector- and mechanism-specific micro-level indicators. Convergence is visible in emerging attempts to harmonise product-level circularity assessment guidance, reporting conventions, and data requirements across sectors. This dual dynamic motivates BIORADAR's design choice: to combine cross-cutting metrics (for comparability) with sector-specific metrics, rather than pursuing a single universal indicator that would either oversimplify or become too complex to deploy routinely.

Most institutional progress in CE measurement has occurred at the macroeconomic level, with Eurostat at the forefront, presenting 23 CE indicators grouped into five categories: production and consumption, waste management, secondary raw materials, competitiveness and innovation, and global sustainability and resilience. However, macro-level indicators typically rely on national accounts and aggregated flows; they lack product granularity and do not provide operational levers that firms can readily act upon. As a result, they are informative for governance and benchmarking at national or regional scales but are of limited direct use for guiding firm-level process changes and product strategy. BIORADAR addresses this gap by operationalising product-level indicators that can be computed from routine industrial records and used for benchmarking and scenario exploration at the firm level.

2.4. Product-level indicators for bio-based products and remaining gaps

Product-level circularity indicators remain comparatively less mature than macro- and firm-level frameworks, and bio-based specificities are still unevenly represented in the available metrics. BIORADAR's, Deliverable 2.1 (Cámara et al., 2024) identified the Ellen MacArthur Foundation's (2015) Material Circularity Indicator (MCI) is among the most widely applied product-level CE metrics, often used alongside Life Cycle Assessment (LCA) —although the latter does not explicitly address circularity. Importantly, a substantial share of CE indicators applied to bio-based products were not originally designed for the bioeconomy; consequently, eco-innovative firms frequently adapt indicators developed for the technical cycle, which can under-represent biological cycling, organic end-of-life routes, and use-phase bio-based functionality.

When reading through the construct-to-attribute translation introduced in section 2.2 (**Figure 2**). Three recurring limitations of the product-level indicator landscape become salient. First, many indicators capture input circularity (e.g., recycled or bio-based shares) but only partially represent how end-of-use materials re-enter productive systems across technical versus biological pathways. Second, several metrics treat loop closure in largely quantitative terms and therefore risk overestimating circularity when quality losses, contamination, or downcycling constrain effective substitution of virgin material. Third, product categories where circularity depends on use-phase performance (most clearly fertilisers) remain poorly served by generic indicators, because core circularity mechanisms hinge on functional delivery and retention in context rather than on material composition alone. These limitations justify BIORADAR's design choice to move from "indicator availability" to "indicator adequacy": rather than assuming that a single product-level metric can capture all CE/CBE mechanisms across fertilisers, packaging, and textiles, BIORADAR adopts a tiered measurement logic. A small core set is prioritised for routine monitoring and cross-sector comparability, while complementary, sector-sensitive indicators are introduced where critical mechanisms are systematically missing or only weakly proxied by generic metrics. This trade-off between completeness and feasibility is made explicit and guides the subsequent methodological steps: the next section operationalises this logic through tag-based characterisation, selection, and a structured gap analysis that translates missing mechanisms into requirements for indicator design.

2.5. From gaps to indicator design

Taken together, the literature indicates that no single product-level indicator can credibly cover all CE/CBE mechanisms across fertilisers, packaging, and textiles without either diluting key mechanisms or imposing unrealistic data requirements. BIORADAR therefore adopts a tiered measurement logic: a small core set of indicators is prioritised for routine monitoring, while additional "good-to-have" indicators can be layered when higher-resolution data and specific decision needs justify added complexity. This choice makes explicit the trade-off between completeness (covering multiple circularity mechanisms) and feasibility (data availability and effort constraints), and it clarifies how the conceptual lens translates into design decisions.

To strengthen transparency in this translation step, the next section makes explicit how recurrent gaps across candidate metrics were converted into indicator requirements and mapped to recognise CE principles before final selection. This "gaps-principles-requirements-indicators" logic clarifies which aspects of CE/CBE the BIORADAR framework captures, and which trade-offs it necessarily leaves for complementary assessment tools (e.g., full sustainability evaluation).

3. Methods

3.1. Methodological approach

This study develops a product-level bio-based circularity monitoring framework, with specific applications to fertilisers, textiles, and packaging materials. We followed the Design Research Method (DRM) (Blessing & Chakrabarti,2009), which supports the development of practice-oriented managerial tools through iterative cycles of (I) problem clarification, (II) artefact design, and (III) empirical evaluation. Compared with expert-consultation or multi-criteria prioritisation approaches such as the Analytic Hierarchy Process (AHP) (Saaty, 1988) or Delphi (Skumolski et al., 2007). DRM is better suited to our purpose because it explicitly combines conceptual construction with testing under real-world data constraints, which is central to developing implementable monitoring tools for industrial decision-making.

3.2. Scope and boundaries

The framework is designed for routine monitoring and benchmarking within firms; it does not aim to quantify overall sustainability performance. Accordingly, we focus on circularity mechanisms that can be tracked at the product level. Indicator calculation relies primarily on data that companies typically maintain for operational, quality, and compliance purposes (e.g., procurement records, mass/energy balances, process yields, and waste and recovery data), complemented, when available, by public product dossiers (e.g., EPD/LCA datasets). Use-phase indicators are included only when they represent a dominant circularity mechanism for a given category (e.g., nutrient release performance for fertilisers) and must be parameterised under specified test or use conditions; reported values are therefore context-dependent and should not be generalised beyond the stated conditions. The framework does not cover broader environmental and social impacts (e.g., full LCA impact categories) and should be used alongside complementary assessment tools when such outcomes are decision-relevant.

3.3. Reproducible workflow

To support transparency and reproducibility, we document the procedure as an explicit six-step workflow as follows:

- Step 1: Build the indicator inventory. Systematic identification and screening of candidate indicators (BIORADAR's Deliverable 2.1; Cámara et al., 2024).
- Step 2: Define theory-informed functional tags and characterise each candidate indicator. Six functional tags were defined to reflect core product-level circularity mechanisms and were applied to the candidate indicators.
- Step 3: Rank and shortlist indicators. Indicators were ranked within each sectoral group by tag coverage. When equal coverage occurred, ties were resolved through a structured qualitative selection rule that prioritised indicator capturing an operationally decisive mechanism (e.g., effective recovery via an efficiency term, or quality-loss representation where relevant), as documented in the indicator comparison.
- Step 4: Identify gaps in the shortlisted indicators. We conducted a structured qualitative gap review of each shortlisted indicator's definition, variables, assumptions, and life-cycle stages represented, and documented missing aspects as traceable "not accounting for…" statements.
- Step 5: Finalise the indicator set. The final monitoring set was assembled by combining the shortlisted indicators with complementary indicators to address recurrent gaps not covered by the existing metrics.
- Step 6: Apply and report the indicators. The final indicators were computed for three sectoral applications, and the datasets and assumptions used for computation (including context-dependent parameters where applicable) were reported to support interpretability and replication.

Likewise, the methodological framework that was adopted, the DRM, comprises four main stages:

1. Research Clarification: examines the research context, including the state of the art and existing gaps, to establish a clear understanding of the problem and guide the study.
2. Descriptive Study I: characterises the current situation by systematically analysing what is being done in practice and identifying key patterns and influencing factors.
3. Prescriptive Study: develops new approaches or interventions to address the identified gaps and improve the system under study.
4. Descriptive Study II: Applies the proposed interventions and evaluates the resulting changes, characterising the new situation and assessing their effectiveness.

In DRM terms, steps 1-6 correspond to: Research Clarification (Step 1), Descriptive Study I (Steps 2-4), Prescriptive Study (Step 5), and Descriptive Study II (Step 6). The following subsections describe each step in detail and specify the data inputs required for each indicator.

3.4. Research clarification: literature review

The first step of the research clarification was a review of widely adopted CE indicators. This first overview contributes to shedding light on the CE metrics that practitioners, entrepreneurs, policy makers, and academics have at hand. Likewise, it strengthens the case for the need of a dedicated set of bio-based tailored indicators.

The core of the research clarification stage was conducted through a systematic literature review, reported in BIORADAR's Deliverable 2.1 (Cámara et al., 2024) that retrieved 561 records from Web of Science using a search string including the concepts circular economy, indicators/metrics, bio-based, fertilisers, packaging, and textiles. That review got a final sample of 46 documents after screening and snowballing. Of these documents, 29 circularity indicators applied to bio-based fertilisers, packaging materials, and textiles were identified.

Before proceeding with the characterisation and classification of the indicators, nine of them that replicated LCA results were filtered out. This decision was made to exclude LCA-based metrics from the analysis because their results fall short of highlighting CE attributes, as they are designed solely to quantify environmental impacts. The process of building the monitoring framework began precisely with the mapping of these 20 indicators and their characterisation.

3.5. Descriptive study I

Descriptive study I aimed to conduct an in-depth and reproducible analysis of the circularity metrics identified in the research clarification stage. It comprised three sequential steps: (I) functional characterization and classification of indicators through a theory-informed tagging scheme, (II) selection of indicators with the broadest functional coverage within each sectoral subset, and (III) a structured gap analysis to identify systematically which circularity dimensions were underrepresented in the selected indicators and to translate these gaps into requirements for the prescriptive study stage.

3.5.1. Functional characterisation and classification of indicators The 20 indicators resulting from the research clarification stage were characterised using six tags, associated with diverse attributes promoted by the CE and CBE conceptual framework. The tags (illustrated in Figure 2) and the criteria used to assign are detailed in Table 1.

Table 1. Criteria for assigning tags to CE indicators.

Tag	Criterion
Material sourcing	The indicator captures the nature of feedstock used during production (e.g., virgin, recycled, reused, biological materials, etc.).
Renewable energy use	The indicator takes into account the types of energy inputs used during production, distinguishing between renewable and non-renewable sources.
Waste handling	The indicator measures the amount of waste produced during the lifetime of a product and the methods employed for waste treatment, encompassing recycling, landfilling or other disposal practices.
Recovery	The indicator measures materials from waste streams, emphasising whether key compounds are reclaimed and to what extent.
Recycling	The indicator considers the feasibility of recycling the product at the end of its life.
Product lifetime	The indicator considers the duration of the product's lifetime.

The six tags were derived from established CE constructs that frame circularity as the ability to slow, narrow, and close material resource loops (Tan & Lamers, 2021). In this framing, material sourcing captures "narrowing" strategies by prioritising renewable and/or secondary inputs; product lifetime operationalises "slowing" by extending functional use cycles; and recovery and recycling represent "closing" mechanisms by returning materials to productive use rather than to unrecoverable waste streams.

This operationalisation is also consistent with recent work arguing that circularity assessment in bio-based product systems should place biological and technical cycles at its core and explicitly account for resource renewability, cascading, and return to the biosphere, as well as inflow/outflow/loop perspectives (Pérez-Hernández et al., 2025). At the micro level, indicator research further highlights the need to represent aspects such as substitution of virgin materials, renewable energy use, recovery/recycling performance, and cascading use/efficiency along product stages, which motivates a compact tag structure spanning both input-side and output-side circularity mechanisms while remaining implementable in product monitoring contexts (Vural Gursel et al., 2023).

Each indicator was assigned as many tags as the criteria it met, based on its stated variables, formula components, and/or explicit data requirements. This served two purposes: (I) to identify the most functionally comprehensive indicators — considered an asset for business actors who benefit from managing a limited number of indicators that still convey substantial information — and (II) to reveal which circularity aspects are more frequently included or neglected across the available indicator landscape. Tag assignment was performed by a single coder following the predefined criteria in **Table 1**. To enhance transparency and reduce subjectivity, the coding was rule-based: each tag was assigned only when the indicator definition, variables, or calculation procedure explicitly met the corresponding criterion.

The criteria cover key variables from "cradle" (e.g., origin of raw materials) to "grave" (e.g., waste handling) and "cradle to cradle" strategies (e.g., recovery and recycling), while also considering energy inputs (e.g., by including renewable energy use) and product lifetime. In principle, an ideal circularity indicator could account for all these stages comprehensively; however, because most available indicators emphasise only subsets of mechanisms, the tagging procedure provides a transparent way to compare the coverage of indicators.

3.5.2. Selection of indicators After tag assignment, indicators were shortlisted by selecting, within each subset (i.e., general purpose, fertiliser, packaging, and textile), those that accounted for the greatest number of criteria (i.e., the highest tag coverage). This resulted in straightforward selection for general purpose and textiles, whereas in packaging and fertilizers all identified indicators achieved the same number of tags.

To break ties among indicators with identical tag coverage, we applied a mechanism-oriented qualitative rule focused on whether the indicator captured performance losses that are critical for interpreting circularity in practice. Specifically, we prioritised indicators that (I) incorporate an explicit efficiency term (distinguishing theoretical/nominal recovery from effective recovery) and/or (II) account for quality losses (distinguishing closed loops from downcycling or degraded outputs). The selection of these two aspects was based, on the one hand, on the EU's emphasis on how to measure effective recycling (Talens Peiro et al., 2018), and on the other hand, on studies highlighting the neglect of quality losses as a shortcoming of existing circularity indicators (Figueirinhas et al., 2026). They also affect circularity interpretation while remaining observable in industrial contexts. Following this rule, the fertiliser rule was resolved in favour of the indicator that explicitly includes a recovery-efficiency factor, thereby enabling differentiation between recoverable flows and actual recovery performance. Likewise, the packaging tie was resolved in favour of the indicator that explicitly represents quality losses, thereby preventing overestimating circularity when recovered material cannot substitute for virgin material at equivalent quality.

3.5.3. Gap analysis A gap analysis was conducted to identify additional measurement needs not covered by the four selected indicators and to inform the design of complementary indicators in the prescriptive study stage. The gap analysis examined the variables, assumptions, and life-cycle stages represented in each selected indicator, and whether they captured key circularity aspects relevant to bio-based products.

The gap analysis proceeded at three depths. First, we documented which tags each selected indicator did not receive, thereby identifying which of the six screening attributes (**Table 1**) were not represented by that metric. Second, we used the selected general-purpose indicator (the most comprehensive in terms of tag coverage) as a reference point to identify which constructs it captured that others did not, making explicit where sectoral indicators narrowed the scope of measurement. Third, we assessed whether each product category involved critical circularity mechanisms that remained absent from the selected indicators, drawing on the conceptual framing of bio-based circularity and on sector-specific considerations discussed in the literature (e.g., fertiliser performance after application, packaging biodegradability/compostability where relevant, textiles' dependence on process-intensive stages such as fibre treatment). Across these three depths, gaps were identified through a structured qualitative review of each indicator's definition, formula, required inputs, and implied system boundaries. A gap was recorded only when the corresponding aspect could not be computed or inferred from the indicator as defined (i.e., when it was absent from the metric's variables, calculation steps, or boundary assumptions). Gaps were documented as "not accounting for…" statements to maintain traceability between indicator structure and missing measurement elements. The resulting gap list is therefore a transparent synthesis of under-represented circularity aspects across the selected indicators and served as the basis for proposing complementary indicators in the prescriptive study.

3.6. Prescriptive study: development of new indicators

This step consisted of designing an indicator to complement each of the four previously selected. It implied selecting one of the identified gaps and drafting an equation that directly addresses it, while keeping simplicity. This resulted in four indicators that, together with the previously selected, conformed to the BIORADAR product circularity monitoring framework.

The guiding principles for developing the new indicators were to produce easy-to-calculate metrics, derived from only a few variables, and capable of directly conveying the degree of circularity associated with a specific CE characteristic.

Since indicators are, by nature, communication tools, an index format was chosen. This allows decision makers to handle values ranging from 0 to 1, thus enabling them to assess the circularity of a product in a straightforward manner.

Two complementary approaches were used:

a) ratios that express the share of a given magnitude meeting a certain criterion; for example, the fraction of total mass derived from biological sources.
b) the complement of such ratios with respect to 1. This second approach captures the gap between ideal (100%) circularity and the share of non-circular inputs. In this case, a ratio equals 1 when no linear input is used and 0 when only linear inputs are used. By calculating their complements, 1 represents ideal circularity and 0 a fully linear scenario.

3.7. Descriptive study II: validation of the monitoring framework

Finally, after selecting and designing the set of indicators that would compose the framework, it was applied to one case per sector to verify its applicability and usefulness in industrial settings.

Specifically, the indicator framework was applied to:

- five bio-based fertilisers —namely algae biomass, compost, feather meal, wood vinegar, and spent mushroom substrate (Iglesias et al., 2025; Iglesias & Paredes Ortiz, 2025);
- paper and cardboard produced by a Spanish company whose identity remains undisclosed for confidentiality reasons (Iglesias & Paredes Ortiz, 2025); and
- three bio-based fibres (i.e., cotton, wool, and hemp), for which resource pressure was calculated and the results compared to those of polyester (Iglesias & Paredes Ortiz, 2025; Iglesias et al., manuscript in peer review).

Most of the variables were collected from life cycle inventories (LCI) and life cycle impact assessments (LCIA) previously carried out for the aforementioned products. Each corresponding indicator was obtained by following the calculation procedures detailed in the Supplementary Material. For the packaging validation, the paper and cardboard manufacturer provided data on material consumption in 2024 (disaggregated by virgin/circular, renewable/non-renewable, etc.), end-of-life scenarios, energy consumption, and a mass balance of recycling stages.

4. Results And Discussion

To begin with, it was deemed necessary to contextualise the wide range of existing CE indicators at different levels. This may help readers locate themselves within the broader landscape of CE monitoring tools and determine whether a specific metric applies to a given sector or product.

Usually, economic analysis focuses on three levels: macro, meso, and micro, with the micro level encompassing companies, consumers, and products. For the purposes of this manuscript, however, the micro level is further divided into two sub-levels: the micro proper, which refers to companies, and the nano, which refers to products. This subdivision is introduced to place a particular emphasis on products, which constitute the main focus of this study. The summary of CE indicators for the macro, meso, micro and nano levels is presented in **Table 2**.

Table 2. Summary of existing circular economy indicators at different levels.

Level	Author or compiler	Indicators	Applicability and scope
Macro (Countries, regions and cities)	Eurostat (2025)	Circular Economy Monitoring Framework	National statistics: recycling rates, uses of secondary raw materials, material consumption, and circular economy employment. Applicable across sectors, but it is not tailored for the bio-based economy.
	OECD (2024)	National and subnational circular economy monitoring frameworks	Compiles CE indicators from the European Commission, France, the Netherlands, Portugal, and Colombia, and from six subnational regions. It encompasses aspects such as material lifecycle, environmental interaction, policies/actions, and socioeconomic opportunities. It is applicable across sectors, but it is not tailored for the bio-based economy.
	OECD (2021)	The OECD Inventory of Circular Economy Indicators	Collects 474 CE-related indicators coming from 29 studies. It includes environment, governance, economic and business, infrastructure, technology and social indicators across sectors such as waste, resources and materials, reuse, repair and share, built environment, energy, food, water, public administration, and air. It is not tailored for the bio-based economy.
	UNECE (2023)	Guidelines for Measuring Circular Economy	Multiscale model with aggregated indicators for comparing countries and regions. It is applicable across sectors, but it is not tailored for the bio-based economy.
Meso (Industrial and technology parks, clusters, hubs, regional or sectoral innovation systems, and industrial symbiosis networks).	Fraccascia et al. (2021)	Ecosystem Indicators for Measuring Industrial Symbiosis	Puts forward a framework for assessing and optimising an industrial symbiosis network, with special emphasis on waste recovery and input savings. It is not specifically tailored for the bio-based economy.
	Camera di Commercio Molise (2022)	Industrial Symbiosis Indicators	Considers 26 indicators accounting for the different dimensions of sustainability: environment, economic and social, as well as the circularity dimension and the social network analysis. Circularity is measured by "environmental impact momentum", utility (lifetime and function served), and environmental cost effectiveness. It is not specifically tailored for the bio-based economy.
Micro (Companies)	Ellen MacArthur Foundation & ANSYS Granta (2019)	Material Circularity Indicator. Methodology. An Approach to Measuring Circularity.	Comprehensive methodology to calculate the circularity of a company by obtaining the material circularity indicator for a reference product range and then aggregating and normalising the product-level results to obtain the company result. It is not specifically tailored for the bio-based economy.
	World Business Council for Sustainable Development (2023)	Circular Transition Indicators (CTI)	Measures company-level circularity: circular flows, recycling, reuse, recycled content, product lifespan, and includes the biological cycle dimension. However, it is not specifically tailored for the bio-based economy.
	International Standardization Organization (2024)	ISO 59020: Circular Economy - Measuring and assessing circularity performance	Standardises the measurement and reporting of company-level circularity by establishing guidelines for appropriate spatial and temporal boundaries, a life-cycle perspective, data traceability, assumptions, and estimates, enabling comparability. It is not specifically tailored for the bio-based economy.
Nano (Products).	Ellen MacArthur Foundation & ANSYS Granta (2019)	Material Circularity Indicator. Methodology. An Approach to Measuring Circularity.	Comprehensive methodology to calculate the circularity of a product. It considers the virgin feedstock, unrecoverable waste, material losses, recycling, and downcycling. It is not specifically tailored for the bio-based economy.
	International Standardization Organization (2025)	ISO 59040: Circular Economy – Product circularity datasheet	Establishes a general methodology for information exchange of CE-related data. The Product Circularity Datasheet accounts for material inputs, circular production, durability and extended lifetime, circularity at the end of the product use period, and positive circular economy impacts. It is not specifically tailored for the bio-based economy.

In parallel to these cross-cutting frameworks, sector-oriented circularity measurement guidance is rapidly expanding. Examples include the World Business Council for Sustainable Development's CTI sector guidance (e.g., fashion & textiles) (World Business Council for Sustainable Development, 2024), and dedicated circularity roadmaps and monitoring-relevance guidance in the United Nations Environment Programme's global roadmap for sustainability and circularity in the textile value chain (United Nations Environment Programme, 2023). Packaging and fertiliser sectoral circularity guidelines appear rather limited to scientific literature and institutional or government reports, and were not easily accessible at the time of writing this manuscript.

It is relevant to mention the emergence of regulatory reporting requirements, such as the EU's CSRD/ESRS E5 on resource use and circular economy (EFRAG, 2025). Such regulations further reinforce demand for consistent, auditable circularity information at firm and product levels.

While **Table 2** compiles the most relevant monitoring frameworks, including those from Eurostat, OECD, UNECE, and ISO, it is important to highlight that most of these indicator sets were designed primarily for macro- or meso-level monitoring. Their structure typically relies on national statistics or aggregated material flows (e.g., recycling rates, domestic material consumption, secondary raw material shares), which limits their managerial applicability for firms. At company level, what is often missing is product granularity and operational traceability: (I) indicators that can be computed at the level of a specific product or product family; (II) explicit links to controllable levers (procurement choices, process yields and losses, recovered content, end-of-life routing and quality outcomes); (III) data requirements aligned with records that firms routinely maintain (procurement data, mass/energy balances, waste and recovery logs); and (IV) outputs that enable benchmarking across products and sectors without requiring national accounts. This is why Eurostat indicators, although comprehensive for tracking national progress, are not directly transferable to product-level monitoring and decision support.

Accordingly, the proposed BIORADAR framework operationalises these higher-level principles by translating circularity mechanisms into a small set of product-level indicators that can be calculated from company records, combining cross-sector comparability with sector-specific relevance, and explicitly representing mechanisms that are decisive in bio-based value chains (e.g., effective recovery and quality losses where relevant).

Moreover, as **Table 2** shows that none of the identified indicators was originally designed for the bio-based economy. As a consequence, critical characteristics of the CBE fall outside the scope of their analysis. In addition, most of these indicators do not enable researchers, practitioners or policymakers to compare different bio-based product options. Such limitations reduce the managerial capacity of eco-innovative companies whose business models aim to increase circularity. The summary also highlights that a greater number of indicators are used at the macro and micro levels, while the meso and nano levels still lack sufficient CE indicators.

Having identified the current landscape of CE indicators across different levels and the need for product-level bio-based-specific indicators, the research continued with a mapping of CBE-specific indicators. This research enabled the authors to characterise how CBE is measured in general and, specifically, within the fertiliser, packaging, and textile sectors. Following BIORADAR's Deliverable 2.1 (Cámara et al., 2024), 20 indicators were identified. The research made clear that, within those 20 indicators, the material sourcing and recovery attributes are the most taken into account, while renewable energy use and waste handling were the most overlooked ones, as detailed in **Table 3**.

Table 3. Characterisation of the CBE indicators identified by the BIORADAR project.

	Indicator	**Source**	**Material sourcing**	**Renewable energy use**	**Waste handling**	**Recovery**	**Recycling**	**Product lifetime**	**TOTAL**
General	Material Reutilization Score (MRS)	Cradle to Cradle Products Innovation Institute (2016)	✓			✓	✓		3
	Material Circularity Indicator (MCI)	Ellen MacArthur Foundation & ANSYS Granta (2019)	✓		✓		✓	✓	4
	Circular Index (CirculAbility model)	Enel (2018)	✓	✓	✓		✓	✓	5
	In-use occupation of materials	Moraga et al. (2021)	✓			✓		✓	3
	Emergy	Odum (1996)		✓					1
	Quality of the recycling framework	Roosen et al. (2023)	✓		✓		✓	✓	4
	Product-level circularity metric	Linder et al. (2017)	✓						1
	MCI based on economic and residual value	Jiang et al. (2022)	✓			✓	✓	✓	4
	Circular Economy Index	Di Maio & Rem (2015)				✓			1
	Circo-economic indicator	Tashkeel et al. (2021)	✓		✓		✓	✓	4
Fertilizers	Nutrient Removal Efficiency Indicator	Council of the European Communities (1991)				✓			1
	Nitrogen Recycling Index	Tadesse et al. (2019)				✓			1
	Circularity Indicators of N and P	Cobo et al. (2018)				✓			1
	Indicator of Circular Economy for Biofertilizer	Molina-Moreno et al. (2017)				✓			1
	Nitrogen Use Efficiency	Oenema (2015)				✓			1
Textiles	Resource Pressure	Desing et al. (2021)	✓				✓	✓	3
	Circularity Index for Textiles	De Oliveira Neto et al. (2022)	✓						1
Packaging	Recycling Effectiveness	Roithner & Rechberger (2020)				✓			1
	Process yield / Net recovery	Lase et al. (2022)				✓			1
	Quality indicator	Lase et al. (2022)				✓			1

4.1. Indicator selection and gap analysis

As a result of the tag assignment, four indicators were selected to integrate the monitoring framework. For general purposes, the Circularity Index (CirculAbility model; Enel, 2018) was assigned five out of six tags, while for textiles, the Resource Pressure indicator received three. Regarding fertilisers and packaging, all indicators received the same number of tags, requiring an alternative tie-breaking approach. This was addressed by applying a tailored approach to account for specific variables. In the case of fertilisers, the Circularity Indicator of Nutrient included a factor for recovery efficiency that others did not, making it stand out. Similarly, for packaging, the Recycling Effectiveness indicator accounted for quality losses, giving it a significant advantage over the other options. Ultimately, these four indicators were selected to form the monitoring framework and subjected to gap analysis.

The results of the gap analysis are presented in **Table 4**. It identifies key aspects not captured by the four selected indicators, serving as the basis for designing complementary indicators to complete the monitoring framework. This is not an exhaustive list but rather highlights gaps that can be addressed within the scope of the study.

Table 4. Identification of gaps in the indicators sourced from the literature review.

Indicator	Identified gaps
Circular Index (CirculAbility model)	No direct comparison to the linear counterpart. Not accounting for biodegradable or compostable content.
Circularity Indicator of Nutrient	Not accounting for nutrient release speed. Not accounting for waste generation during the manufacturing process.
Recycling Effectiveness	Not accounting for energy consumption Not accounting for waste ultimately generated at the end of life. Not considering the ratio of bio-based materials to total product weight. Not considering the consumption of virgin materials during manufacturing and recycling.
Resource pressure	Not considering energy consumption during the production process. Not considering the mass of non-renewable waste generated. Not considering the biodegradability of the material. Not considering synthetic substances-intensive stages such as fibre treatment.

To clarify how the identified gaps relate to recognised CE principles, **Table 4** can be interpreted as a principle-to-measurement mapping across four core mechanisms relevant to circular bio-based products. First, gaps related to biodegradable/compostable content correspond to the biological loop and "return to the biosphere" pathways, which are central for bio-based materials when organic recycling is a plausible end-of-life route. Second, the lack of nutrient release speed in the fertiliser indicator reflects an omission in nutrient cycling and use-phase functional performance: circularity in fertilisers depends not only on recovered nutrient content but also on how effectively nutrients are delivered and retained after application. Third, gaps related to quality losses connect to preservation of material quality and value retention, distinguishing nominal loop closure from effective substitution of virgin material, Finally, gaps concerning virgin material use, bio-based share, and end-of-life leakage (waste ultimately generated) relate to "closing loops" in the technical cycle, since they capture whether circular inputs and recovery translate into reduced virgin demand and reduced unrecoverable outputs. This mapping guided the prescriptive study by translating each missing principle into an explicit requirement for complementary indicators (e.g., biological-route representation, functional nutrient delivery, quality-sensitive recovery, and virgin-demand reduction).

Beyond listing missing variables, the gap analysis also revealed conceptual inconsistencies among existing metrics. For instance, some indicators overemphasise material recovery while neglecting energy circularity or biological degradation pathways. This highlights the need for a multidimensional approach to circularity monitoring, in which material, energetic, and functional loops are simultaneously assessed. Such insight guided the selection of complementary indicators to ensure that the BIORADAR framework provides a balanced representation of technical and biological circularity.

The calculation methodology for the four chosen indicators is available in the Supplementary material.

4.2. General-purpose complementary indicator proposal

To complement the Circular Index, the selected gap was the lack of accountability for biodegradable or compostable content. To do so, a straightforward indicator was designed by formulating a ratio, which is presented in **Equation 1**.

Equation 1. Biodegradable/compostable content calculation formula.

$$BC = \frac{Bm}{Tm}$$

Where BC is the biodegradable/compostable content, Bm is the total mass of biodegradable/compostable materials used in manufacturing (kg), and Tm is the total mass of the product (kg).

It aims to shed light on how much of the product is made from biodegradable/compostable materials when used alongside the Circular Index, which provides a sense of the material's overall circularity and its production process.

The difference between biodegradability and compostability is not a minor one. Flachenecker (2024) explained it carefully, highlighting that the term compostable is more commonly used in the packaging industry, as it conveys more guarantees of the transformation of the material into an organic substance within a specific time frame, having specific certification schemes. In contrast, the term compostable does not add any value to fertilisers, as all of them are designed to be incorporated into agricultural soil. For that reason, when assessing fertilisers, considering biodegradable ones is a better option. It is also common practice in the textile industry. Therefore, when applying this indicator to packaging materials, the concept to apply is the compostability of materials, while when applying it to fertilisers or textiles, the concept to apply is the biodegradability of materials.

The consideration of whether a material is compostable or biodegradable is based on the corresponding standardised certification, such as EN 13432 (European Committee for Standardization, 2001), ISO 17088 (International Standardization Organization, 2021), TÜV OK Compost Industrial, OK Compost Home, OK Biodegradable Soil, OK Biodegradable Water (TÜV Austria, 2025), etc.

4.3. Fertiliser Complementary Indicator Proposal

To complement the Circularity Indicator of Nutrient, the selected gap was the lack of accountability for nutrient release speed. This is one of the key characteristics of any fertiliser, since the rapid release of nutrients may prevent crops from timely absorbing them and thus cause them to be lost through leakage. Nutrient leakages are one of the main causes of fresh and groundwater pollution. But it also addresses the CE concept of prolonging the use time of materials. If nutrients are released more slowly and crops can benefit from them, the next fertiliser application can be postponed, thereby consuming fewer resources overall.

The proposed indicator was called the nutrient slow-release index, and its calculation is detailed in **Equation 2**.

Equation 2. Nutrient slow-release index calculation formula.

$$\boldsymbol{NSRI = 1 - \frac{minNRC_n}{bioNRC_n}}$$

Where NSRI is the nutrient slow-release index, $bioNRC_n$ is the soil nutrient relative content "n" days after the application of a bio-based fertiliser, and $minNRC_n$ is the soil nutrient relative content "n" days after the application of a mineral (e.g. fossil-based) fertiliser.

Both minNRCn and bioNRCn must be measured over the same timeframe and under the same test conditions to ensure comparability. The indicator ranges between 0 and 1: it equals 0 when bio-based and mineral fertilisers show the same nutrient release speed (less circular), and approaches 1 as the bio-based fertiliser releases nutrients increasingly more slowly than the mineral option (more circular). Evidence from controlled incubations commonly reports faster initial N release from mineral fertilisers compared with organic pellets, supporting the rationale for using the mineral option as a "fast-release" benchmark in many contexts (Niedziński et al., 2021a).

However, we do not assume that bio-based fertilisers always release nutrients more slowly than mineral fertilisers ($bioNRC_n > minNRC_n$). Nutrient release from bio-based/organic fertilisers is mediated by mineralisation and therefore varies with fertiliser source/formulation and environmental and soil conditions (e.g., soil type and temperature), which can materially affect release kinetics (De Jesus et al., 2024). Accordingly, when $bioNRC_n \leq minNRC_n$ under the specified conditions, the indicator is set to 0 (i.e., the framework does not credit circularity via slower nutrient delivery in that case), and the result should be interpreted as "no slow-release advantage observed" rather than as a failure of the bio-based option.

Measurements of soil nutrient relative content can be conducted following the Kjeldahl procedure (International Standardization Organization, 1995), and have been reported in scientific literature (Niedziński et al., 2021b).

4.4. Packaging complementary indicator proposal

The complement of the Recycling Effectiveness indicator was designed to bridge the gap in accounting for the consumption of virgin materials during the manufacturing and recycling stages. Many packaging manufacturing processes, despite having bio-based materials as the core input, consume significant virgin products. This fact can easily be overlooked when using the Recycling Effectiveness indicator, and because of its relevance, it was deemed relevant to include it in the framework.

The indicator was named the virgin material consumption index, and its calculation rationale is presented in **Equation 3**.

Equation 3. Virgin material consumption index calculation formula.

$$VMCI = 1 - \frac{VM}{TO}$$

Where VMCI is the virgin material consumption index, VM is the mass of virgin materials (kg), and TO is the mass of the total output, or the mass of the final product (kg).

The indicator ranges between 0 and 1, resulting in 0 (less circular) when the product is totally manufactured out of virgin materials, and 1 (more circular) when the product is manufactured entirely from non-virgin materials (i.e. recycled, reused, upgraded, etc.).

4.5. Textile complementary indicator proposal

Regarding textiles, the selected gap to be addressed was the lack of accountability for the use of synthetic substances during fibre treatment. Most bio-based fibres require post-manufacturing treatments to improve their characteristics, be it for consumer acceptance (e.g., softness) or durability. Most of these treatments consume significant amounts of non-renewable materials that may reduce the circularity of the process. While the Resource Pressure evaluates several aspects of circularity and sustainability, this aspect was left out.

To include it within the monitoring framework, the fibre treatment circularity index was designed, as detailed in **Equation 4**.

Equation 4. Fibre treatment circularity index calculation formula.

$$FTCI = 1 - \frac{m_{nr}}{m_{fibre}}$$

Where FTCI is the fibre treatment circularity index, m_{nr} is the mass of non-renewable additives used in the fibre treatment, and m_{fibre} is the mass of the fibre treated.

This indicator enables the quantification of the non-renewable resource intensiveness of the post-manufacturing treatment of the fibre. It ranges from 0 to 1, 0 being the case where the non-renewable additives mass is identical to the treated fibre (less circular), and 1 the case where no non-renewable additives are consumed (more circular).

4.6. Validation of the framework

The validation phase was designed as an interpretive, feasibility-oriented assessment rather than a statistical performance evaluation. Its purpose was to test: (I) computability with realistic industrial data, (II) the framework's ability to discriminate between product options, and (III) managerial interpretability through benchmarking and a targeted scenario exercise. Consequently, the analytical approach is primarily descriptive: it demonstrates feasibility and interpretive usefulness across the three sectoral applications. Results should therefore be interpreted as comparative screening and scenario exploration outputs under the tested conditions, not as definitive estimates suitable for certification-like claims.

Indicator computability depends on data availability and on the definition of consistent system boundaries across cases. For fertilisers, the nutrient slow-release indicator requires product- and content-specific nutrient release measurements (relative soil nutrient content over a defined time window), which were only available for a subset of products in this study. For packaging, indicator computation combined primary operational data (process yields, recovery performance, impurity/quality information) with EPD/LCA background inventories for benchmarking, which may vary in representativeness across producers. For textiles, validation was limited to the Resource Pressure indicator computed from life cycle inventory/impact datasets and interpreted relative to planetary boundaries; therefore, conclusions are constrained to that indicator and do not constitute a full sectoral validation of the complete monitoring set.

Against this validation scope and data context, the following subsections report the three sectoral applications and illustrate how the framework performs under the available datasets and boundary assumptions.

Once the monitoring framework was completely defined with eight indicators, its validation was conducted among the three sectors. For fertilisers, five products were analysed using the corresponding set of indicators (i.e., algae biomass, compost, feather meal, spent mushroom substrate, and wood vinegar), allowing to identify different levels of circularity among them (Iglesias et al., 2025). This application validated the applicability of the framework to bio-based fertilisers, relying on data available in life cycle inventories and life cycle impact assessments.

The validation exercise not only tested the computational feasibility of the framework but also, and more importantly, its interpretive power. By applying the indicators to fertilisers, packaging materials, and textiles, it was possible to identify sector-specific sensitivities. For example, fertilisers demonstrated a strong dependence on nutrient-release kinetics, while packaging performance was largely influenced by the quality of recovered materials. These differences underline the necessity of sector-tailored indicators within a unified structure, confirming that product-level circularity cannot be meaningfully assessed using generic metrics alone.

The results obtained from the application of the framework to fertilisers are presented in **Figure 3**, including their uncertainty bars.

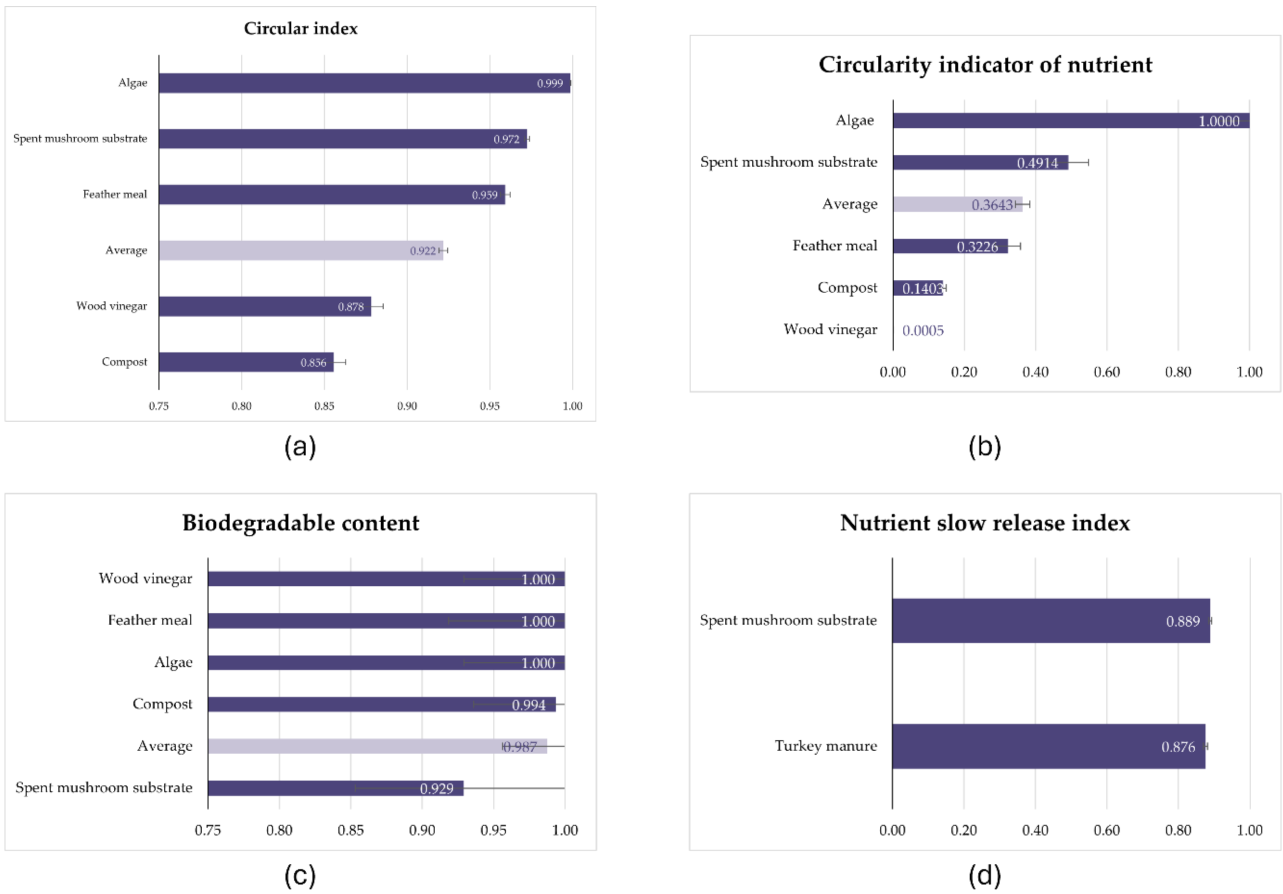

Figure 3. Results of the application of the BIORADAR product circularity monitoring framework to fertilisers. Source: Iglesias et al. (2025), licensed under CC BY 4.0.

As can be seen in **Figure 3**. The monitoring framework enables companies to compare different fertilisers among them, aiding the selection of higher circularity levels. The results for the nutrient slow- release index (**Figure 3d**) are dependent on specific data that is not yet publicly available (i.e., the relative nutrient content on soil after a given time period). Because of that, it could only be calculated for spent mushroom substrate and turkey manure. However, a fertiliser manufacturer could easily obtain the values for their targeted fertilisers by following the standardised measurement method referenced in Iglesias et al. (2025).

Likewise, the monitoring framework was applied to an industrial case of a Spanish paper and cardboard recycling company that has published the Environmental Product Declaration (EPD) of its products. This application served two validation purposes: (I) to verify that the required inputs can be populated from routine company records, and (II) to test whether the resulting indicator outputs are interpretable and useful for managerial decision-making when compared with peer materials.

In this packaging case, the company was able to provide data for nearly all required variables through existing operational records. Primary data inputs included, among others, process yields and recovery performance (e.g., net recovered fractions), and impurity/quality-related information relevant for computing the recycling effectiveness indicator and for running a sensitivity-style scenario exploration. EPD/LCA information was used as complementary background inventory and to support benchmarking comparisons within the BIORADAR dataset, rather than as the sole data basis for indicator computation.

The results obtained for the company's paper and cardboard products (**Figure 4**) yielded identical scores across the computed indicators, which facilitated interpretation and internal communication of performance across product lines. These scores were benchmarked against other packaging materials included in the BIORADAR dataset when interpreting the packaging-specific indicators, and against the broader set of bio-based products when interpreting the general-purpose indicators. In addition, at the company's request, a scenario analysis was performed by varying the recovery capacity of a relevant process (**Figure 4c**), which produced corresponding changes in the recycling effectiveness indicator. This exercise supported the managerial team in exploring feasible circularity targets under technical and economic constraints.

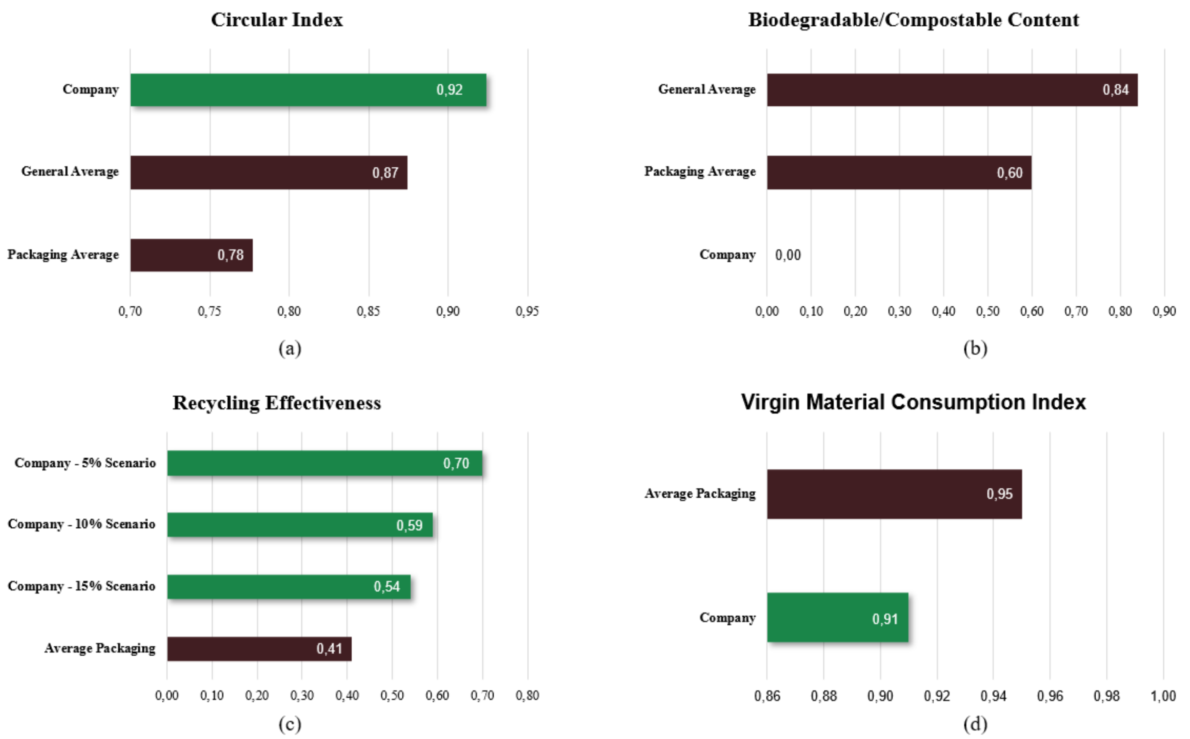

Figure 4. Results of the application of the BIORADAR product circularity monitoring framework to packaging materials.

Beyond feasibility, the company's feedback provides user-oriented validation evidence aligned with the intended purpose of the framework. Company representatives reported that the framework made their circularity performance more transparent and quantifiable than expected, and that the resulting circularity level was higher than they intuitively anticipated, highlighting the value of credible, standardised metrics for external communication. They also expressed interest in repeating the assessment after operational changes to track improvements over time, and emphasised the importance of ongoing standardisation efforts to ensure that circularity claims are comparable and trustworthy.

For textiles, the validation was limited to the application of the Resource Pressure (RP) indicator to three bio-based fibres (i.e. cotton, wool, and hemp) and one fossil-based fibre (i.e. polyester). Such application identified the different orders of magnitude that can be obtained when applying the indicator, and the impact of the environmental impacts and their relationship with the corresponding planetary boundary. The results of this validation are awaiting publication (Iglesias et al., manuscript in peer review).

Figure 5 summarises the results of the application of the RP indicator to four different textile fibres**. Figure 5a** demonstrates the notably higher pressure that cotton exerts on resources, considering the relevant planetary boundary. For the other three fibres, there was no statistically significant difference between them (**Figure 5b**). This was identified through an analysis of variance (ANOVA) with 0.05 as the threshold for statistical significance. To do such an analysis, a multiple linear regression was fitted with RP as the dependent variable, and year, fibre type, and interaction terms between year and each type of fibre as the independent variables. The cotton coefficient was highly significant ($p < 0.001$) as well as the year-cotton interaction, suggesting differences in both baselines and temporal evolution; on the other hand, between hemp, wool, and polyester, no statistical difference ($p > 0.001$) was found either in intercept or trend.

Both charts in **Figure 5** also illustrates how the longer a given fibre is used, the lower its pressure on natural resources. The results of this application show how using life cycle inventories and life cycle impact assessments, and linking them with the planetary boundaries conceptual framework, enables a contextualised comparison between materials under the selected LCI/LCIA datasets and boundary assumptions.

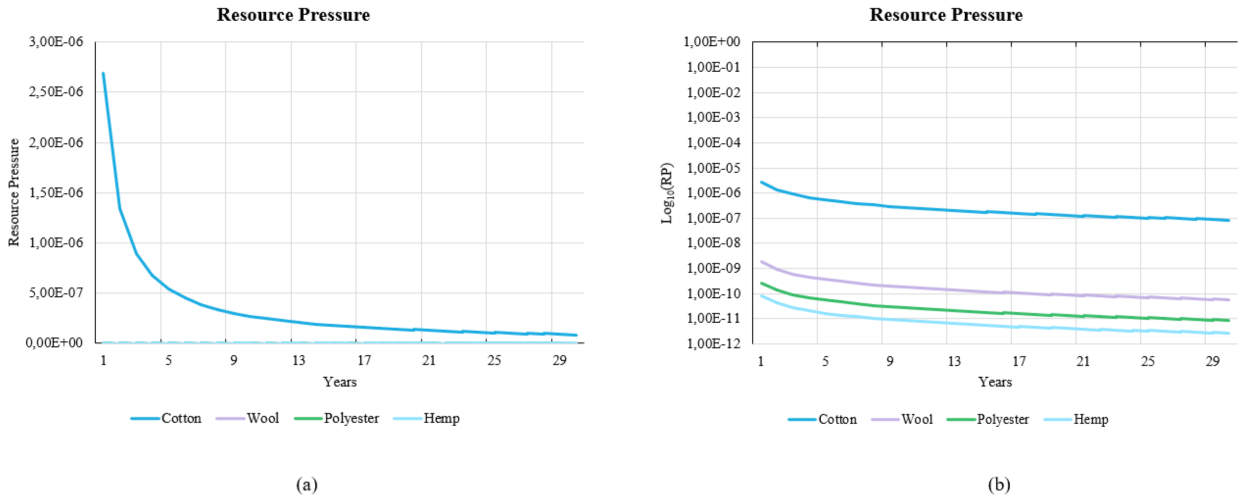

Figure 5. Results of the application of the Resource Pressure indicator to textile fibres. Source: Iglesias et al. (manuscript in peer review).

The comparison of bio-based and fossil-based fibres further illustrates how the framework can support decision-making beyond traditional life cycle indicators. By linking the RP results to planetary boundaries, the analysis provides a contextual understanding of material performance, highlighting where substitution strategies may deliver the greatest sustainability gains.

To assess managerial usability, we presented the framework to seven companies across the targeted sectors in four EU-member states (four manufacturers of fertilisers, two of packaging materials, and one of textile fibres). Participating firms reported that the required data were generally available in existing records. In the packaging validation, the company highlighted that the unexpectedly high circularity score helped them quantify strengths they perceived qualitatively, while the scenario analysis supported prioritisation of improvement options relative to technical and economic constraints. The company also expressed interest in repeating the assessment after process changes to track progress over time.

The validation directly addresses the study objectives by showing that a product-level CBE monitoring framework can be reconstructed and implemented with feasible data inputs across heterogeneous sectors. Specifically, the fertiliser and packaging applications demonstrate that the indicator set can (a) be computed from company records and/or standard inventory sources, and (b) provide interpretable signals that differentiate product options and support managerial prioritisation. The textile application illustrates how contextualization relative to planetary boundaries can change the interpretation of material choice, reinforcing the need for sector-appropriate indicators within a unified monitoring logic. Together, these cases support the framework's intended use as a monitoring and decision-support tool, while also delineating where additional empirical testing and uncertainty treatment are needed.

Overall, the design of the BIORADAR product circularity monitoring framework highlights the current situation of existing CE metrics, their advantages and gaps, and offers an example of how to complement them in a way that facilitates the business adoption of the framework. The validation of the proposed indicator framework is an example of the feasibility of its application in the academic and industrial environment, and how its results can be used to guide managerial decisions in eco-innovative firms.

These validations address the study objectives by demonstrating that the proposed product-level monitoring framework is (I) computable with realistic industrial and inventory data, (II) discriminatory enough to differentiate product options and reveal sector-specific sensitivities (e.g., nutrient-release kinetics in fertilisers; quality losses in packaging), and (III) managerially interpretable, as illustrated through benchmarking and scenario exploration. At the same time, the results delineate where further work is needed (e.g., larger datasets, harmonised baselines, and formal sensitivity/uncertainty treatment) to strengthen robustness for broader comparative claims.

5. Recommendations

The CE literature and practice continue to expand across regulation, standardisation, academia, and business. Within this rapidly evolving landscape, bio-based value chains raise additional measurement challenges — particularly around biological and end-of-life pathways, cascading use, and the preservation of material quality— which can hinder decision-making at firm and product levels. This article contributes by systematically screening existing metrics and consolidating a product-level monitoring framework, complemented with new indicators where key circularity mechanisms were insufficiently represented.

At the same time, the BIORADAR framework should be interpreted as a feasibility-tested, early-stage monitoring approach, rather than a mature, certification-like method. Its deployment is conditioned by data availability and boundary choices. In particular, some use-phase parameters (e.g., nutrient-release kinetics for fertilisers) may require context-specific measurements, and benchmarking results may depend on the representativeness of available inventory datasets and sectoral assumptions. Future implementations should therefore prioritise transparent documentation of data sources, boundary definitions, and any context-dependent measurement conditions.

Based on the validation results, we recommend three practical directions for further development and uptake. First, future research should strengthen analytical depth through formal sensitivity and uncertainty treatment (e.g., parameter sensitivity for recovery performance and quality-loss assumptions, and uncertainty propagation where feasible), supported by larger and more diverse industrial datasets. Second, the framework should be further operationalised through standardised data templates and digital tooling that align indicator computation with routine company records (procurement, mass/energy balances, yields, recovery, and impurity data), thereby reducing reporting burden and improving comparability. Third, harmonisation efforts should focus on mapping product-level indicators to recognised CE/CBE principles (e.g., nutrient cycling, biological vs. technical loops, quality/value retention, and cascading), so that sector-specific indicators remain comparable within a unified structure while preserving mechanism fidelity.

Overall, this research helps bridge the methodological gap between conceptual circular economy principles and product-level operational monitoring. By integrating a compact set of general-purpose and sector-sensitive indicators, the BIORADAR framework supports cross-sector comparison while acknowledging sector-specific circularity mechanisms. Future work should expand empirical testing with larger datasets, refine context-dependent parameters (especially in the use phase), and explore integration pathways with emerging standards and reporting requirements to enable broader industrial adoption.

Acknowledgements This research has received funding from the Circular Bio-based Europe Joint Undertaking (CBE JU) under the European Union's Horizon Europe research and innovation program under grant agreement No. 101112457 (Monitoring system of the environmental and social sustainability and circularity of industrial bio-based systems). The content of this publication reflects only the author's view, and the CBE JU and the European Commission are not responsible for any use that may be made of the information it contains. The authors wish to acknowledge the members of the BIORADAR project, whose contributions have supported the overarching research framework in which this manuscript is embedded: Yaghma BV, Hochschule für angewandte Wissenschaften Hamburg, Iris Technology Solutions SL, Next Technology Tecnotessile RL, Kneia SL, and UNI—Ente Italiano di Normazione.

Author Contributions Hasler Iglesias: Conceptualisation, methodology, Validation, formal analysis, data curation, writing – original draft. Ana Paredes Ortiz: Conceptualisation, formal analysis, data curation. Francisca Sánchez-Liarte: Funding acquisition, project administration, supervision. David Fernández-Gutiérrez: Writing – review and editing, supervision, project administration. Andrés J. Lara-Guillén: Writing – review and editing, supervision, project administration.

Data availability All data used for the manuscript are contained in it. The calculation methodologies for the four existing metrics selected are included in the supplementary material.

Declarations

Competing Interests The authors declare no competing interests.

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