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CirDEF: Standardised information framework to address the information needs of circularity indicators

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ABSTRACT

Circularity indicators are widely used to assess progress toward sustainability through circular economic practices. However, the diverse data requirements for these indicators often result in inconsistencies, overlaps and misinterpretations when evaluating circularity. This study addresses the absence of a unified, standardised approach to defining and applying circularity indicators, by developing a framework, named "CirDEF". This standardised and holistic information framework supports the varied information needs of circularity indicators across system scales, indicator types, and stakeholder contexts. A systematic literature review was conducted, analysing 75 resources to identify existing circularity indicators. The resulting standardised information framework structured around input, process, and output model incorporated with key attributes such as business, time, dimensional, impact, and performance. This allows for the creation of a holistic platform that can redefine existing circularity indicators and improve decision-making. The framework was validated through expert interviews using face, content, and construct validation methods, to ensure theoretical and practical relevance. CirDEF enables dynamic, context-specific circularity assessments by allowing users to apply any relevant circularity indicators instead of relying on fixed indicators. This adaptability supports real-time decision-making, traceability, and proactive implementation of the circular economy. By resolving ambiguities, overlaps, and the static measurement limitations, CirDEF serves as a comprehensive system that facilitates data-driven decisions and aligns with SDGs. This is the first study of its kind to provide a thorough resource for academics, industry practitioners, and policymakers, enabling a holistic evaluation of circularity indicators through a standardised information framework across various processes and life cycles on a global scale.

1. Introduction

1.1. Background and motivation

A transition to a circular economy (CE) is eminent due to the resource scarcity, climate change, and environmental, economic, and social imbalances signalling the limitations of linear consumption models (Kevin van Langen et al., 2021). CE offers a sustainable alternative by promoting zero waste, optimising resource use, and fostering innovative business models. The Ellen MacArthur Foundation and Granta Design (2015) defined CE as a restorative and regenerative system that maximises material utility within technical and biological cycles. This understanding further influenced concepts like cradle-to-cradle, industrial symbiosis, and performance economy, embedding circularity in production systems globally (Ogunmakinde et al., 2021). These concepts of CE promote business models that integrate environmental, economic, and social considerations (Geisendorf and Pietrulla, 2018a; Geissdoerfer et al., 2017).

Circularity indicators (CIs) track and evaluate CE performance across processes, systems, and organizations serving as a gauge to measure the degree of circularity implementation and its function within a given context (Rossi et al., 2020; Saadé et al., 2022). Circularity measurement approaches vary, including life cycle assessments (LCA), material circularity, waste management, and environmental and social impacts assessments. The scope ranges from macro-level regional assessment (Ghisellini et al., 2016) to the nano-level product evaluation (Khadim et al., 2022). CI comprise diverse sub-indicators both qualitative or quantitative. For example, Material Circularity Indicators (MCI) and

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Social Life Cycle indicators cover sub-indicators like scarcity, geopolitical availability, mass of virgin materials, unrecoverable waste, and quality of life (Moraga et al., 2019). A diverse range of sub-indicators with varying scopes requires thorough monitoring and precise measurement to evaluate circularity. The complexity and variations in CIs create challenges in monitoring and evaluation, leading to inconsistencies, overlaps, and misinterpretations. The lack of a standardised framework to support circularity information requirements hinders effective circularity assessment and decision-making.

1.2. Research gap

Click or tap here to enter text.Click or tap here to enter text.As the transition to a CE progresses, the focus is shifting from waste-based indicators to a more holistic set of CIs (World Business Council for Sustainable development (WBCSD), 2024). A unified standard is essential to prevent overlaps and misinterpretations. Despite cross-sectoral efforts, a significant gap remains in CI classification and understanding, particularly regarding their functionality at different levels. This gap hinders the comprehensive evaluation of circularity performance (Gomis et al., 2023). A standardised information framework, a one-stop solution, is needed to support the information needs of circularity indicators to enhance transparency, and foster coherence in decision-making.

1.3. Research questions

This study addresses the following key questions.

1. What are the main indicators in the body of knowledge?
2. What sub-indicators and their functions are associated with the main indicators?
3. What key components are needed to map the circularity information needs into a standardised information framework?
4. How can the standardised information framework be validated theoretically and practically?

1.4. Aim & objectives

The aim of this study is to develop a standardised information framework to support the information needs of the circularity indicators. To achieve this, the following objectives were pursued: 1. identify the main indicators within the existing body of knowledge; 2. Analyse sub-indicators of the main indicators based on their functionality; 3. Develop a standardised information framework to map the information needs of circularity indicators; and 4. Validate the framework through theoretical and practical underpinnings.

2. Literature review

2.1. Circularity indicators (CI)

"Circularity" is a crucial concept for monitoring and enhancing the CE across various scales. It is defined as "the alignment of a material or energy flow, product, processes, or system to a set of CE strategies (redesign, product disassembly, recycling, use of renewable energy, etc.) that meet general CE goals" (Oliveira et al., 2021, p. 456). CI measure circularity by considering factors that impact its level, with variations in analysis depth and data availability (either qualitative or quantitative) (Albæk et al., 2020). CIs serve as key performance indicators to benchmark industries, inform consumer choices through product labels, and support regulatory change (Saidani et al., 2019). The categorisations of CIs focus on designing-out concepts, material circularity, waste management; environmental, economic and social impacts; LCA, climate change and energy; stocks and sufficiency and context-based assessments (Niero and Kalbar, 2019; Oliveira et al., 2021; Rossi et al., 2020). To facilitate circularity measurement, CIs are classified into nano, micro, meso or macro levels (de Oliveira et al., 2019; De Pascale et al., 2023). Macro-level CIs assess infrastructure and social systems redesign, focusing on industrial and economic changes at regional or city levels (Kirchherr et al., 2017). Meso-level CIs explore symbiotic relationships, while Micro-level CIs monitor CE progress at the organisational level. Nano-level CIs examin product, component, and material circualrity (Khadim et al., 2022; Saidani et al., 2017).

Regardless of measurement scale or categorisation, each indicator may include various qualitative and quantitative sub-indicators (Khadim et al., 2022; Moraga et al., 2019). These sub-indicator are identified and applied separately. For instance, Sustainability Circular Index (SCI) includes sustainability reports (e.g., Triple Bottom Line, Global Reporting Initiative), and MCI (Moraga et al., 2019). MCI evaluates micro-level circularity by assessing virgin material use, unrecoverable waste and product utility (Bracquené et al., 2020; Ellen MacArthur Foundation and Granta Design, 2015). Similarly, Global Resource Indicator (GRI), incorporates sub-indicators like scarcity, geopolitical availability, and recyclability (Moraga et al., 2019). This demonstrates that sub-indicators serve distinct purposes and apply to various contexts.

2.2. Information needs of CIs

The CI serve as valuable analytical tools for standardising the information requirement in circularity measurement(Oluleye et al., 2023; de Oliveira and Oliveira, 2023). Indicators integrate both qualitative and quantitative data (Moraga et al., 2019). For instance, MCI assesses mass of virgin, and recycled materials, alongside product life span focusing primarily on quantity, while qualitative factors, such as market-driven properties like time or economic value, also warrant consideration. Global Circularity Protocol (GCP) for Business, by WBCSD (2024) highlights significant overlaps in indicators across various frameworks, particularly in material flow assessment. Click or tap here to enter text.Terminologies like "recyclability," "recycling rate, " and "reusability rate" are often used interchangeably leading to inconsistencies and ambiguities in measuring circularity (Silvestri et al., 2024). Saidani et al. (2019) further emphasise that while numerous CE indicators have emerged, their development remains inconsistent in scope, purpose, and application. The lack of academic and scientific clarity on CI remains a barrier to effective implementation. Additionally, the use of different terminologies for similar metrics creates confusion, impeding comprehensive circularity assessment.

To address these ambiguities a standardised information framework is needed to evaluate circularity systematically (Haas et al., 2015). Saidani et al. (2019) stress that CI standardisation requires data collection across the entire value chain. However, data sharing is often restricted due to time, cost, and confidentiality concerns. Given the diverse data requirements at different lifecycle stages, prioritizing key circularity information is crucial for developing a standardised information framework.

2.3. Circularity frameworks

Several reviews and empirical studies have explored and categorised CIs, to establish a standardised approach. Geisendorf and Pietrulla (2018b), found that while many indicators address specific aspects of CE, they can also inspire operationalisation. Oliveira et al. (2021) advanced this by systematically categorising CIs at nano and micro levels, facilitating information exchange for decision-makers. Khadim et al. (2022) followed a similar approach in the construction industry, but did not examine the specific information needs of each CI, which are crucial for streamlining information exchange. De Pascale et al. (2021) developed a CE indicator framework to identify assessment focus, highlight metrics, and outline methodologies for measuring CE performance at micro, meso, and macro levels. However, it lacked a standardised measurement approach (Moraga et al., 2019). classified micro-and macro-scale CE indicators based on their scope and effectiveness but did not focus on the information needs within indicators. Silvestri et al. (2024) integrated sustainability indicators and impact categories from LCA, S-LCA, and LCC tools to guide circularity measurement in the agri-food sector. However, it lacked a detailed mapping of information needs for each indicator. Similarly, Pilipenets et al. (2025) introduces a framework assessing process-level circularity by integrating resource flows and operational emissions, yet it did not focus on the information mapping of the CI.

Amidst the global push for circularity, various macro-level policies and frameworks have emerged to guide governments in transitioning towards CE (Wasserbaur et al., 2022). GCP for Business 2024, launched by WBCSD (2024) in collaboration with the One Planet Network (OPN), serves as a leading action framework for companies to set targets, measure, report, and disclose progress on resource efficiency and circularity. WBCSD also developed the Circular Transition Indicators (CTI), a standardised methodology for measuring and improving circularity performance (WBCSD, 2024). ISO 59020 provides a global framework for measuring circularity at different levels (product, company, sector), while Global Reporting Initiative Circularity Standard, defines reporting guidelines on material flows, waste, and recycling, aiding companies in CE performance disclosure. The EU's CE Monitoring Framework aligned with ISO 59020, categorizes indicators into five areas: production and consumption, waste management, secondary raw materials, competitiveness and innovation, and global sustainability and resilience (Eurostat, 2023). These frameworks align with key SDGs, particularly those related to energy, economic growth, responsible consumption, climate action, and biodiversity preservation (Garcia-Saravia Ortiz-de-Montellano et al., 2023). Despite the emphasis on data-driven decision-making in circularity (WBCSD, 2024), no existing framework comprehensively addresses the information needs of CIs. This gap highlights the need for a framework that systematically maps these information needs. Click or tap here to enter text.

A strategic approach to structuring and mapping circularity information needs is the Input-Process-Output (IPO) model (MacCuspie et al., 2014) developed by Davis (1998) Click or tap here to enter text.for information systems. The model is valuable for several reasons. It provides a structured understanding of circularity dimensions, help stakeholders identify areas for improvement, facilitates targeted strategies and policies that address specific challenges and supports benchmarking across industries and regions, fostering best practices and accelerating CE transition (Deng et al., 2022; MacCuspie et al., 2014).

3. Research methodology

To achieve the objectives, a systematic literature review (SLR) was conducted to identify CI and their sub-indicators, which were analysed and classified by functionality to develop a standardised information framework. The information needs of the identified CIs were mapped against the IPO model. Subsequently, expert interviews were carried out to validate the framework. This project was judged to be low risk by Massey University, New Zealand (Ethics Notification No. 4000028457).

3.1. Phase 1: SLR

The SLR was underpinned by the PRISMA framework to systematically identify, screen and extract relevant articles focusing on CIs within the CE body of knowledge(Aromataris and Pearson, 2014). The search utilised the string.

(TITLE-ABS-KEY ("circular econom*" OR "circular industrial econom*" OR "Cradle-to-cradle" OR "performance economy" OR "regenerative design" OR "Reverse Logistics" OR "Greening Industry" OR "Greening of Industry") AND TITLE-ABS-KEY ("Construction" OR "Buil*" OR "Infrastructure") AND TITLE-ABS-KEY ("LCA" OR "Life cycle Assessment" OR "Life cycle Analysis" OR "Lifecycle Assessment" OR "Life-cycle Assessment" OR "Life-cycle Analysis" OR "Lifecycle Analysis")).

The initial search string using keywords related to indicators and metrics yielded limited peer-reviewed articles explicitly featuring these terms in indexed fields (title, abstract, or keywords). Initial screening revealed that CI were often embedded within broader CE and LCA studies. To capture a wide range of peer-reviewed papers, the search was expanded to include CE and LCA keywords, later scrutinised based on in-depth screening. Given the global distribution of CE and CI studies, the search was conducted in major academic databases, Scopus and Web of Science (Arsova et al., 2022; Foroozanfar et al., 2022). Additionally, search engines like "Google" and "Bing" identified further literature, generating 712 articles.

Clear inclusion and exclusion criteria were established to ensure transparency. The 712 articles included journal articles, conference papers, editorials, and grey literature in English. Peer-reviewed articles were prioritized for their stringent quality control, with other sources considered only when no peer-reviewed articles were available to support the study. This further ensured methodological rigor and focus maintaining the reliability and academic integrity of the SLR. The search spanned 2010–2024 to capture emerging trends in circularity. According to Fig. 1 once duplicates (n = 239) were removed, screening eliminated non-journal papers (n = 151), and articles lacking circularity information (n = 261) (Fig. 1).

The remaining 61 articles were subjected to content analysis to identify CIs and their functionalities. The recognized CIs were further analysed to understand their function and the sub-indicators used. In some cases, the literature lacked detailed information on the functions of sub-indicators within the main indicators. As a result, additional literature, including peer-reviewed articles and publications from government agencies, research institutes, and organizations (Kamil et al., 2022) was reviewed using the forward and backward snowballing method to obtain the necessary information. De Pascale et al. (2023) also emphasise the need to investigate beyond scientific articles to bridge the gap between academic literature and practical CE implementation. The snowball method enabled the capture of further relevant literature from citations and references of the identified sources (Linåker et al., 2022; Wnuk and Garrepalli, 2018). This approach helped capture influential, widely cited papers that may have been missed in the initial keyword-based search due to variations in terminology or indexing limitations. Both backward snowballing (reviewing references in the 61 articles) and forward snowballing (tracking studies that cited the 61 articles) were conducted iteratively until no further relevant sources emerged. This process added 14 more articles, bringing the final total to bringing the final total to 75 articles (See appendix A). The extracted data were analysed using thematic and content analysis. Thematic analysis is a systematic approach that handles large qualitative datasets to derive meaningful themes and patterns (Saunders et al., 2019). In this study, thematic analysis categorised the sub-indicators into key themes, while content analysis examined their functionalities to identify circularity information needs. Subsequently, the "CirDEF" framework (Circularity Indicator Development Framework, See Section 5 and Appendix B) was developed using the IPO model.

3.2. Phase 2: expert interviews

This framework is a qualitative representation of the requirements of the sub-indicators, necessitating discourse between the researcher and participants. This included explaining the CirDEF functions clarifying user queries to help participants understand the framework. Interviewing is a process where knowledge is created through interaction, enabling a subjective view of the world (Creswell and Poth, 2016; Hennink et al., 2020). Therefore, semi-structured interviews using both open-ended and closed-ended questions, were chosen as the most suitable method to validate the framework.

For validation, professionals with experience in waste reduction and CE-related practices and research, from various global regions, were

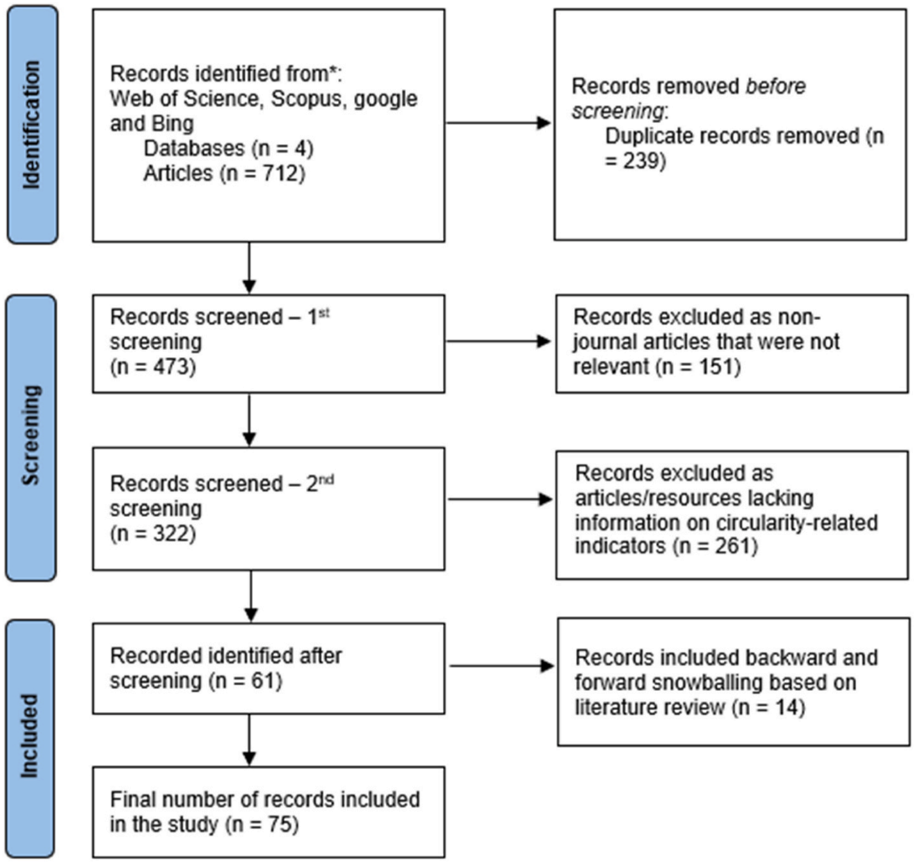

Fig. 1. Prisma method.
(Source: adapted by Liberati et al. (2009; Moher et al., 2009))

selected as participants. Given the niche focus, purposive sampling was employed to acquire participants, ensuring representation cutting across the sector. Inclusion criteria required participants to have (i) experience in CE-related research or practice, (ii) relevant publications or academic contributions, or (iii) professional involvement in sustainability-related projects. From an intended population of 10 validation participants, the minimum required sample size, based on a 90 % confidence level and a 10 % error margin, was 9 (Bekele and Ago, 2022; Saunders et al., 2019). Ultimately, 11 participants were involved, exceeding the required sample size. The sample included participants with varying levels of experience: four with at least 5 years, four with 5–15 years, and three with over 16 years. The group also consisted of 6 experts in CE-related research or practice, 8 with relevant academic contributions, and 5 with professional involvement in sustainability projects.

Before the interviews, the framework, guidelines, consent form and a short explanatory video were sent to participants. Once participants consented, online meetings were scheduled at their convenience. The interview process, lasting 45–60 min, was twofold. It began with an explanation of the functions of CirDEF, followed by time for questions and clarifications. Participant feedback was collected through a questionnaire with a 5-point Likert scale (1-Strongly Disagree to 5-Strongly Agree) and open-ended questions for deeper insights (Joshi et al., 2015; Kahandawa et al., 2021). The framework was validated or face, content, and construct validity. Face validation checks whether questions measure what is intended, content validation assesses whether all required components are included, and construct validation evaluates how well the questions test theoretical concepts (Bryman and Bell, 2011; Saunders et al., 2019). After each validation, participants provided reasoning for rating below 4 or 5. Open-ended questions gathered overall views of the framework. A pilot study with five academics was conducted before data collection to verify the process. The collected data was analysed both statistically, using box plots and thematically. Based on the results, the framework was upgraded.

4. Analysis and results

4.1. Introduction

The results section consists of three parts. 4.2) Thematic and content analysis of indicators and sub-indicators categorised into five themes, 4.3) the development of the CirDEF framework using the IPO model, and 4.4) the validation results followed by improvements made to the final CirDEF framework.

4.2. Thematic and content analysis

Both thematic and content analysis were essential in mapping the circularity information needs of sub-indicators into the standardised information framework, categorising and integrating circularity aspects. First main indicators were analysed for purpose, functionality, and sub-indicator composition. This breakdown offers insights into circularity components and their contribution to the system. Following this, thematic analysis was conducted on the identified information, resulting in five key themes, summarised in Table 1: re-consumption, resource optimisation, production LCA, social well-being, and environmental impact. The sub-indicators were then organised independently of their original main indicators under each theme. (see Appendix A). Some sub-indicators are commonly used across multiple main indicators, while others are unique to specific ones, highlighting their varied roles in evaluating circularity.

These themes formed the foundation for developing the standardised information framework, mapping each sub-indicator to the

Table 1
Themes identified after Thematic and Content Analysis.

Theme	Explanation
Re-consumption of resources	Re-utilising a resource made available after being used in a previous step, ensuring continuous resource flow, reduces the need for virgin materials, and aligns with sustainability principles. It provides holistic resource mapping, capturing the impact of each resource to enhance efficiency.
Production LCA	complete LCA analyses the environmental aspects of a product's entire life cycle, related to the manufacturing process.
Resources Optimisation	Makes the best/most efficient use of available resources, considering dimensional and performance attributes.
Environmental Impact	Environmental impact refers to the effect of human activities, enabling the measurement and evaluation outcomes to mitigate negative effects.
Social Wellbeing	The overall quality of life and satisfaction that individuals and communities experience within their social relationships, networks, and interactions ensuring broader societal implications of circular practices at meso and macro levels.

corresponding theme. A similar categorisation was done by Åkerman (2016) to analyse the core indicators derived from the existing indicators. Therefore, the sub-indicators were analysed in this study to identify the most relevant and primary circularity information needs, representing the core of circularity. By examining sub-indicators, the framework ensures that all fundamental circularity information needs are captured at the most granular level. This comprehensive approach guarantees that essential data points, often overlooked in broader indicator analyses, are systematically integrated into the information needs framework. As a result, the standardised information framework provides a more precise and holistic platform for measuring and evaluating circularity.

The "CirDEF" was constructed based on identified circularity information needs, utilising content analysis of the purpose and functionality of the sub-indicators (See Appendix B). The findings aligned with the IPO model, incorporating relevant attributes. This mapping ensured that all circularity information needs were captured holistically, enhancing CE practices. The framework was verified by redefining sub-indicators based on the circularity information needs mapped in the framework (see Appendix C).

4.3. Results: framework validation

The validation process used 5-point Likert scale and open-ended questions to collect data, with the results on face, content and construct validation discussed below.

4.3.1. Face validation

The results of face validation are illustrated in Fig. 2.

As shown in Fig. 2, respondents generally agreed on the clarity and readability of the framework, scores above 4. However, understandability had a slightly lower mean (average 3.73) compared to the overall structure and readability, suggesting minor refinements. Overall, results indicate that participants found the framework clear, readable, and understandable.

4.3.2. Content validation

The results of content validation are illustrated in Fig. 3.

According to Fig. 3, all statements relating to content validation scored above mean value of 4.27, indicating strong agreement on the relevance and importance of the input, outputs, process, attributes, and categorisation of definitions. These results highlight participants' confidence in CirDEF's structure and components, reinforcing its conceptual rigor and the importance of its overall flow and categorisation.

4.3.3. Construct validation

Construct validation evaluated the application of several sub-indicators within the framework (See Fig. 4), sub-indicator themes (See Fig. 5) and examined the applicability of the framework (See Fig. 6).

4.3.3.1. Measuring sub-indicators. During validation, five examples were used to demonstrate the applicability of CirDEF (See Appendix C). Fig. 4 shows that all indicators scored a means of 4 or higher, indicating the validity of the application of sub-indicator measurements and CirDEFs' applicability across various CIs.

4.3.3.2. Assessing sub-indicator themes. When validating the sub-indicator themes discussed in section 4.2, participants showed high agreement, with all themes scoring a mean of 4 or above (Fig. 5). This confirms the validity of the sub-indicator themes and their accurate representation of CI dimensions within the CE context.

4.3.3.3. Applicability within the current context. Fig. 6 shows that with a mean above 4.45, participants agreed the framework is globally applicable across industries, including construction. These results confirm CirDEF's broad applicability, flexibility, adaptability and the scalability reinforcing its potential as a standardised information framework to support the information needs of the CIs.

4.3.4. Feedback on framework and suggestions for improvement

Overall, participants recognized CirDEF as a significant advancement in CE research. Their feedback confirmed that the framework addresses a key research gap by consolidating fragmented knowledge on CIs into a holistic structure, providing a comprehensive understanding of circularity. Participants also highlighted its extensive coverage of circularity information needs and its potential as an industry tool, similar to LCA Quick, if simplified and supported by regulatory bodies.

Additionally, participants identified areas for improvement in the face, content, and construct validation processes, which were compiled

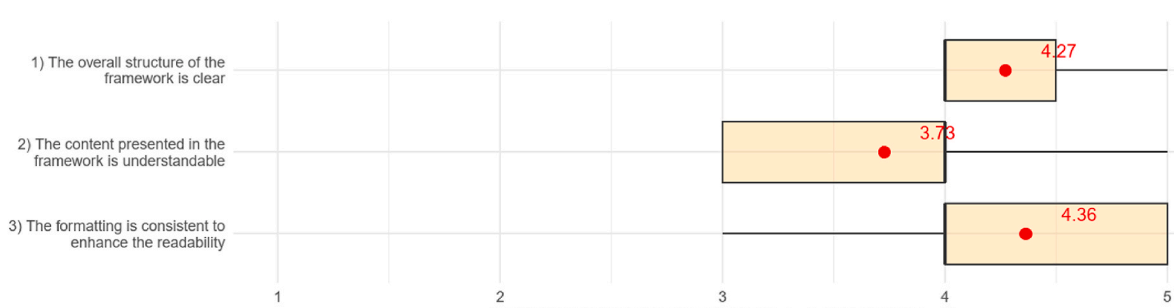

Fig. 2. Face validation results.
(Source: Authors'own)

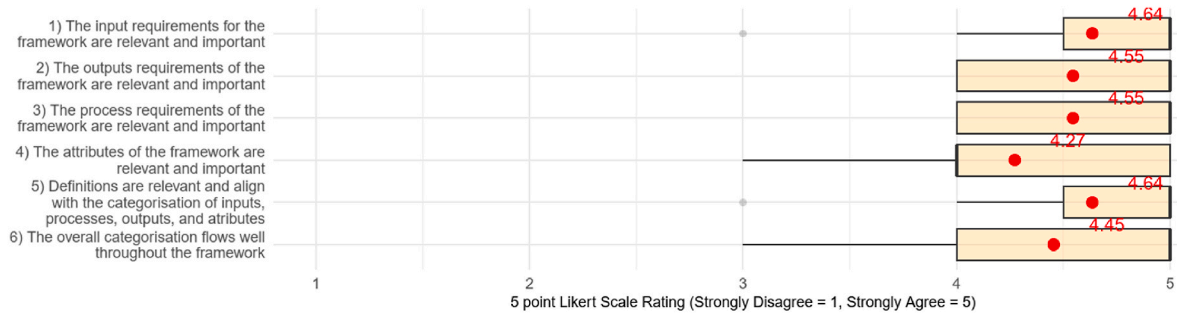

Fig. 3. Content Validation results.
(Source: Authors'own)

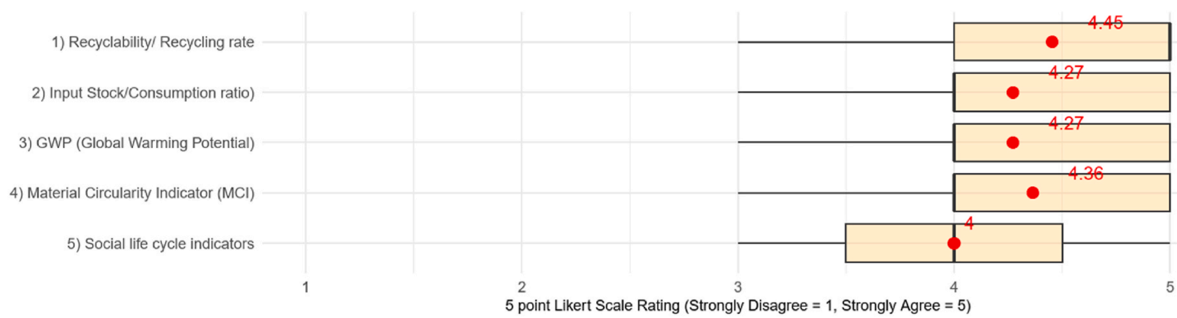

Fig. 4. Construct Validation results.
(Source: Authors'own)

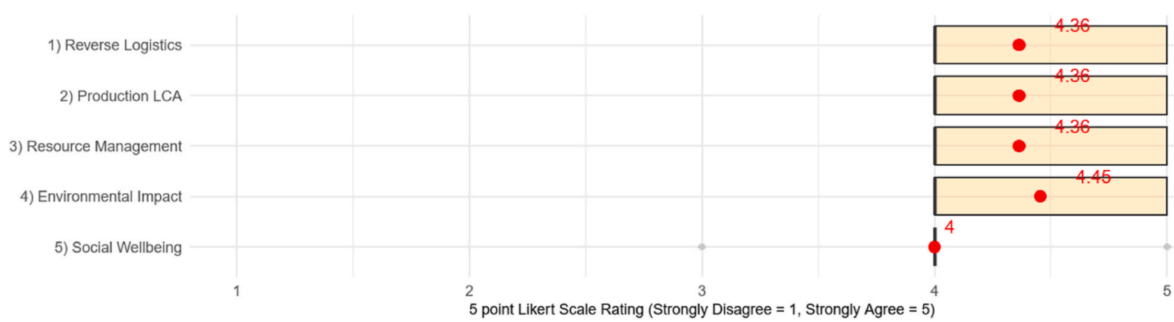

Fig. 5. Results from sub-indicator assessment.
(Source: Authors'own)

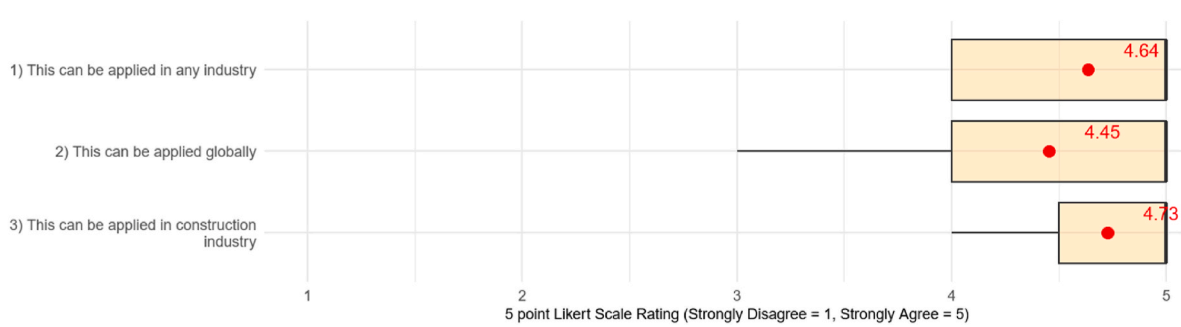

Fig. 6. Results from applicability assessment.
(Source: Authors'own)

into Table 2 along with the proposed actions by the authors.

5. CirDEF: Circularity Indicator Development Framework

The CirDEF was developed considering 3 levels as discussed in Sections 5.1 and 5.2.

Table 2
Feedback on framework and suggestions for improvement.

Suggestions for improvement	Actions
Face Validation	
Simplify the Framework's Structure: Framework is complex and suggested removing sub-categories to focus on main attributes for better readability and clarity.	When addressing multiple variables within the broader context of circularity, simplifying the framework while maintaining comprehensiveness is challenging. This can be achieved through an interactive software model.
Ensure consistency and formatting: Improving consistency in terminology (e.g., "capital" vs. "monetary funds") and addressing formatting issues (e.g., missing headings, typographical errors) for clearer communication.	The framework was updated based on the feedback
Enhance Usability: Adding a legend, providing examples, and making the framework more interactive or accompanied by supporting materials would help users better understand and navigate the content.	This can be achieved through an interactive software model.
Content validation	
Simplifying and clarifying terminologies included: • The framework's representation of cycles lacks clarity, especially in cases like 'monetary funds' and 'information', where interpretation is difficult. A clear rationale is needed for cycle representation. • The distinction between 'process options' and 'logistics' needs to be explicitly defined. • Classification of 'people' as outputs is confusing. • Terms like 'information' should be replaced with more appropriate alternatives like 'knowledge'.	Explanations for cycles, monetary funds, information and other unclear areas were revised with the example indicators. - The distinction between 'process options' and 'logistics' was clarified. - The term 'people' was replaced with 'competencies.' - 'Information' was retained as the correct term, as 'knowledge' is something a person acquires.
Clearly communicating the purpose within the framework	The front page of the framework guide outlines its purpose (See Appendix B)
Establishing the relationship between the attributes, inputs, process and outputs	The relationship was established based on the existing literature. Therefore, explicitly defining these relationships was considered beyond the scope of this study. However, this is further discussed in the guide on using this framework, which would be incorporated into the software development process with interactive elements and explanations.
Construct Validation	
This indicates lower understandability of Global Warming Potential (GWP) compared to other examples discussed.	A separate document is available detailing how each indicator is defined within the framework (See Appendix B and C)
Suggestions were made under construct validation regarding the framework's application, accessibility, and impact on global policy frameworks.	Further research is needed to refine the framework, enhancing accessibility and exploring its integration into global policy frameworks to ensure theoretical soundness and practical applicability.

5.1. CirDEF-level 1

Level 1 consists of 4 sections. 3 sections of IPO model; input, process and output forms the basis of the CirDEF. To describe the characteristics of the components in IPO, "Attributes" section is used, as shown in Fig. 7. Each of these elements is categorised to ensure that all aspects of circularity are considered.

5.2. CirDEF-level 2

In Level 2 each section is divided into sub-sections to ensure all aspects of circularity are considered as shown in Fig. 8. *Inputs* include the items required to initiate and sustain a process, and are categorised into monetary funds, materials, equipment, energy, people, and information.

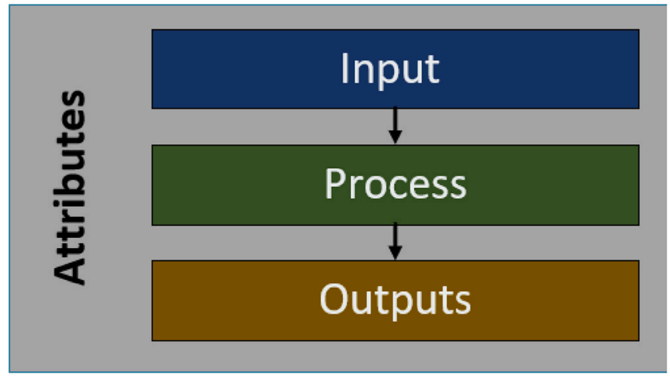

Fig. 7. CirDEF-level 1.
(Source: Authors'own)

Process involves actions or tasks that need to be performed in a predetermined order to achieve the intended outputs using the required inputs. The process includes items such as process options and logistics. *Outputs* are any tangible or intangible results of the process. Outputs encompass tangible and intangible outcomes. *Attributes* are classified into: Business, Time, Dimensional, Impact and Performance Attributes.

5.3. CirDEF- level 3

Level 3 is the comprehensive version of CirDEF which provides a detailed breakdown of the components and their interrelationships (See Fig. 9) with guidelines for using the framework and definitions for each item under the components (See Appendix B).

The components are explained in Table 3.

The framework can then be used to redefine the identified sub-indicators (See Appendix C for examples).

6. Discussion

Currently available CE models and frameworks often lack a holistic approach that addresses the diverse information needs of CIs across different system scales, indicator types, and client requirements. For instance, the Circular Transition Indicator (CTI) focuses on material flows within a company, aiming to reduce material inflows and outflows (World Business Council for Sustainable development (WBCSD), 2018). However, it does not consider factors such as social impacts or systems beyond the organisational level. Similarly, the EU Circular Economy Monitoring Framework, while aligned with ISO 59020, primarily offers macro-level insights and lacks guidance on defining circular metrics that support decision-making. It is limited to five key areas: production and consumption, waste management, secondary raw materials, competitiveness and innovation, and global sustainability and resilience (Eurostat, 2023), without addressing production at the organisational level. MCI evaluates product-centric resource usage to assess regenerative and recycled material use (Poolsawad et al., 2023). However, it also falls short in capturing system-wide interactions and providing standardised information for decision-making and policy implementation. Consequently, a significant gap exists in the knowledge base concerning systematic and holistic methods that can effectively meet the diverse information needs of CIs across different system sizes, indicator types, and stakeholder requirements. To address the gaps, CirDEF framework has been developed through a systematic process that analysed CI and sub-indicators to identify their functionalities and specific information needs. These needs were mapped against the IPO model, resulting in a comprehensive system that supports all types of CIs, something current frameworks do not achieve.

CirDEF presents several advantages over other frameworks. By leveraging the IPO model, it provides a clear and intuitive structure

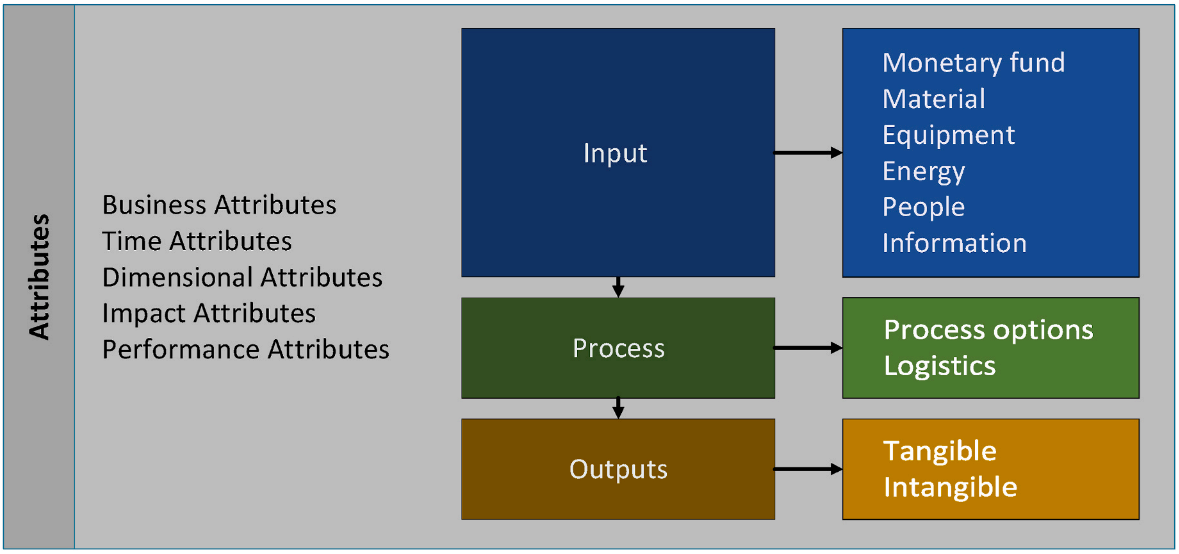

Fig. 8. CirDEF-level 2.
(Source: Authors'own)

where the Input, Process, and Output components distinctly represent the system's workflow. For example, in inputs like monetary funds, stakeholders' inputs and information needs were considered, while in outputs, economic, social and competency outputs were considered. By explicitly incorporating both economic and social inclusion, CirDEF addresses a crucial knowledge gap and significantly improves over existing frameworks, which often emphasise one dimension while neglecting others. For instance, frameworks such as the MCI and the EU Circular Economy Monitoring Framework focus primarily on economic aspects and material flows while offering limited attention to social inclusion (Eurostat, 2023; Poolsawad et al., 2023). The IPO model serves as the foundation for CirDEF, which then adopts key attributes that define the characteristics associated with the system, such as Business, Time, Dimensional, Impact, and Performance. This adaptation enhances the uniqueness of the model and its ability to contextualise and communicate complex information needs effectively. After rigorous analysis, the CirDEF was constructed and subsequently validated by professionals with expertise in waste management and CE-related practices, further supporting the robustness and adaptability of the developed framework.

Additionally, CirDEF goes beyond the limitations of current frameworks, which are often aimed at static indicator measurement. The proposed framework is a holistic and dynamic decision-making tool that can be applied across various system scales for micro-level activities to macro-level strategies while accommodating diverse CI information needs. Unlike other frameworks that prescribe both the type of system and the indicators to be used, CirDEF provides the necessary information and flexibility for users to evaluate their systems using any CI relevant to their specific context. This adaptability enables users to shift focus as needed, supporting proactive CE assessment and implementation. In contrast, tools like the EU Circular Economy Monitoring Framework, GCP, and GRI often result in limited flexibility and static evaluation processes (Eurostat, 2023; Moraga et al., 2019). If further developed, CirDEF could also support real-time circularity assessment and the automation of circular tracking, strengthening compliance with CE principles.

The structured mapping within the CirDEF framework enhances its practicality and relevance for policymaking, setting it apart from existing circular economy measurement tools. This strength is further demonstrated through its alignment with several Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (United Nations (UN), 2017). CirDEF supports the achievement of SDG 9.4 by improving resource efficiency, encouraging the adoption of clean technologies, facilitating digital transformation, and promoting circular business models (Schröder and Barrie, 2024). By addressing key limitations such as information gaps, inconsistencies, and fragmented approaches found in existing circular economy frameworks, CirDEF positions itself as an innovative and comprehensive solution for circularity measurement. It represents a significant advancement in making circularity assessments more standardised, actionable, and effective in supporting the global transition towards a sustainable circular economy.

6.1. Practical implications

CirDEF serves as a valuable tool for industries, policymakers, and stakeholders engaged in the implementation and evaluation of CE practices. It provides a detailed, uniform, and standardised yet flexible structure for defining and applying CIs and resolves the ambiguities, duplications and overlaps in definitions and inconsistencies found in current circularity assessment models. It supports the use of multiple indicators within a unified system, enhancing comparability and clarity across diverse contexts. Importantly, CirDEF addresses the major limitation highlighted by WBCSD (2024), the inability of current standards to assess circularity beyond organisational boundaries. CirDEF tackles this by encompassing the full life cycle of a product and service, from input-to-process-to-output, and accounting for stakeholder-specific information needs across micro-, meso-, and macro-level systems.

In the long term, the framework also promotes innovation and system thinking, supporting the identification of "other cycle" and "new cycle" (Baldassarre et al., 2019). These insights can foster industrial symbiosis, new product development, and emerging business models that advance CE transitions, creating new market opportunities and driving technological advancements. Furthermore, CirDEF provides a structured method for policy development related to CE practices, offering a comprehensive and well-categorised knowledge base that is relevant to multiple sectors and stakeholders.

To improve usability, Appendix B outlines guiding steps for navigating through the framework using the definitions used for each single element. This serves as a blueprint for users, offering guidance on applying the framework across various contexts. Publishing the framework in an open-access repository will further promote engagement, accessibility and credibility, enhancing its role in enabling data-driven,

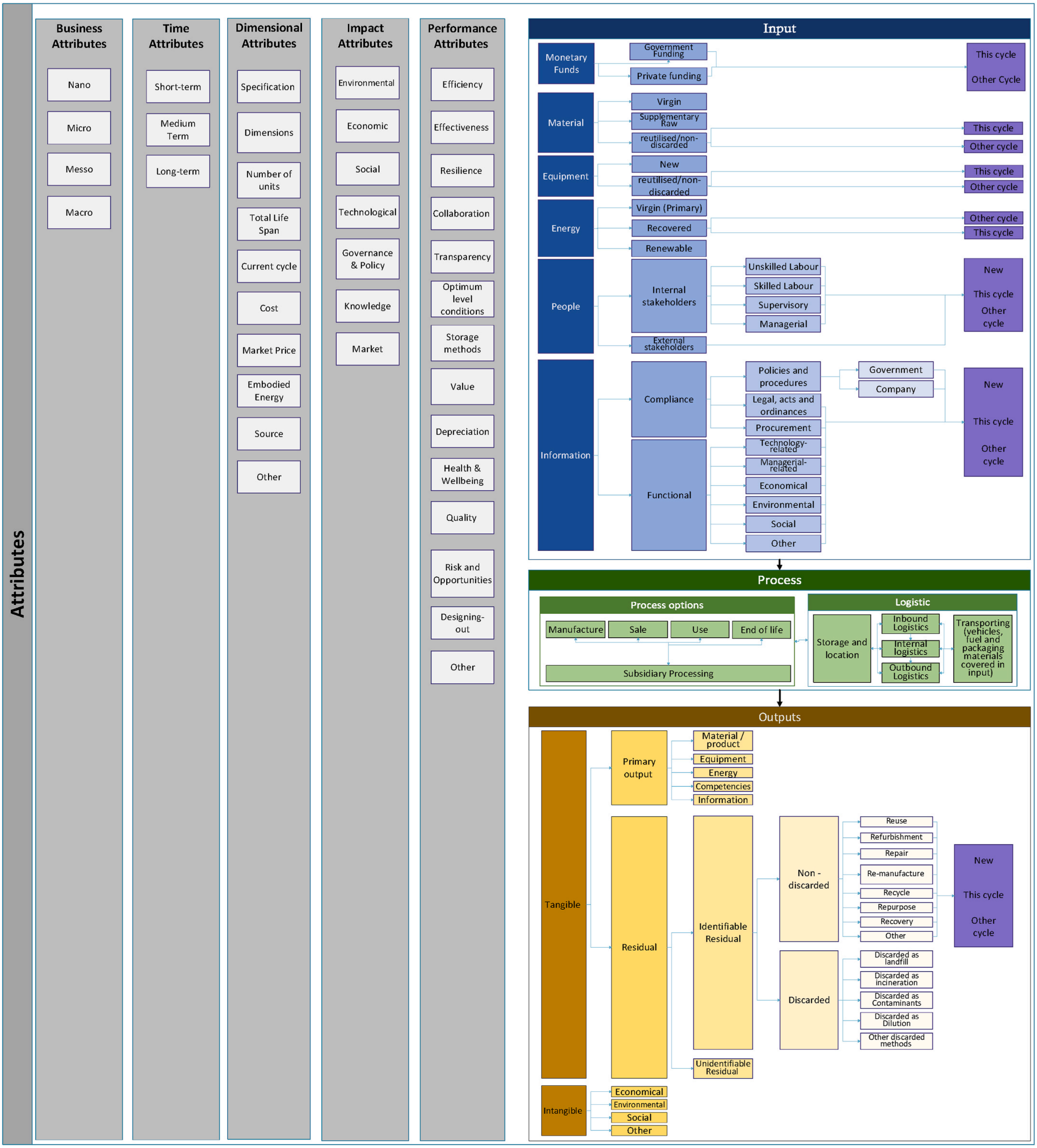

Fig. 9. Updated CirDEF.
(Source: Authors'own)

coordinated, and scalable CE transitions.

6.2. *Theoretical implications*

This study makes several important theoretical contributions to circularity and CE body of knowledge. Firstly, it advances the conceptual understanding and identification of sub-indicators by analysing the main indicators, highlighting the significance of understanding the sub-indicators as the core of circularity (Åkerman, 2016). The sub-indicators are categorised into five thematic clusters (See Section 4.2), which represent a comprehensive set of sustainability dimensions. This clustering allows for the extraction of core information needs necessary for evaluating circularity, thus addressing previously overlooked dimensions in the CE literature.

Table 3
Main components of the CIrDEF and explanation.

Components	Explanation
Inputs	
Monetary funds	Funds that are used to acquire the necessary inputs required for the process which are divided into 'Government funding' and 'private funding'
Material inputs	Three types 'Virgin', 'Supplementary raw' and 'Reutilised/non-discarded'. '**Virgin**' are unprocessed materials or components obtained directly from natural resources or chemical synthesis '**Supplementary raw**' are materials or components developed for this process. '**Reutilised/non-discarded**' and recycled items coming from this or another cycle were originally considered waste.
Equipment	Tools, machinery, or plants that are required to support a process. Divided into 'New' and 'Reutilised/non-discarded'. • '**New**' are items new to this cycle • '**Reutilised/non-discarded**' recycled items coming from this or another cycle were originally considered waste.
Energy	Any form of energy that is required to support a process to transform inputs into outputs. Three main divisions: 'Virgin', 'Recovered' and 'Renewable'. • '**Virgin**' focuses on new energy coming from the original sources, while '**Recovered**' focuses on energy obtained from by-products. • '**Renewable**' focuses on energy derived from naturally replenishing resources.
People	Any human resources required for the process, which mainly includes internal and external stakeholders. • '**Internal stakeholders'** cover human resources that directly contribute to its operations, which includes unskilled labour, skilled labour, supervisors, and managers. • '**External stakeholders**' cover people who influence the process but do not directly contribute.
Information	All data and information required for the process to operate, which can be related to function and compliance. • '**Functional**' covers information needed for executing a process, including roles and responsibilities, system performance, and workflow efficiency, covering technology, managerial, economic, environmental, social and other information. • '**Compliance**' covers legal regulations, governmental and company policies, as well as mandatory procedures, which are imperative for effectively carrying out the process.
Process	
Process options	The user can define what process they want to focus on. Processes like manufacturing, sale, use and end-of-life. This can also include any subsidiary process that is intended to support the main process.
Logistics	These are categorised into inbound logistics, internal logistics and outbound logistics. This covers recourses related to transport, storage, and location needs before, during and after a process, respectively.
Outputs	
Primary Outputs	Outcomes from a process, which can be material equipment, energy, people, or information.
Residual	Other tangible outputs that are not intended, which can be 'Identifiable Residual', 'Discarded' or 'Un-identifiable residual'. • '**Identifiable residual**' covers outputs that are not intended but identifiable and measured, which further divided as 'Discarded' and 'Non discarded'. o '**Discarded**' items focus on residuals at the end of life, which can be categorised as landfill, incineration, contamination, or other discarded methods. o '**Non-discarded'** items are intended for further use in another process through secondary action and are categorised into reuse, repair, refurbishment, recycle, repurpose, recovery or other methods. • '**Un-identifiable residual**' are residual items that cannot identified or measured.
Intangible outputs	Non-physical, abstract outcomes resulting from a process, including environmental, economic, social, and other related effects.
Attributes	
Business Attributes	Evaluate the extent and scale of CE activities, ranging from nano covering company level to macro levels covering global process.
Time Attributes	Focuses on the duration and number of cycles based on the scope of analysis. This can be short-term, which would be one cycle, or it can be long-term, focusing on the beginning of the first cycle to the end of the last cycle of the process.
Dimensional Attributes	Focuses on specifications such as size, weight, and number of units. Dimensional attributes are essential for assessing the material and physical characteristics of products.
Impact Attributes	Measure the effects and influences created by the process in terms of social, economic, environmental, technological, governance and policy-based, knowledge, and market. For example, impact attributes might include the reduction of greenhouse gas emissions, improvements in social equity, or increases in resource efficiency.
Performance Attributes	Focuses on the operational attributes of systems. Performance attributes assess how well processes function in terms of efficiency, effectiveness, resilience, collaboration, transparency, optimum level conditions, storage methods, value, depreciation, health and wellbeing, quality, risk and opportunities, designing out, and other factors

Secondly, CirDEF is the first framework to consolidate fragmented circularity knowledge into a holistically integrated and standardised system, overcoming the lack of cohesion found in existing tools. Prior research has highlighted the inconsistencies in how CIs are defined, interpreted and applied across different sectors (Saidani et al., 2019). By applying the IPO model and aligning it with attributes, CirDEF offers a unified platform that supports both quantitative and qualitative evaluations (Cayzer et al., 2017). This systematic structure supports comparative analysis, cross-sector adaptability and traceability, filling a critical gap in the existing body of knowledge on CE frameworks.

Thirdly, the framework addresses both economic and social dimensions of circularity, which are often neglected in existing frameworks, marking a meaningful shift in how CE performance can be theorised and operationalised. Thereby, CirDEF provides the foundation for a more inclusive, system-oriented framework of circularity.

7. Conclusions, limitations and future research directions

CE practices are being adopted globally to achieve sustainability; however, there is no standardised approach for holistically measuring and evaluating circularity performance. Existing models are often fragmented, either focusing on material flows, product-level assessments, or offering macro-level insights without sufficient guidance for operational-level circularity assessment. This research addresses that gap by developing CirDEF, a standardised, holistic information framework that supports the diverse information needs of CIs across system scales, indicator types, and stakeholder contexts by applying the IPO model and integrating attributes such as Business, Time, Dimension, Impact, and Performance, offering a comprehensive decision-support structure that accommodates complexity without sacrificing usability.

The framework was developed using a SLR by analysing the main indicators found in 75 sources within the existing CE body of knowledge. Subsequently, sub-indicators of the identified main indicators were derived, and their functionalities were analysed to extract the most relevant circularity information needs. These needs were then mapped onto the IPO model, supported attributes, to describe the characteristics of each element that support the information needs of CIs. During the expert validation process, several indicators (such as Recyclability/Recycling Rate, Input Stock/Consumption Ratio, GWP Value, MCI, and Social Life Cycle Indicators) were redefined using the identified information needs and their respective definitions. These indicators were tested and verified, thereby demonstrating the framework's ability to standardise circularity measurements, integrating both quantitative and qualitative attributes. This approach helps resolve ambiguities that may arise from differing interpretations of key terms.

CirDEF's feasibility and adaptability enable users to evaluate circularity dynamically, tailoring the application of CI to specific contextual needs. This positions CirDEF as a strategic ad dynamic decisions-making tool that explicitly incorporates both economic and social dimensions. It is the first framework to map circularity information needs irrespective of context or industry. The CirDEF serves as a critical enabler in advancing CE adoption across industries and, when applied strategically, can play a pivotal role in driving circular transformation, aligning with UN SDGs and beyond.

As highlighted during the validation process, the framework needs to be integrated into regulatory policies and simplified for broader accessibility. This would enable both experts and non-experts to effectively implement sustainable practices across diverse contexts, ensuring its overall effectiveness. To address the complexity of managing extensive information, future developments should focus on translating CirDEF into a software-based platform with interactive features, enabling real-time circularity assessments, automated tracking, and broader stakeholder engagement.

Even though the framework was validated by the experts, it still requires real-world testing through case studies to fully demonstrate its operational utility across industries, which would further verify its practical applicability in meeting circularity information needs (Pilipenets et al., 2025). In parallel, industry-specific adaptations, particularly in high impact sectors such as construction, manufacturing, agriculture, or transportation, could enhance its practical value and policy alignment specifically in light of UN SDGs. This adaptation would address the unique needs of a more tailored set of stakeholders (Saidani et al., 2019).

While this study develops a standardised information framework for CIs, future research could incorporate quantitative comparisons with existing CI frameworks to further validate its effectiveness. Conducting empirical assessments across different industries would enable a direct comparison of the CirDEF performance against established models, highlighting its improvements and novelty in terms of accuracy, comprehensiveness, and applicability.

While further empirical work is needed, the framework sets a strong foundation for standardised yet flexible CI implementation, bridging fragmented knowledge and fostering more inclusive, dynamic, and informed decision-making in support of CE.

CRediT authorship contribution statement

Ravindu Kahandawa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Ruchini Senarath Jayasinghe:** Writing – review & editing, Writing – original draft, Validation, Project administration, Formal analysis, Conceptualization. **Kasun Gomis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145611.

Data availability

The data that has been used is confidential.

References

Åkerman, E., 2016. Development of Circular Economy Core Indicators for Natural Resources. Royal Institute of Technology (Masters Thesis).

Albæk, J.K., Shahbazi, S., McAloone, T.C., Pigosso, D.C.A., 2020. Circularity evaluation of alternative concepts during early product design and development. Sustainability 12, 1–25. https://doi.org/10.3390/su12229353.

Aromataris, E., Pearson, A., 2014. SYSTEMATIC REVIEWS, Step by Step the Systematic Review: an Overview, vol. 114. The Joanna Briggs Institute.

Arsova, S., Genovese, A., Ketikidis, P.H., 2022. Implementing circular economy in a regional context: a systematic literature review and a research agenda. J. Clean. Prod. 368. https://doi.org/10.1016/j.jclepro.2022.133117.

Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., Calabretta, G., 2019. Industrial symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives. J. Clean. Prod. 216, 446–460. https://doi.org/10.1016/j.jclepro.2019.01.091.

Bekele, W.B., Ago, F.Y., 2022. Sample size for interview in qualitative research in social sciences: a guide to novice researchers. Research in Educational Policy and Management 4, 42–50. https://doi.org/10.46303/repam.2022.3.

Bracquené, E., Dewulf, W., Duflou, J.R., 2020. Measuring the performance of more circular complex product supply chains. Resour. Conserv. Recycl. 154. https://doi.org/10.1016/j.resconrec.2019.104608.

Bryman, A., Bell, E., 2011. Business Research Methods, third ed. Oxford University Press, Oxford, UK.

Cayzer, S., Griffiths, P., Beghetto, V., 2017. Design of indicators for measuring product performance in the circular economy. Int. J. Sustain. Eng. 10, 289–298. https://doi.org/10.1080/19397038.2017.1333543.

Creswell, J.W., Poth, C.N., 2016. Qualitative Inquiry & Research Design: Choosing Among Five Approaches, fourth ed. Sage Publications, Thousand Oaks, California.

Davis, W.S., 1998. HIPO (hierarchy plus input-process-output). In: Davis, S.W., Yen, D.C. (Eds.), The Information System Consultant's Handbook: Systems Analysis and Design. CRC press, Boca Raton, pp. 503–510. https://doi.org/10.1201/9781420049107.

de Oliveira, C.T., Mônica, M.M.M., Campos, L.M.S., 2019. Understanding the Brazilian expanded polystyrene supply chain and its reverse logistics towards circular economy. J. Clean. Prod. 235, 562–573. https://doi.org/10.1016/j.jclepro.2019.06.319.

de Oliveira, C.T., Oliveira, G.G.A., 2023. What circular economy indicators really measure? An overview of circular economy principles and sustainable development goals. Resour. Conserv. Recycl. 190. https://doi.org/10.1016/j.resconrec.2022.106850.

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: the 61 indicators. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.124942.

De Pascale, A., Di Vita, G., Giannetto, C., Ioppolo, G., Lanfranchi, M., Limosani, M., Szopik-Depczyńska, K., 2023. The circular economy implementation at the european union level. Past, present and future. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2023.138658.

Deng, J., Huang, S., Wang, L., Deng, W., Yang, T., 2022. Conceptual framework for smart health: a multi-dimensional model using IPO logic to link drivers and outcomes. Int. J. Environ. Res. Publ. Health 19. https://doi.org/10.3390/ijerph192416742.

Ellen MacArthur Foundation and Granta Design, 2015. Circularity Indicators - an Approach to Measuring. Accessed 23rd October 2024.

Eurostat, 2023. Circular economy monitoring framework. https://ec.europa.eu/eurostat/web/circular-economy/overview. Accessed 4 June 2025.

Foroozanfar, M.H., Imanipour, N., Sajadi, S.M., 2022. Integrating circular economy strategies and business models: a systematic literature review. Journal of Entrepreneurship in Emerging Economies. https://doi.org/10.1108/JEEE-10-2021-0411.

Garcia-Saravia Ortiz-de-Montellano, C., Samani, P., van der Meer, Y., 2023. How can the circular economy support the advancement of the sustainable development goals (SDGs)? A comprehensive analysis. Sustain. Prod. Consum. 40, 352–362. https://doi.org/10.1016/J.SPC.2023.07.003.

Geisendorf, S., Pietrulla, F., 2018a. The circular economy and circular economic concepts—a literature analysis and redefinition. Thunderbird Int. Bus. Rev. 60, 771–782. https://doi.org/10.1002/tie.21924.

Geisendorf, S., Pietrulla, F., 2018b. The circular economy and circular economic concepts—a literature analysis and redefinition. Thunderbird Int. Bus. Rev. 60, 771–782. https://doi.org/10.1002/tie.21924.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Gomis, K., Kahandawa, R., Jayasinghe, R.S., 2023. Scientometric analysis of the global scientific literature on circularity indicators in the construction and built environment sector. Sustainability (Switzerland) 15 (1). https://doi.org/10.3390/su15010728.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: an assessment of material flows, waste production, and recycling in the European union and the world in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/jiec.12244.

Hennink, M., Hutter, I., Bailey, A., 2020. Qualitative Research Methods, second ed. Sage Publications, London, England.

Joshi, A., Kale, S., Chandel, S., Pal, D., 2015. Likert scale: explored and explained. Br. J. Appl. Sci. Technol. 7, 396–403. https://doi.org/10.9734/bjast/2015/14975.

Kahandawa, R.K.A.V.D., Domingo, N.D., Chawynski, G., Uma, S.R., 2021. Earthquake damage repair loss estimation in New Zealand: what other variables are essential based on experts' opinions? Buildings 11. https://doi.org/10.3390/buildings11090385.

Kamil, A., Izz, M., Ismail, N.A.A., Hassan, A.A., Rooshdi, R.R.R.M., Marhani, M.A., 2022. Satisfaction of quantity surveying students towards online distance learning (ODL) during Covid-19 pandemic. Asian Journal of University Education 18, 422–429. https://doi.org/10.24191/ajue.v18i2.17996.

Kevin van Langen, S., Vassillo, C., Ghisellini, P., Restaino, D., Passaro, R., Ulgiati, S., 2021. Promoting circular economy transition: A study about perceptions and awareness by different stakeholders groups. J. Clean. Prod. 316. https://doi.org/10.1016/j.jclepro.2021.128166.

Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2022.131859.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P.A., Clarke, M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. PLoS Med. 6.

Linåker, J., Papatheocharous, E., Olsson, T., 2022. How to characterize the health of an open source software project? A snowball literature review of an emerging practice. In: ACM International Conference Proceeding Series. Association for Computing Machinery. https://doi.org/10.1145/3555051.3555067.

MacCuspie, R.I., Hyman, H., Yakymyshyn, C., Srinivasan, S.S., Dhau, J., Drake, C., 2014. A framework for identifying performance targets for sustainable nanomaterials. Sustain. Mater. Technol. 1, 17–25. https://doi.org/10.1016/j.susmat.2014.11.003.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Br. Med. J. https://doi.org/10.1136/bmj.b2535.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: a proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002.

Ogunmakinde, O.E., Sher, W., Egbelakin, T., 2021. Circular economy pillars: a semi-systematic review. Clean Technol. Environ. Policy 23, 899–914. https://doi.org/10.1007/S10098-020-02012-9/TABLES/1.

Oliveira, C.T. De, Eduardo, T., Dantas, T., Soares, S.R., 2021. Nano and Micro Level Circular Economy Indicators : Assisting decision-makers in Circularity Assessments, vol. 26, pp. 455–468. https://doi.org/10.1016/j.spc.2020.11.024.

Oluleye, B.I., Chan, D.W.M., Antwi-Afari, P., Olawumi, T.O., 2023. Modeling the principal success factors for attaining systemic circularity in the building construction industry: an international survey of circular economy experts. Sustain. Prod. Consum. 37, 268–283. https://doi.org/10.1016/j.spc.2023.03.008.

Pilipenets, O., Gunawardena, T., Hui, F.K.P., Mendis, P., Aye, L., 2025. A novel circular economy framework: assessing process circularity through resource flow and emissions analysis. Resour. Conserv. Recycl. 215. https://doi.org/10.1016/j.resconrec.2024.108083.

Poolsawad, N., Chom-in, T., Samneangngam, J., Suksatit, P., Songma, K., Thamnawat, S., Kanoksirirath, S., Mungcharoen, T., 2023. Material circularity indicator for accelerating low-carbon circular economy in Thailand's building and construction sector. Environ. Prog. Sustain. Energy 42. https://doi.org/10.1002/ep.14105.

Rossi, E., Bertassini, A.C., Ferreira, C. dos S., Neves do Amaral, W.A., Ometto, A.R., 2020. Circular economy indicators for organizations considering sustainability and business models: plastic, textile and electro-electronic cases. J. Clean. Prod. 247. https://doi.org/10.1016/j.jclepro.2019.119137.

Saadé, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., Roux, C., 2022. Combining circular and LCA indicators for the early design of urban projects. Int. J. Life Cycle Assess. 27, 1–19. https://doi.org/10.1007/s11367-021-02007-8.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling 2. https://doi.org/10.3390/recycling2010006.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.10.014.

Saunders, M., Lewis, P., Thornhill, A., 2019. Research Methods for Business Students, eighth ed. Pearson Education, Harlow, England.

Schröder, P., Barrie, J., 2024. How the circular economy can revive the sustainable development goals: priorities for immediate global action, and a policy blueprint for the transition to 2050. https://doi.org/10.55317/9781784136222.

Silvestri, C., Silvestri, L., Piccarozzi, M., Ruggieri, A., 2024. Toward a framework for selecting indicators of measuring sustainability and circular economy in the agri-food sector: a systematic literature review. Int. J. Life Cycle Assess. 29, 1446–1484. https://doi.org/10.1007/s11367-022-02032-1.

Wasserbaur, R., Sakao, T., Milios, L., 2022. Interactions of governmental policies and business models for a circular economy: a systematic literature review. J. Clean. Prod. 337, 130329. https://doi.org/10.1016/J.JCLEPRO.2021.130329.

Wnuk, K., Garrepalli, T., 2018. Knowledge management in software testing: a systematic snowball literature review. E-Informatica Software Engineering Journal. https://doi.org/10.5277/e-Inf180103.

World Business Council for Sustainable development (WBCSD), 2024. Global Circularity Protocol for Business: Landscape Analysis: Corporate Performance & Accountability, and Policy & Regulations.

World Business Council for Sustainable development (WBCSD), 2018. Circular Transition Indicators (CTI) → Sector Guidance - Electronic Devices. https://www.wbcsd.org/resources/circular-transition-indicators-cti-sector-guidance-electronic-devices/. Accessed 4 June 2024.