Advancing Circular Economy Practices: A Literature Review of Micro-Level Indicators and Recovery Strategies

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Abstract: Transitioning from a linear economic model to a more circular one underscores the need for effective monitoring tools to track the impact of adopted changes and support ongoing improvement processes. In response, many tools have been proposed, including user-friendly indicators, to gauge progress towards a Circular Economy (CE). These tools offer various classifications that assess the efficacy of CE across different scales: micro-level for individual products and companies, meso-level for industrial symbiosis systems and eco-parks, and macro-level for governmental entities at national, regional, and municipal levels. While much attention in the literature focuses on macro and meso-level indicators, there's a gap in exploring the practical contributions of micro-level indicators, leaving few actionable insights for business practitioners. Simultaneously, to ease the integration of CE practices, several frameworks have been proposed. These frameworks, categorized under different CE recovery (R) strategies, encompass primary approaches for intelligent product use and production, extending product and component lifespans, and optimizing material utilization. To provide practical tools for CE monitoring and enhancement, this study proposes a systematic literature review of the key most recent micro-level indicators based on 15 revised manuscripts. These indicators align with the strategies of the 9R framework (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) and the triple bottom line (TBL) approach to economic, environmental, and social sustainability. Results reveal that these micro-level indicators, while valuable, lack standardization and exhibit a diverse range of complexities. Some indicators focus on specific R strategies, like recycle and reuse, making them less accessible to companies not already engaged in such practices. Additionally, within the TBL framework, there's an observed trend towards economic and environmental sustainability, gaining emphasis also on the social dimension.

Keywords: Circular Economy, Micro level, Indicator, 9R framework, Literature review.

1. Introduction

In a world facing increasing resource limitations, there is a growing interest among governmental bodies, businesses, and consumers in strategies that prevent product disposal and raw material waste. This interest has driven a shift towards circular economy (CE) practices, which represent a departure from the unsustainable linear model of take-make-dispose towards the circular principles of reduce, reuse, and recycle (Neves and Marques, 2022). This transition is not just about conserving natural resources, energy, and fluids; it also aims to reduce carbon footprint. Moreover, embracing a CE approach offers economic benefits, including cost savings, enhanced efficiency, and the creation of new business opportunities. However, despite numerous studies exploring the environmental and economic impacts of CE principles, the social dimension at the micro-level remains largely unexplored (Scarpellini, 2022).

Global initiatives such as the United Nation's Sustainable Development Goals and a growing recognition of the need for sustainable practices further bolster interest in the CE. However, ongoing debates about its conceptualization have hindered the development of standardized indicators, leading to contradictions and implementation challenges (Milios, 2018). Scholars argue that the literature lacks substantial information about the theory and methodology required to implement CE (Kusumo et al., 2022). To address this gap, there's a need for the development of measurement and improvement tools for CE adoption (Ferraro et al., 2024). The existing literature has proposed various indicators based on different lifecycle stages (Vural Gursel et al., 2023). However, due to the complexity of the CE, a singular measure is not sufficient, and instead, multi-dimensional indicators are provided (Rossi et al., 2020) Therefore, alongside quantitative indicators that represent circularity through a single number, analytical tools and composite indicators have been proposed. The former categorizes circularity using guidelines, tools, or models and provides qualitative assessments, while the latter combines quantitative indicators and analytical tools (Matos et al., 2023).

At a hierarchical level, Kirchherr et al., (2017) proposed a classification of the CE based on the level of application, defining micro-level approaches for the adoption of CE within products, processes, and organizations, meso-level approaches for symbiotic systems and eco-industrial parks, and macro-level approaches for governmental entities at national, regional, and municipal levels. Similarly, studies on CE indicators have explored theoretical and practical aspects under this classification

(Kristensen and Mosgaard, 2020). However, the current state of research indicates a lack of in-depth investigation into CE assessment and indicators, particularly at the micro level (Elia et al., 2017). In addition to the limitations of studies on micro-level CE indicators, proposed tools exhibit heterogeneity in terms of content, length, and number of questions, and they often fail to incorporate the specific characteristics of different organizational sectors. Similarly, authors argue that the problem extends beyond sectors to products, as some tools are excessively narrow, focusing on only a few aspects of the entire product life cycle, which hampers the practitioners' adoption (Matos et al., 2023).

While some authors have delved into this concept in the literature, the majority of reviews tend to be critical without following a systematic methodological approach (de Oliveira and Oliveira, 2023; Jerome et al., 2022; Khadim et al., 2022; Kristensen and Mosgaard, 2020). Furthermore, although significant interest has been directed towards evaluating the relationship between CE and sustainability pillars through the Triple Bottom Line (TBL) framework (Elkington, 1998), few studies have comprehensively explored CE recovery (R) strategies using the framework proposed by Potting et al. (2017). Known as the 9R framework, it serves as a reference for CE strategies, classifying approaches based on the level of circularity into primary approaches for intelligent product use and production, extending product and component lifespans, and optimizing material utilization. More in detail, the 9R framework considers the CE strategies of refuse (R0), rethink (R1), reduce (R2), reuse (R3), repair (R4), refurbish (R5), remanufacture (R6), repurpose (R7), recycle (R8), recovery (R9). Based on the above, the objective of this study is to investigate, through a systematic literature review (SLR), the key most recent literature on quantitative micro-level indicators for evaluating the CE, as well as R strategies and sustainability pillars. The remainder of the paper is structured as follows. Section 2 analyses the methodology used for conducting the literature review. Section 3 reports the results within an in depth-discussion. To conclude, the conclusions are drawn and future directions are provided.

2. Methodology

Within this study, a literature review is conducted using the SLR methodology proposed by (Tranfield et al., 2003). The objective of the study is precisely to address three research questions (RQs) to investigate the relationships between micro-level indicators, CE strategies, and sustainability pillars.

RQ1) What are the most extensively and recently researched micro-level indicators?

RQ2) Which CE strategies have received the most attention in research?

RQ3) Which sustainability pillars are the focus of the majority of studies?

This study focuses on technical, non-biological cycles expressed by quantitative and/or composite indicators to assess the CE of products, processes, and organizations. Articles not meeting these criteria were not considered for inclusion in the study.

To achieve this objective, keywords were initially identified using a search string composed of keywords and Boolean operators. As shown in Table 1, the search string is divided into three semantic areas linked by AND operators, within which the keywords used are connected by OR operators. The three semantic areas encompass keywords related to CE (Semantic Area 1), indicators and measurement tools (Semantic Area 2), and the level of utilization, which in this case is micro-level (Semantic Area 3). Additionally, the operator " was used to fix the order of words enclosed within it, and the operator * was used to identify word variants sharing the same root.

Table 1: Search keywords and classification for SLR

Semantic Area 1	Semantic Area 2	Semantic Area 3
"circular economy"	indicator	"micro level"
"CE"	kpi	"nano level"
"circular supply chain "	"key performance indicator"	
	index	
	assess*	
	measur*	

Figure 1 illustrates the SLR methodology conducted through the PRISMA diagram. From the initial pool of 104 articles identified by the search string, the application of inclusion criteria narrowed the analysis down to 61 manuscripts. In the screening phase, all articles that did not meet the following inclusion criteria were excluded:

- Papers belonging to the subject area of "environmental science", "engineering", "energy", "business management and accounting", "social sciences", and "decision sciences";
- Papers classified as "article" and "conference paper" document type;
- Papers classified ad "journal" and "conference proceedings" source type;
- Paper classified as "final" publication stage
- Papers published between 2013 and 2024.

The remaining articles were then filtered based on title and abstract, and subsequently, full texts were reviewed. During the eligibility phase, 16 manuscripts were excluded. These exclusions were due to a lack of focus on indicators. Additionally, 10 manuscripts did not evaluate CE from a micro-level perspective, while 5 did not align with CE approaches. One manuscript considered biological cycles of consumed goods instead of technical cycles of materials used, and 8 presented comparisons of CE assessment tools. Furthermore, 5 manuscripts applied CE assessment tools, and 1 manuscript was unavailable for full-text reading. As a result of these exclusions, 15 manuscripts were included in this review to analyze micro-level CE indicators, their relationship with R strategies, and assessments of economic, environmental, and social sustainability (Table A1).

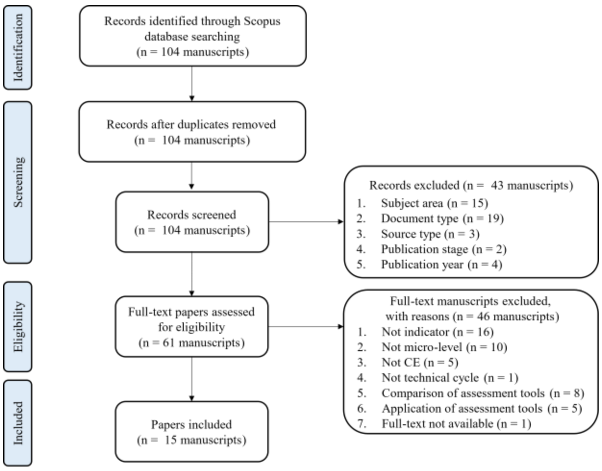

Figure 1: PRISMA diagram

3. Results

The 15 selected manuscripts were initially analyzed through a descriptive analysis and subsequently through content analysis to critically address the three RQs. The selected sample, predominantly consisting of articles (14) compared to conference papers (1), spans from 2020 to 2024, despite the inclusion criterion allowing for publications dated from 2013 onwards. Regarding journal types, all fall within the environmental sciences and industrial engineering domains, with Journal of Cleaner Production and Sustainability standing out with 3 publications each. Geographically, the majority of articles originate from researchers in Brazil, contributing 4 publications, followed by Canada, China, Denmark, Germany, and Spain, each with 2 publications.

To address RQ1, the 15 included articles were classified based on the analysis criteria of the number of CE strategies adopted and the number of sub-indicators evaluated (Table 2). These criteria aim to identify the generalizability of assessing CE at the micro-level through a greater number of recovery strategies, while also considering the complexity of indicator measurement. Additionally, since micro-level indicators encompass products, processes, and organizational elements, these concepts were analyzed in relation to other meso and macro levels.

Table 2: Analysis of complexity, generalizability, and relationships of CE micro-level indicators

Indicator	Sub-indicator	Strategy	Relationships
CE indicators	18	5	Micro
CE levels	13	2	Micro
Circularity Performance Index (CPI)	58	10	Micro
Economic Circularity (EC)	25	3	Micro
Building Circularity Indicator (BCI)	1	5	Micro, Meso
Resource Efficiency Account (REA)	7	3	Micro
CED	6	0	Micro, Meso, Macro
Product Circularity Indicator (PCI)	5	3	Micro
Circular Economy Indicator (CEI)	60	10	Micro
Comparative Circular Economy Assessment (CCEA)	22	2	Micro, Meso, Macro
Overall Circularity Effectiveness (OCE)	15	2	Micro
Circular Economy Performance Index (CEPI)	6	5	Micro
Circular Economy for Universities (CExUNV)	82	6	Micro, Meso
Local Circularity Rate (LCR)	33	2	Micro, Meso, Macro
Circular Economy and Circularity (CEC)	19	2	Micro, Mesi, Macro

As depicted in Figure 2, the majority of indicators tend to exhibit low levels of complexity in measurement and generalizability. Specifically, 12 indicators assess CE with fewer than 35 sub-indicators, of which 9 consider only 3 end-of-life strategies. On the other hand, only 3 indicators measure CE with a high level of generalizability, considering at least 6 end-of-life strategies. However, these indicators significantly increase measurement complexity, with the number of sub-indicators reaching 82 for the CExUNV index (Valls-Val et al., 2024), 60 for the CEI index (Kowalski et al., 2023), and 58 for the CPI index (Franco et al., 2021).

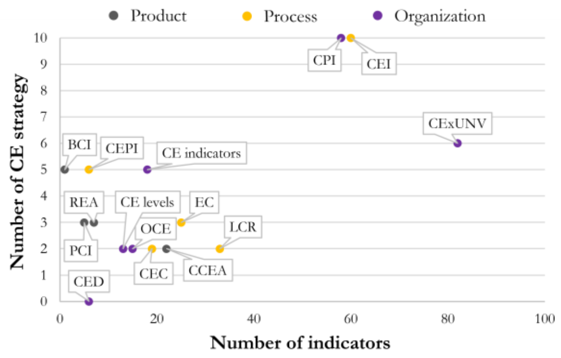

Figure 2: CE micro-level indicators

Regarding the scope of application, the results included in this review exhibit a consistent pattern in both quantity and temporal trend for assessing CE across products (in grey), processes (in yellow), and organizations (in purple), with 4, 5, and 6 studies respectively. Of particular interest is the relationship of micro-level indicators for assessing elements from both meso and macro perspectives, as shown in Figure 3. Despite the majority of studies evaluating CE solely from a micro-level perspective (9 out of 15 manuscripts), some studies allow for consideration of CE from both micro and meso perspectives (2 out of 15 manuscripts) (Cottafava and Ritzen, 2021; Valls-Val et al., 2024), as well as from micro, meso, and macro perspectives (4 out of 15 manuscripts) (Ahmed et al., 2022; Bai et al., 2024; Cui and Zhang, 2022; de Souza et al., 2024).

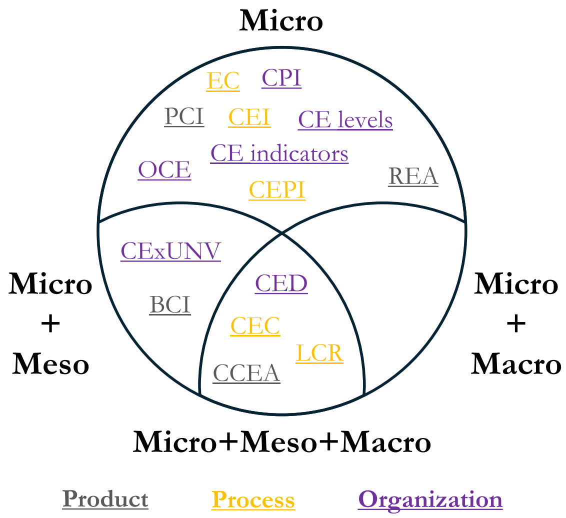

Figure 3: Level relationships

As highlighted, not all studies provide a comprehensive overview of CE strategies. Based on the 9R framework proposed by Potting et al. (2017), to answer RQ2 it is evident that the majority of studies focus on strategies with a medium level of circularity, categorized under the extend lifespan class, followed by those classified as useful application of materials class with a lower level of circularity. Upon closer examination of individual strategies, it becomes apparent that the most investigated strategies are recycle (in dark blue, with 14 out of 15 studies) and reuse (in yellow, with 12 out of 15 studies). However, despite researchers' significant contributions, strategies such as repair (in light green, with 6 publications out of 15) and remanufacture (in light blue, with 5 publications out of 15) remain relatively underexplored. Regarding the temporal evolution of strategies reported in Figure 4, despite the narrow time interval, there is a discernible trend towards a more comprehensive evaluation of CE, with an increasing number of strategies being considered over time.

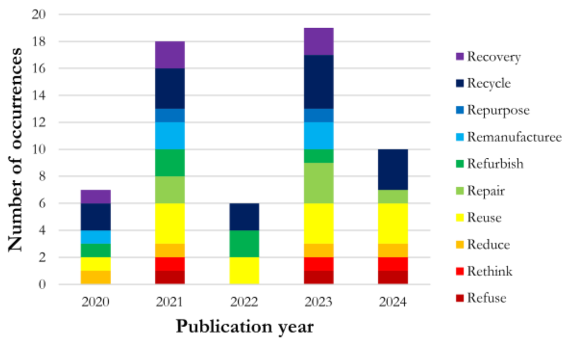

Figure 4: End-of-life strategies evolution

Finally, to address RQ3, the review examines how the 15 selected articles integrate sustainability pillars within the evaluation of CE using the TBL framework. Despite the confirmed findings from published reviews indicating limited integration of the social sustainability pillar, it is considered in more than half of the reviewed works (8 out of 15 studies), followed by environmental sustainability (13 out of 15 studies) and economic sustainability (14 out of 15 studies). This increasingly comprehensive contribution to sustainability is also evident temporally, with social sustainability being integrated into alternative assessments in recent years, as demonstrated in Figure 5.

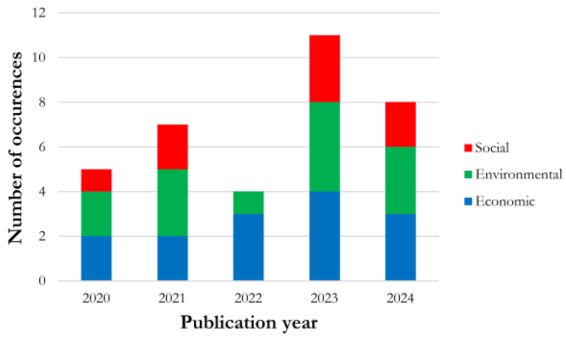

Figure 5: Sustainability pillars evolution

4. Conclusion

In response to growing resource constraints, there is increasing interest in CE practices, aimed at reducing waste and promoting sustainability. In the literature, various alternatives have been proposed, including micro-level indicators, which have received less attention compared to those at the meso and macro levels. This study conducted a SLR of 15 selected manuscripts to address the RQs concerning the most recent CE micro-level indicators, R strategies, and sustainability pillars. The results revealed insights into the generalizability and complexity of CE indicators. While most indicators exhibited low complexity and generalizability, some showed higher complexity and generalizability, albeit with increased measurement intricacy. Regarding CE strategies, the study highlighted the prevalence of strategies such as recycling and reuse, while also indicating a relative lack of exploration in repair and remanufacturing strategies. Finally, from a TBL perspective, while social sustainability integration lagged behind environmental and economic sustainability, recent years have witnessed an increasing consideration of social sustainability within CE assessments.

The proposed study makes significant contributions both theoretically and practically. Initially, employing a systematic methodological approach, it corroborates the primary findings of existing critical reviews in the literature. It accomplishes this by integrating an analysis of micro-level indicators with the 9R framework, shedding light on an emerging trend towards sustainability. This trend encompasses not only economic and environmental aspects but also social dimensions. From a practical standpoint, the study presents the latest micro-level indicators, offering comparisons in terms of complexity and generalizability. Additionally, it equips practitioners with the means to identify the most pertinent indicators based on their specific application context (product, process, or organization) and their interplay with meso and macro levels. In this regard, for the adoption of CE practices, practitioners can employ the most suitable micro-level indicators as descriptive, comparative, and prescriptive tools. As a descriptive tool, organizations can evaluate their state of circularity through an AS IS and TO BE scenario analysis. As a comparative tool, these assessments facilitate internal and external benchmarking. Furthermore, as a prescriptive tool, the adoption of these indicators can provide a foundation for identifying strengths and weaknesses, thereby enabling targeted improvements by uncovering opportunities in product, process, and organizational application contexts.

However, the study does have its limitations, which could be addressed in future research. Firstly, its methodological approach relies solely on a bibliographic review, which could benefit from supplementation with a bibliometric analysis to explore the temporal evolution and thematic classification across a broader sample. Secondly, while the focus is on analyzing micro-level indicators, there is potential to extend this analysis to include meso and macro-level indicators, incorporating insights from both scientific and grey literature. Lastly, the study exclusively examines quantitative indicators, overlooking analytical and composite ones, which could be integrated into future investigations.

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Appendix A

Table A1: CE micro-level indicators

Ref	Indicator	R strategy	TBL	Scope
(Rossi et al., 2020)	CE indication	R1, R3, R5, R6, R8	ECO, ENV, SOC	O
(Aranda-Usón et al., 2020)	CE levels	R8, R9	ECO, ENV	O
(Franco et al., 2021)	CPI	R0, R1, R2, R3, R4, R5, R6, R7, R8, R9	ECO, ENV, SOC	O
(Rukundo et al., 2021)	EC	R3, R8, R9	ECO, ENV, SOC	Ps
(Cottafava and Ritzen, 2021)	BCI	R3, R4, R5, R6, R8	ENV	Pr
(Halada et al., 2022)	REA	R3, R5, R8	ECO	Pr
(Cui and Zhang, 2022)	CED	-	ECO	O
(Bracquené et al., 2022)	PCI	R3, R5, R8	ECO, ENV	Pr
(Kowalski et al., 2023)	CEI	R0, R1, R2, R3, R4, R5, R6, R7, R8, R9	ECO, ENV, SOC	Ps
(Ahmed et al., 2022)	CCEA	R4, R8	ECO, ENV, SOC	Product
(Baumer-Cardoso et al., 2023)	OCE	R3, R8	ECO, ENV, SOC	O
(James et al., 2023)	CEPI	R3, R4, R6, R8, R9	ECO, ENV	Ps
(Valls-Val et al., 2024)	CExUNV	R0, R1, R2, R3, R4, R8	ECO, ENV, SOC	O
(de Souza et al., 2024)	LCR	R3, R8	ECO, ENV	Ps
(Bai et al., 2024)	CEC	R3, R8	ECO, ENV, SOC	Ps

R0: Refuse, **R1**: Rethink, **R2**: Reduce, **R3**: Reuse, **R4**: Repair, **R5**: Refurbish, **R6**: Remanufacture, **R7**: Repurpose, **R8**: Recycle, **R9**: Recover, **ECO**: Economic sustainability, **ENV**: Environmental sustainability, **SOC**: Social sustainability, **O**: Organization, **Ps**: Process, **Pr**: Product.