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CHALLENGES OF CIRCULAR ECONOMY ASSESSMENT TOOLS AT THE MICRO LEVEL: A BIBLIOMETRIC EXPLORATION AND SYSTEMATIC REVIEW

Desafios das ferramentas de avaliação da economia circular no nível micro: Uma exploração bibliométrica e revisão sistemática

Desafíos de las herramientas de evaluación de la economía circular a nivel micro: Un análisis bibliométrico y una revisión sistemática

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ABSTRACT

The degree of circularity is related to the progress of circular economy (CE), particularly at the level of products, materials, companies, and consumers. In this context, metrics, indicators and assessment models may not fully capture the complexities of the system and its relationships. Despite several analyses of indicators and proposals for evaluation methods, few studies discuss in depth their limitations and challenges for implementation at the micro level. This article aims to identify the limitations and challenges associated with performance assessment methodologies to verify CE progress at the micro level and propose a research agenda. The research design applied bibliometric analysis and a systematic literature review. Our results highlight five limitations, and the findings underscore that tools fail to embrace the systemic essence of CE. It represents a gap in assessment frameworks, highlighting the need for a more integrated and comprehensive approach to assessing the transition toward CE.

Keywords: circular economy, indicators, evaluation framework, limitations, sustainable development.

RESUMO

O grau de circularidade está relacionado com o avanço da economia circular (EC), ao nível dos produtos, materiais, empresas e consumidores. Neste contexto, diversas métricas, indicadores e modelos de avaliação podem não captar as complexidades do sistema e das suas relações. Apesar dos vários métodos de avaliação, poucos estudos discutem as suas limitações e desafios para a implementação no nível micro. Este artigo identifica as limitações e desafios associados às metodologias de avaliação para verificar o progresso da EC no nível micro e propor uma agenda de pesquisa. A pesquisa aplicou análise bibliométrica e revisão sistemática da literatura. Os resultados destacam cinco limitações, e as conclusões salientam que as ferramentas não conseguem abranger a essência sistêmica da EC. Isso representa uma lacuna nos modelos de avaliação, destacando a necessidade de uma abordagem integrada para avaliar a transição para a EC.

Palavras-chave: *economia circular, indicadores, estrutura de avaliação, limitações, desenvolvimento sustentável.*

RESUMEN

El grado de circularidad está relacionado con el avance de la economía circular (EC), a nivel de productos, materiales, empresas y consumidores. En este contexto, es posible que diversas métricas, indicadores y modelos de evaluación no capturen las complejidades del sistema y sus relaciones. A pesar de varios métodos de evaluación, pocos estudios discuten sus limitaciones y desafíos para su implementación a nivel micro. Este artículo identifica las limitaciones y desafíos asociados con las metodologías de evaluación para verificar el progreso de la EC a nivel micro y proponer una agenda de investigación. La investigación aplicó análisis bibliométrico y revisión sistemática de la literatura. Los resultados resaltan cinco limitaciones y los hallazgos subrayan que las herramientas no logran abarcar la esencia sistémica de la EC. Eso representa una brecha en los marcos de evaluación, lo que destaca la necesidad de un enfoque integrado para evaluar la transición hacia la EC.

Palabras clave: economía circular, indicadores, marco de evaluación, limitaciones, desarrollo sostenible.

INTRODUCTION

An emerging paradigm gaining traction as an alternative to the linear economic model of extract-produce-dispose is Circular Economy (CE). CE offers a sustainable framework for economic operation, aiming to eradicate waste, optimize resource utilization, and mitigate adverse impacts through systemic innovations while concurrently enhancing economic, environmental, and social capital (Garcia-Saravia Ortiz-de-Montellano & van der Meer, 2022). In recent years, there has been a discernible surge in interest in transitioning from the prevailing linear economic model to CE (Valls-Val et al., 2023). However, adopting this approach presents complex challenges, encompassing meeting diverse stakeholder needs, developing new business models, and implementing more innovative production and consumption techniques (Cimpan et al., 2023).

The challenges inherent in implementing CE demonstrate the need for specific methodologies to evaluate CE transition across various contexts. Indicators and analytical tools are crucial in distilling relevant information to facilitate improvements and provide a comprehensive understanding of the system (Singh et al., 2012). Developing such assessment tools is pivotal for evaluating CE adoption (Saidani, 2018). These tools monitor and check the advancement of specific systems or processes (Oliveira et al., 2021).

Several researchers have addressed this issue, offering diverse methodologies for assessing the impacts or progress of CE (Droege et al., 2021; Elia et al., 2017; Garcia-Saravia Ortiz-de-Montellano & van der Meer, 2022; Sassanelli et al., 2019; Superti et al., 2021; Vinante et al., 2021). However, despite the indicators and methods outlined in the literature, the proposed approaches remain partially satisfactory. According to Rincón-Moreno et al. (2021), existing assessment tools fail to provide a comprehensive outlook on CE, its principles, and its interconnectedness with sustainable development. Assessing progress toward adopting circular practices requires suitable and applicable tools and methodologies; however, this remains elusive in practice (Cimpan et al., 2023).

Circularity has emerged as a guiding principle increasingly adopted by companies, industries, and policymakers as they strive toward broader sustainability objectives. The levels of circularity are intricately linked to CE progress, with the micro level encompassing products, their constituent materials, companies, and consumers (Franklin-Johnson et al., 2016). Given its complexity, various metrics designated as indicators may not fully capture the system's intricacies and could yield divergent interpretations (Roos Lindgreen et al., 2020). Currently, there is a lack of universally accepted metrics capable of assessing both circularity's efficiency and causal effects (Cimpan et al., 2023). Despite several analyses of indicators and proposals for assessment methods (Corona et al., 2019; De Pascale et al., 2021; Kristensen & Mosgaard, 2020; Nowaczek et al., 2023; Papageorgiou et al., 2021; Roos Lindgreen et al., 2020), few studies discuss their limitations and challenges for implementation at the micro level in depth. Thus, the research question is: how does previous literature lead the assessment frameworks and indicators, explicitly examining

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the limitations and challenges in evaluating CE systems at the micro level? This paper aims to identify the limitations and challenges associated with performance assessment methodologies tailored to check CE systems at the micro level, focusing on products, their materials, and companies and propose a research agenda.

CIRCULAR ECONOMY

The concept of CE is rooted in various interconnected domains. In 1966, Boulding conceptualized the Earth as a closed, circular system with finite assimilation capabilities, significantly influencing subsequent discourse (Boulding, 1966). Building upon this foundation, Stahel and Reday (1976) furthered the discourse by introducing elements of CE, with a particular focus on the industrial economy. They delineated the concept of a closed-loop economy to encapsulate industrial strategies aimed at waste reduction, regional employment generation, resource maximization, and diminished reliance on materials within the industrial framework.

From 1980 onward, the term 'Circular Economy' appeared in the literature, aiming to characterize a closed system of interactions between the economy and the environment (Pearce & Turner, 1990). Since its inception, the contemporary understanding of CE has evolved to encompass a spectrum of facets and contributions from various concepts that share the fundamental notion of closed loops. Noteworthy among these theoretical influences are regenerative design (Lyle, 1994), industrial ecology (Graedel & Allenby, 1995), biomimetics (Benyus, 2002), the cradle-to-cradle concept (McDonough & Braungart, 2002), and performance and circuit economics (Stahel, 2010). Furthermore, a significant contributor to the conceptualization and dissemination of CE is the Ellen MacArthur Foundation, which gained prominence through the report titled 'Towards the Circular Economy: Accelerating the Scale-up across Global Supply Chains,' launched at the World Economic Forum. This report heightened global awareness regarding CE, emphasizing its economic, environmental, and social benefits while exemplifying successful implementation (Ellen MacArthur Foundation, 2014).

CE has emerged to address urgent global challenges, notably resource scarcity and waste management (Reike et al., 2018). This perspective contrasts with the linear system, where natural resources are extracted, used in producing goods and services, and discarded as waste (i.e., take-make-waste), predominantly resulting in environmental degradation and natural resource depletion. However, this linear approach is increasingly unsustainable for both present and future generations, as natural resources are finite, and the generated waste has a significant environmental impact (Elia et al., 2017). Although CE has garnered considerable attention across various domains and may appear as a relatively straightforward concept, it still evokes bewilderment among stakeholders. This stems from the ambiguity of its definition, its global and universal scope, and the need for more specificity in its application (Kirchherr et al., 2017).

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According to some authors, CE is considered an umbrella concept, as it encompasses different approaches, strategies, and practices to transition the current economic system to a circular one (Homrich et al., 2018; Moraga et al., 2019). Essentially, CE constitutes an economic model predicated on business methodologies that supplant the conventional 'end-of-life' notion with the reduction, alternative reuse, recycling, and recovery of materials across production, distribution, and consumption processes, thereby fostering equilibrium among environmental integrity, economic prosperity, and social equity, to serve both present and future generations (Kirchherr et al., 2017). This approach engenders environmental conservation, enhances resource efficiency, and facilitates the establishment of sustainable economic avenues (Murray et al., 2017). CE endeavors to advance sustainable development through innovation and systemic transformation across three distinct levels: the micro level, the meso level, and the macro level (Ellen Macarthur Foundation, 2014; Saidani et al., 2019).

The three systemic levels delineate the hierarchical dimensions wherein CE principles are operationalized. While subject to variability across the scholarly discourse, these levels generally delineate as follows: the micro level pertains to entities such as products, firms, or consumers; the meso level encompasses eco-industrial parks and industrial symbiosis initiatives; and the macro level encompasses municipalities, provinces, regions, or nations (Kirchherr et al., 2017). Precision in delineating the scope of analysis—whether focusing on individual consumers, products, municipalities, regions, or global contexts—is imperative for a nuanced comprehension of CE endeavors across diverse settings. Kuzma et al. (2021) argue that the micro level can be further dissected into analytically coherent units, progressing from the broader category (products) to the most elemental unit (materials), contingent upon the nature of the evaluated actions. Based on the understanding of the principles of CE, it is crucial to implement specific strategies to achieve circularity.

Circularity strategies

The R-strategies, also called R-frameworks, entail strategies directed toward waste minimization, resource optimization, and the extension of product and material lifespans (Potting et al., 2017). The configurations of EC R-strategies vary, encompassing models such as 3Rs, 4Rs, or 6Rs (Reike et al., 2018), with diverse sequences employed and organized according to priority (de Oliveira & Oliveira, 2023). The 'Rs' are sequenced contingent upon the level of circularity inherent in the product or material. The 9Rs (Table 1) are most congruent with the thematic focus of this research, as they encompass multiple levels of circularity.

Identifying and defining key metrics that align with circularity goals is essential to reflect the performance of circularity strategies (Cimpan et al., 2023). Businesses can track and enhance their CE initiatives by linking circularity strategies and measurable metrics, leading to more sustainable and resilient operations (Garcia-Saravia Ortiz-de-Montellano & van der Meer, 2022).

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Table 1. 9Rs Strategies

Circularity Level	Strategy	Objective
Smarter product usage and manufacturing	R0 – Refuse	Make the product obsolete either by discontinuing its function or delivering the same function through a substantially different product.
	R1 – Rethinking	Increase product utilization by encouraging product sharing or introducing multifunctional products to the market.
	R2 – Reduce	Enhance efficiency in manufacturing or product utilization by reducing the consumption of natural resources and materials.
Extending the lifespan of products and their constituent components	R3 – Reuse	Another consumer reusing a discarded product that remains in good condition and serves its original purpose.
	R4 – Repair	Repair and maintain the defective product to restore its original functionality.
	R5 – Refurbish	Revitalize an outdated product by modernizing it.
	R6 – Remanufacture	Incorporate components from the discarded product into a new product with identical functionality.
	R7 – Repurpose	It utilizes the discarded product or its components in a new product serving a different purpose.
Effective utilization of materials	R8 – Recycle	Processing materials to achieve equivalent quality or reduced quality.
	R9 – Recover	Burning materials with energy recuperation.

Source: Elaborated by authors based on Potting et al., (2017).

Indicators and metrics in a circular economy

Saidani et al. (2019) state that indicators assume a significant role as valuable analytical instruments, simplifying intricate information. Indicators primarily aim to track, monitor, and quantify the progress and efficacy of systems or processes (de Oliveira et al., 2021). Indicators and their metrics emerge as fundamental methodologies in checking the advancements of CE, providing insights for policy and strategy development, and identifying and assessing impacts arising from its implementation (Valls-Val et al., 2023). However, the determination of 'what to measure' remains a subject of intense debate (Moraga et al., 2019).

Despite the emergence of numerous indicators, metrics, and evaluation tools for CE in recent years, research and discussion persist (De Pascale et al., 2021). For companies, indicators are invaluable, serving internal purposes such as progress tracking and evaluation of potential shifts

in product portfolios and external functions, including benchmarking and communication with customers and suppliers (Saidani et al., 2019). Regarding sustainable development, the formulation of monitoring metrics designed to assess progress toward CE is undergoing extensive deliberation (Elia et al., 2017; Pauliuk, 2018). Recent endeavors to establish universal metrics diverge in their objectives and scopes, resulting in broad coverage and varied focus (Iacovidou et al., 2017). The recommendation is to adopt a set of indicators to ensure a comprehensive approach to CE strategies (Moraga et al., 2019). However, further research must discern the complementarity among existing indicators (Parchomenko et al., 2019).

The advancement and estimate of circularity, alongside monitoring circular processes, necessitate pragmatic, easily comprehensible, and sustainable indicators over time (scalable) (Iacovidou et al., 2019). Comprehensive sustainability assessments should augment these indicators. Moreover, sustainability assessments should account for recovery effects and compensations (Cimpan et al., 2023). Developing tools to measure CE is pivotal, ensuring that the circular strategies and practices implemented yield positive environmental and societal impacts (Saadé et al., 2022). Thus, it becomes pertinent to identify the limitations of evaluation methods, enabling the proposition of strategies to mitigate them.

This study assumes that CE is a multidimensional concept with limited application at the micro level. While circularity strategies offer a structured approach to resource optimization and waste reduction, the methods for measuring their performance remain fragmented. Indicators and metrics to evaluate circularity are crucial to tracking CE progress, but current tools must not capture the full complexity of circular systems. This limitation impacts the usefulness of indicators for companies and policymakers as they adjust their strategies. Closing these gaps is crucial for achieving more precise and meaningful circularity measurements.

METHODOLOGY

This article aims to identify the limitations and challenges associated with performance assessment methodologies to verify CE progress at the micro level and propose a research agenda. Thus, this study's review model employed quantitative and qualitative approaches in two stages: bibliometric analysis and content analysis (Piao et al., 2023). Bibliometric methods offer a quantitative means to describe, assess, and identify published research, and they are particularly helpful in systematic reviews as they allow for the objective mapping of a research field (Piao et al., 2023; Zupic & Čater, 2015). Bibliometric analysis emerges as a foundational tool to achieve the empirical objective, enabling the quantification of advancements within a specific thematic area (Bellis, 2009). Bibliometric methodologies have been leveraged to furnish metrics that enhance the analysis of systematic literature review (SLR). The SLR contributes to formulating content analysis for data coding and categorization (Bardin, 1986). These approaches intertwine, bringing complementary advantages (Donthu et al., 2021).

Stage 1 - Bibliometric

The bibliometric analysis follows the three steps outlined by Tranfield et al. (2003): (1) Review planning, (2) Review execution, and (3) Reporting and dissemination.

Step 1 – Review planning

The research question was formulated during this step, and the review protocol was created.

Step 2 – Review execution

Table 2 shows the keyword groups and the search protocol used in the Web of Science and Scopus databases, aggregating scientific publications from various journals and offering centralized access to a broad spectrum of current international literature.

Table 2. Search Protocol

Period	**Without a temporal scope**
Document Type	Articles, Reviews
Keywords	Group 1: metrics, indicators, assessment, circular*, circular economy Group 2: metrics, indicators, assessment, circular*, circular economy, framework Group 3: Indicators, assessment, circular*, circular economy, framework
Boolean Operator	AND between search terms. OR between groups.
Database	Web of Science and Scopus
Language	English
Search Fields	Title, abstract, and keywords

The keywords were carefully selected based on preliminary exploratory searches and refined through discussions among the research team to ensure they aligned with the scope of the study. This study uses a systematic review method that follows a scientific, transparent, and replicable approach (Tranfield et al., 2003).

Step 3 – Reporting and dissemination

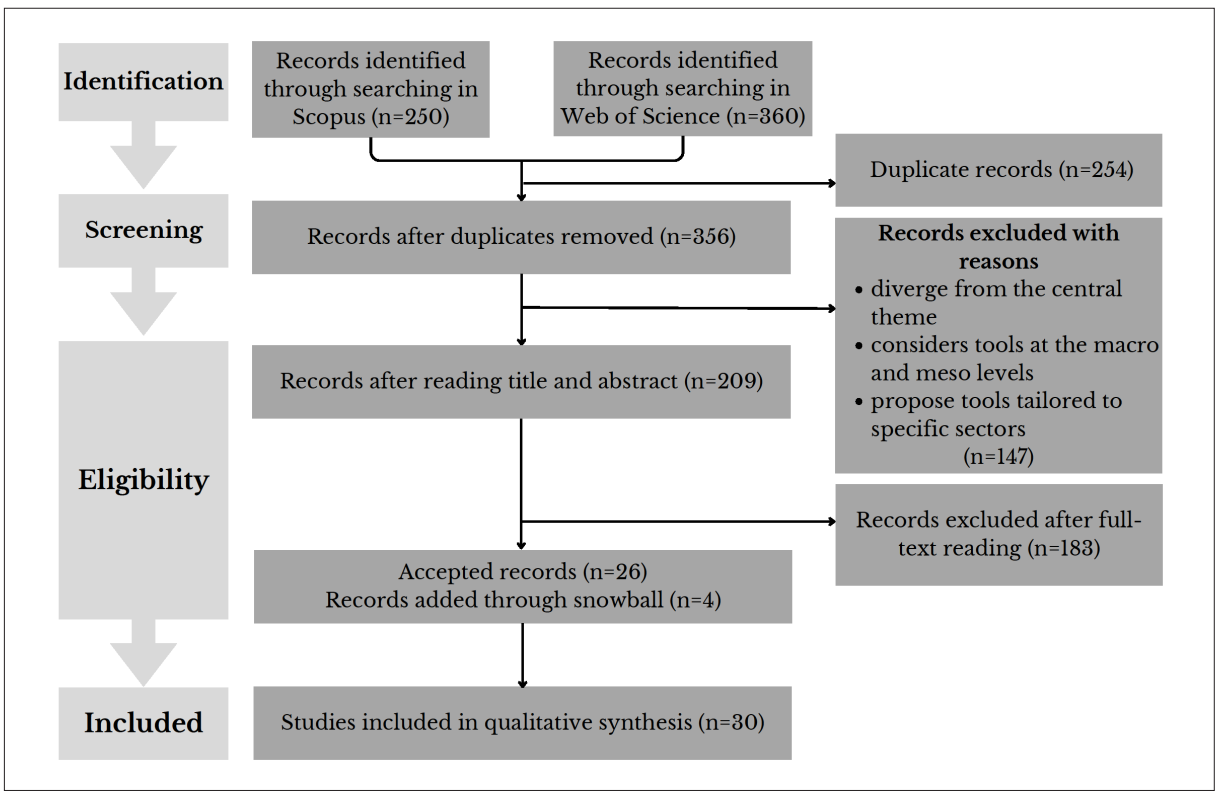
We used the RStudio software (version 4.3.2) and the Bibliometrix and Bibliosiny packages to extract specific bibliometric parameters (Aria & Cuccurullo, 2017). These parameters include the number of articles per annum, which delineates the evolution of production over time,

scientific contributions by country, facilitating the identification of the most prolific countries in publications, and thematic evolution, aiding in comprehending the progression and alteration of themes, concepts, and approaches across the analyzed timeframe.

Stage 2 – Content analysis

For literature selection, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was implemented (Moher et al., 2010). Furthermore, leveraging a reference network, the snowball technique was employed (Naderifar et al., 2017). Figure 1 provides an overview of the distinct stages of acquiring and selecting literature.

Figure 1. PRISMA Flowchart for Article Selection for Content Analysis



Initially, a total of 610 articles were retrieved from the databases. The first exclusion criterion involved eliminating duplicates, resulting in the exclusion of 254 documents. Following the approach suggested by de Oliveira et al. (2023) to minimize errors and researcher bias, two researchers independently verified the data based on predefined criteria, with an additional review conducted by a third researcher. Articles not focusing on CE assessment tools were excluded first, accounting for 107 documents. Subsequently, articles addressing assessment tools at the macro and meso levels were omitted, excluding 9 and 8 documents, respectively. Thirdly, articles proposing tools for specific sectors were excluded, totaling 22. Fourthly, the

remaining documents were scrutinized based on the following criteria: articles proposing tools or indicators at the micro level aligned with the objectives concerning R-strategies and dimensions of CE. Following the examination of the content of these articles, a total of 26 documents were deemed relevant. Four additional documents were identified through the snowball technique, culminating in the inclusion process and resulting in 30 articles for analysis.

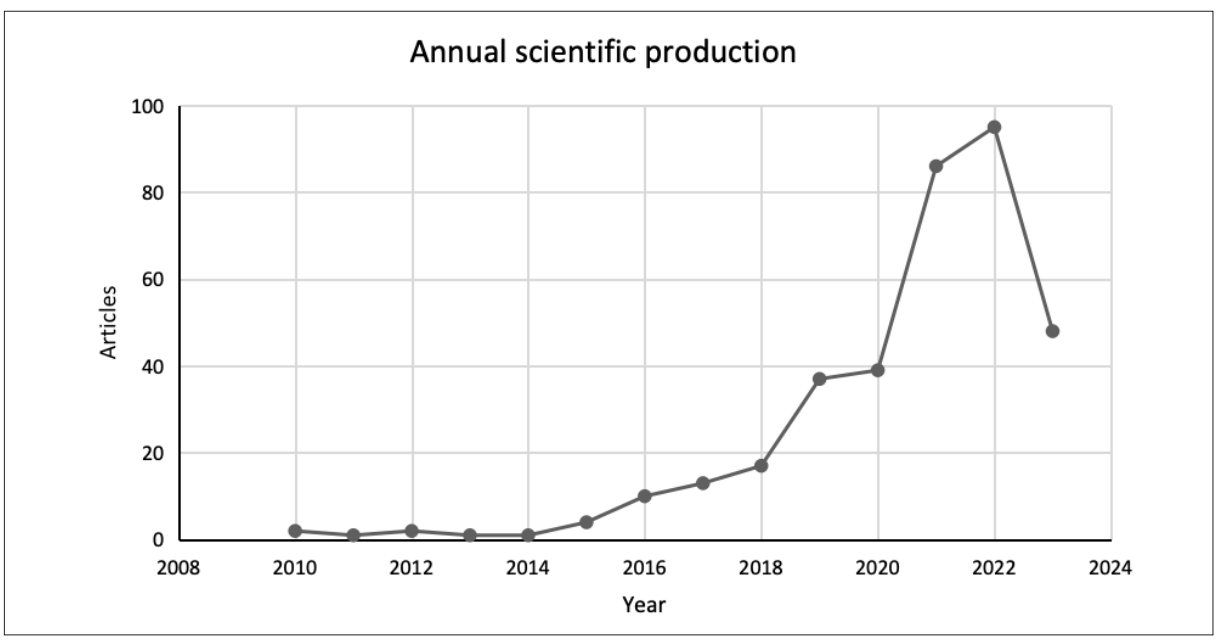
RESULTS

Bibliometric analysis

This section conducts a performance analysis of select metadata components, presenting a comprehensive literature perspective.

Figure 2 illustrates the annual scientific output spanning from 2010 to the first semester of 2023, with 2022 exhibiting the highest number of publications. Notably, there has been a discernible increase in scientific output from 2015 onward, despite the inception of CE adoption more than a decade earlier in European Union (EU) countries and China (Alcalde-Calonge et al., 2022). This trend is attributable to the expanding international reach and stringent regulations of the EU, which have gained prominence owing to resource depletion, elevated consumption patterns, and the burgeoning global population (Ellen Macarthur Foundation, 2015; World Manufacturing Foundation, 2018).

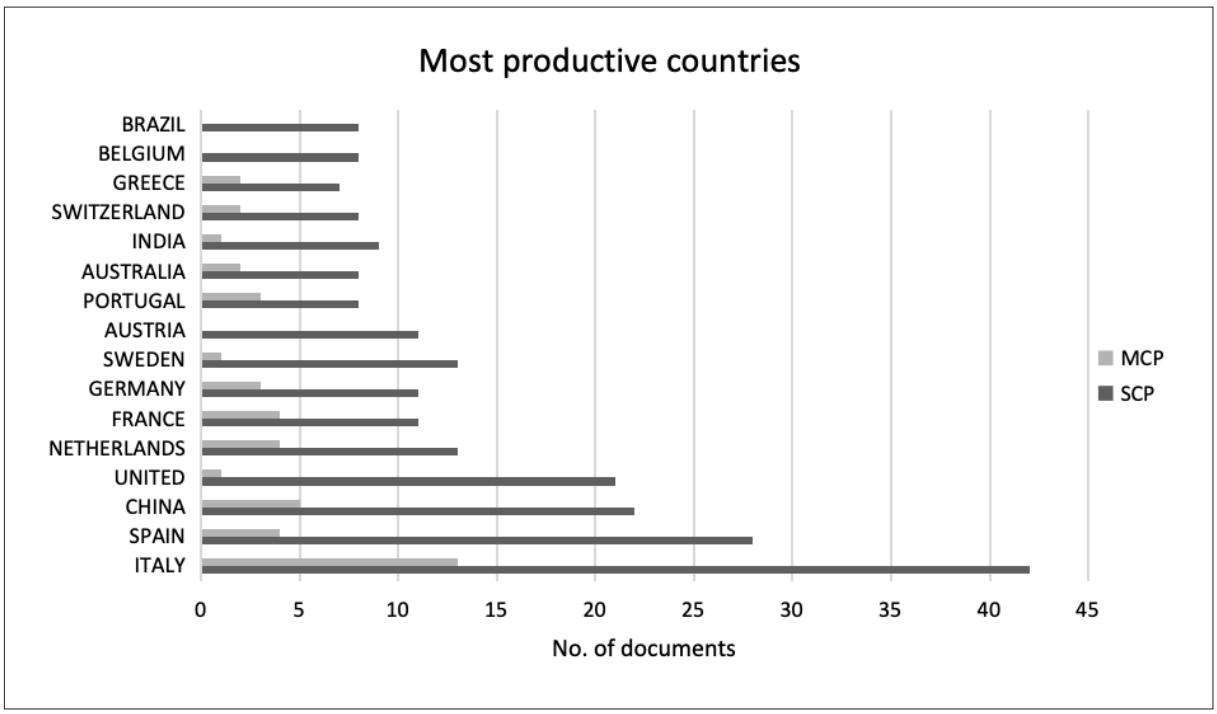
Figure 2. Annual Scientific Production from 2010 to 2023



Source: Elaborated by the authors utilizing the Bibliometrix R-package.

The number of scientific productions per country was examined to ascertain the nations with the highest volume of published articles (Figure 3). The analysis uses the graph generated by the Bibliometrix and Biblioshiny packages, categorizing publications by the first author's affiliation (Single Country Publications - SCP) or, in cases of multiple affiliations, articles with affiliations from different countries (Multiple Country Publications - MCP).

Figure 3. Scientific Production by Country

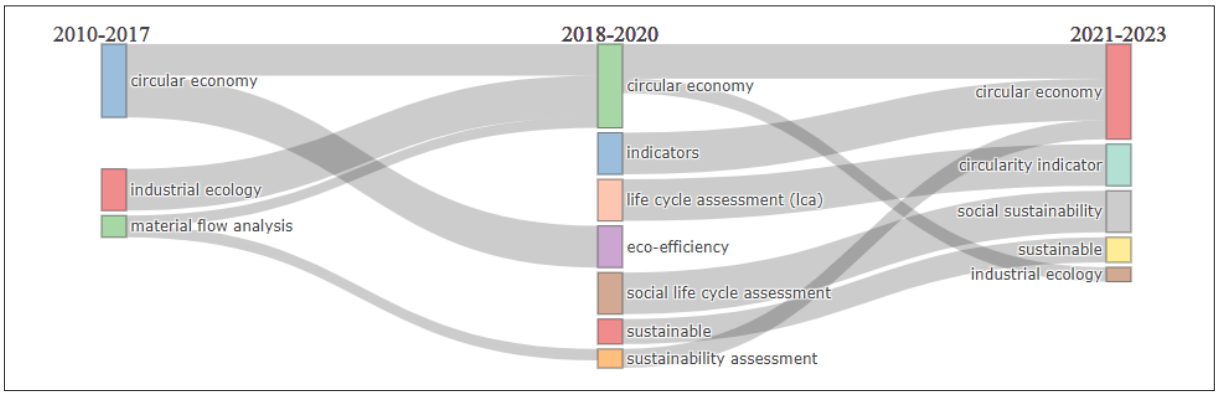


Source: Elaborated by the authors utilizing the Bibliometrix R-package.

Figure 3 illustrates that European countries predominantly exhibit higher production, with Italy, Spain, China, the United Kingdom, and (the Netherlands emerging as the top five, respectively. This ranking underscores the European leadership in global scientific research concerning metrics and assessment of CE.

The analysis of thematic evolution over the past 13 years provides significant insights into the pivotal issues that have shaped the field of CE (Figure 4). A "thematic evolution map" elucidates such evolution, featuring temporal segments. Each temporal segment comprises a set of clusters, denoting blocks of varied sizes corresponding to the occurrence of keywords. Generally, larger cluster sizes indicate higher frequencies of respective keywords within the period and vice versa. The thematic evolution map, depicted in Figure 4, partitions the period into three distinct temporal segments: 2010 to 2017, 2018 to 2020, and 2021 to 2023, with this segmentation aligned with the annual scientific production graph. The investigation highlights the growth of interest in CE in recent decades, starkly evidenced by the escalation and diversification of the addressed topics.

Figure 4. Thematic Evolution Map



Source: Elaborated by authors utilizing the Bibliometrix R-package.

Figure 4 shows that from 2010 to 2017, the predominant themes encompassed CE, Industrial Ecology (IE), and, to a lesser degree, Material Flow Analysis (MFA). As elucidated by Ghisellini et al. (2016), CE exhibits a close association with IE, representing a strategy geared toward transitioning from open cycles to closed cycles, a correlation more pronouncedly evident in the subsequent period (2018 – 2020), where the two concepts amalgamate within the EC cluster. Concurrently, other themes, including sustainability, indicators, and Life Cycle Assessment (LCA), gained prominence during this period.

In the third phase (2021 – 2023), a discernible expansion of the EC cluster is evident, attributed to the incorporation of additional keywords from the preceding period. Moreover, the emergence of new thematic elements, such as circularity indicators and social sustainability, is noteworthy. In summary, the analysis of the thematic evolution map reveals the emergence of diverse topics, particularly over the past five years, indicating the burgeoning prominence of CE and sustainability-related themes.

Content analysis

Through the SLR, a comprehensive perspective of the contributions over the analyzed period was attained to quantify CE alongside the levels of perspective, R-strategies, and dimensions addressed (Table 3). Within the document selection, classifications and propositions of tools exhibit notable variations concerning the methodology employed, sets of indicators used, calculation formulas, units of measurement, and predominant evaluation objectives. For instance, while some tools aim to streamline the indicator selection process (Saidani et al., 2019), others propose monitoring new product development based on the CE perspective (Pauliuk, 2018). Taxonomies serve to identify and categorize metrics (Corona et al., 2019; De Pascale et al., 2021), and their organization varies according to the scope of application, such as the use in specific sectors (Superti et al., 2021). Conversely, methodologies employed are typically executed through environmental assessment tools like LCA and MFA (Elia et al., 2017; Linder et al., 2020; Sassanelli et al., 2019), representing

a well-established field or through Multicriteria Decision-making Methods (MDM) (Niero & Kalbar, 2019). Consequently, these tools exhibit diversified structures and evaluate the progress of CE from various perspectives, mirroring the multifaceted nature of the CE concept.

The level of perspective can be subdivided into more detailed units that correspond to the scope of analysis. Four significant perspectives were identified among the tools examined in this SLR: material, product, organizational, and different levels. According to the results outlined in Table 1, the majority of the tools and indicators were designed to assess the organizational level (11), followed by the product level (9), evaluations at the material level (6), and finally, metrics capable of estimating different levels (5).

The results also delineate the proportion of tools addressing the social, environmental, and economic dimensions of CE. Environmental metrics are the most developed, owing to a robust framework of tools within this sustainability-related domain. Economic metrics, while less prevalent, often intersect with the environmental dimension. Conversely, social indicators are less prominent (de Oliveira et al., 2021). Despite notable progress, several authors highlight the absence of comprehensive methodologies encompassing all three dimensions (Corona et al., 2019; Iacovidou et al., 2017; Sassanelli et al., 2019). Reviews show the paucity of indicators for evaluating social aspects within the CE context (Garcia-Saravia Ortiz-De-Montellano & van der Meer, 2022; Kristensen & Mosgaard, 2020). In a study scrutinizing 29 indicators and assessment tools at the micro-level, only 9 incorporated the social dimension (De Pascale et al., 2021).

CE appraisal tools incorporate the R-strategies in their development. However, most fail to encompass many strategies in their evaluation, resulting in repetitive metrics and indicators addressing the same Rs. In order of predominance, Reuse, Recycle, Reduce, Repair, Refurbish, Remanufacture, Recover, Repurpose, and Reject are those with incidence among the proposed assessments. At the same time, Rethink was not addressed by any of the tools and indicators in this review. According to Kristensen and Mosgaard (2020), although recycling and, to some extent, Remanufacturing are older strategies aimed at extending the lifespan of resources and products, reuse is one of the most recent strategies articulated in the environmental field. Furthermore, it is imperative to note that R-strategies have garnered increased attention among CE interventions (Superti et al., 2021), a trend corroborated by the findings discussed in this review.

Table 3. Selection of Articles with Proposals for Tools and Indicators

Author(s)	Indicators/Tools	Level of perspective	R-frameworks	Dimensions		
				Soc	Env	Econ
Franklin-Johnson et al. (2016)	Proposal of a longevity indicator	Organizational	R3, R4, R5, R6, R7, R8		x	x
Elia et al. (2017)	Framework for guidance on a potential methodology for assessing EC based on the LCA approach.	Material	R2, R5 e R8		x	
Linder et al. (2017)	Circularity metric at the product level.	Product	R3, R4, R5, R6, R7, R7		x	

Continue

Table 3. Selection of Articles with Proposals for Tools and Indicators

Author(s)	Indicators/Tools	Level of perspective	R-frameworks	Dimensions		
				Soc	Env	Econ
Iacovidou et al. (2017)	Complex Value Optimization for Resource Recovery (CVORR): Assessing how complex value is created, destroyed, and distributed in the resource recovery of waste systems.	Material/Product	R3, R4, R5, R6, R8, R9		x	
Kazancoglu et al. (2018)	Green Supply Chain Management Performance Evaluation Framework	Organizational	R2, R3, R6 e R8	x	x	x
Pauliuk (2018)	Set of qualitative indicators for evaluating EC approaches in companies.	Material	R2, R3 e R8	x	x	x
Bianchini et al., (2019)	Circular Business Model Evaluation Tool facilitating the comparison between linear and circular paradigms.	Organizational	R2, R3, R4, R5, R6, R7, R8 e R9	x	x	
Corona et al. (2019)	Identification and classification of indicators into a taxonomy.	Product or service	R2, R3 e R8		x	x
Garza-Reyes et al. (2018)	Proposed a Circularity Measurement Toolkit (CMT).	Organizational	R2, R3, R4, R5, R6, R7, R8 e R9		x	
Kravchenko et al., (2019)	Database of leading performance indicators.	Different levels	R2, R3, R4, R5, R6, R3, R8 e R9	x	x	x
Moraga et al. (2019)	Indicator classification framework.	Material	R3 e R8	x	x	x
Niero & Kalbar (2019)	Multicriteria decision analysis coupling circularity indicators with LCA.	Product	R3 e R8		x	
Parchomenko et al. (2019)	It established a framework and classification for a set of metrics and associating these elements with specific points within a system.	Material	R3, R6, R8		x	
Saidani et al. (2019)	C Indicators	Different levels	R3 e R8		x	

Continue

Table 3. Selection of Articles with Proposals for Tools and Indicators

Author(s)	Indicators/Tools	Level of perspective	R-frameworks	Dimensions		
				Soc	Env	Econ
Sassanelli et al. (2019)	Framework for positioning with EC performance evaluation methods according to the Triple Bottom Line (TBL) perspective, involved variables, and life cycle stage.	Organizational	R3 e R8		x	x
Alamerew et al. (2020)	Multicriteria evaluation method for circularity strategies at the product level.	Product or service	R3, R4, R5, R6, R8, R9	x	x	x
Bracquené et al. (2020)	Product Circularity Indicator (PCI)	Product	R2, R3, R4, R5, R6, R8, R9		x	
Linder et al. (2020)	Analysis of the relationship between Circularity Indicators C and LCA	Product	R3, R4, R5, R6, R7, R8		x	
Kristensen & Mosgaard (2020)	Categorization of 30 micro-level indicators.	Organizational/ Product	R3, R6, R8		x	x
Droege et al. (2021)	Framework encompassing system definitions, 35 EC evaluation elements, evaluation goals, and indicators.	Organizational	R0, R2, R3, R5, R3 e R8	x	x	x
Ladu & Morone (2021)	The Integrated Assessment Tool (IAT)	Product	R2 e R8	x	x	x
Moraga et al. (2021)	A set of indicators proposed to measure and quantify how materials are used in different product life cycles.	Material	R2, R3, R4, R5, R8 e R9		x	
Rincón-Moreno et al. (2021)	Comprising 14 relevant indicators for companies, focused on the practical implementation of CE.	Organizational	R2 e R8		x	
Sacco et al. (2021)	Proposal of a circularity and maturity assessment tool at the company level (CM - FLAT).	Organizational	R2, R3, R4, R8 e R9		x	
Vinante et al. (2021)	365 metrics organized within a circular value chain framework.	Organizational	R2, R3, R4, R8 e R9		x	
De Pascale et al. (2021)	Framework of 61 indicator classifications.	Different levels	R2, R3, R6	x	x	x

Continue

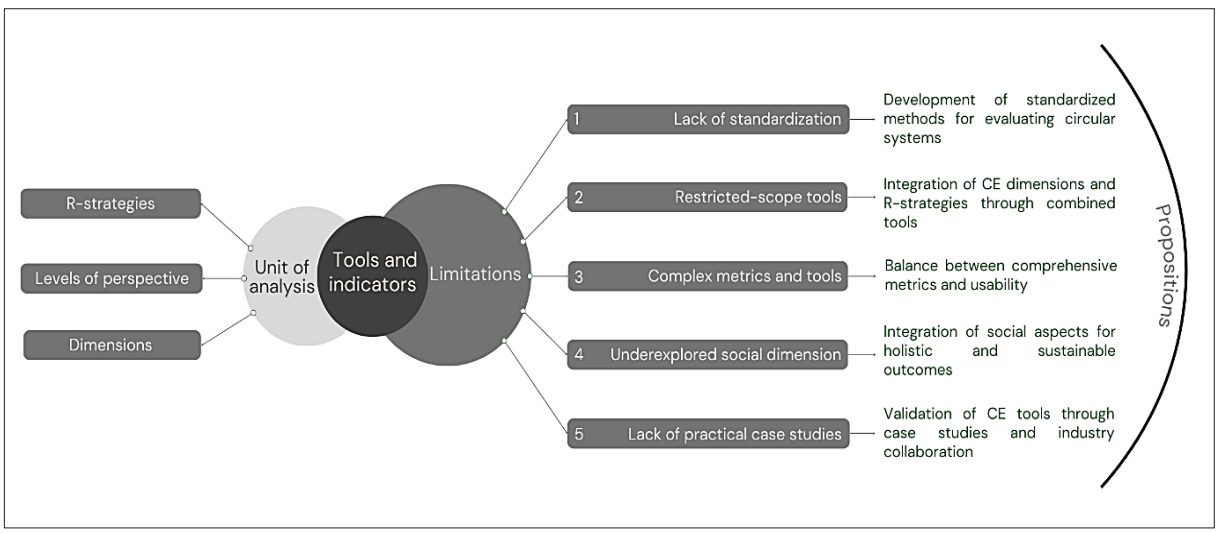
Table 3. Selection of Articles with Proposals for Tools and Indicators — Concludes

Author(s)	Indicators/Tools	Level of perspective	R-frameworks	Dimensions		
				Soc	Env	Econ
Superti et al. (2021)	Proposal of a comprehensive framework to categorize EC interventions.	Different levels	R0 – R9		x	x
Baratsas et al. (2022)	Circular Microeconomy Index (MICRON)	Organizational	R2, R3, R4, R5, R8 e R9		x	
Brändström & Eriksson (2022)	Material Efficiency Metric (MEM)	Organizational	R2, R3, R5, R4, R8		x	
Garcia-Saravia Ortiz-de-Montellano & van der Meer (2022)	A holistic and standardized framework is proposed, dividing CE into circular impacts and practices.	Different levels	R2, R3, R4, R5, R6, R7, R8 e R9	x	x	x

Limitations in tools and their associated challenges

Upon examining the selected scientific literature, it is evident that there is a growing interest in quantifying and developing tools capable of evaluating CE. This interest manifests in the proliferation of proposals for indicators and tools characterized by diverse scopes, varied calculations, and applicability. Five prominent limitations (Figure 5) were identified: (1) Lack of standardization in tools and metrics, (2) Approaches focused on specific aspects, lacking a holistic view of strategies and social, environmental, and economic impacts, (3) Complexity of indicators, (4) Underexplored social dimension, and (5) The dearth of practical contributions regarding the proposed tools.

Figure 5. Limitations Identified in the Literature and Corresponding Propositions



Despite the burgeoning interest and contributions in metrics and evaluation tools for CE, the absence of standardized methods to measure and evaluate CE remains a significant limitation. This culminates in a notable disparity in understanding what facets should be considered in CE assessment (De Pascale et al., 2021). While indicators prove invaluable for comprehending CE strategies and impacts, the absence of standardization and clear guidelines can impede the comparison and interpretation of results, resulting in diverse and sometimes conflicting approaches and metrics (Elia et al., 2017; Vinante et al., 2021). Furthermore, the lack of consistency in evaluation frameworks directly correlates with the absence of standardization and can impede organizations' adoption of circular practices (Sacco et al., 2021). These arguments lead to the following proposition:

> Proposition 1: It is essential to develop standardized measurement methods to establish a solid foundation for evaluating and promoting the performance of circular systems.

The limitation of segmented evaluation tools characterized by narrow focus presents a significant barrier to the holistic and comprehensive approach requisite in CE. Many existing appraising tools in the field tend to concentrate on specific facets, such as LCA for assessing environmental impacts (Alamerew et al., 2020) and MFA for measuring material circularity (Pauliuk, 2018). While indicators harbor valuable information in particular domains, the absence of an integrated approach can impede system evaluation. This stems from the fact that organizations may overlook other equally crucial elements by fixating on only one aspect of CE, leading to a lack of comprehensive consideration. This fragmented approach compromises a holistic view of the impacts induced by the product or organization under evaluation by the tool. According to Elia et al. (2017), focusing on a constrained set of indicators that only partially encapsulate the dimensions relevant to CE represents a constraint in the proposed evaluation process. These points give rise to the following proposition:

> Proposition 2: It is imperative to integrate different dimensions of CE (social, environmental, and economic) along with multiple R-strategies. This could be achieved by combining existing tools, such as LCA and MFA, with others that assess circular practices, offering a broader and more interconnected perspective.

The intricacy of metrics and tools can present considerable challenges. The computation and interpretation of indicators often demand specialized technical expertise, as exemplified in methodologies like LCA and MFA (Moraga et al., 2021). This can cause barriers to practical application, particularly for companies and organizations lacking proficiency in these domains (Saidani et al., 2019). Moreover, the array of available metrics and the imperative to select those most pertinent to a specific context can prove daunting (Parchomenko et al., 2019). Excessive complexity may yield an arduous evaluation to comprehend and communicate, rendering it less accessible to a broader audience. However, Droege et al. (2021) assert that an excessively

simplistic tool may fail to capture the multidimensionality of CE. From these arguments, the following proposition emerges:

> Proposition 3: A balance between the need for comprehensive metrics and usability should be achieved to ensure that the evaluation of CE remains effective and accessible to all stakeholders, thereby preventing system under-optimization.

The social dimension within the context of CE is often marginalized, with predominant discussions centered on the economic and environmental dimensions. Nonetheless, it is imperative to acknowledge that CE extends beyond efficient resource management and the mitigation of environmental impacts; it also encompasses social ramifications. CE can stimulate local employment, foster social inclusion, enhance working conditions, and fortify relationships within value chains (Geissdoerfer et al., 2017; Ghisellini et al., 2016). Based on these arguments, the following proposition is presented:

> Proposition 4: It is important to develop metrics and tools by effectively integrating social aspects. This approach facilitates maximizing its potential, preventing incomplete system evaluations, and promoting more balanced and sustainable outcomes across all dimensions.

Despite the burgeoning interest and development of metrics and assessment tools, a noteworthy limitation in the literature is the lack of validation through concrete examples and practical case studies demonstrating the implementation of these tools in practice. One of the hurdles organizations encounter when transitioning their business models to a CE paradigm stems from the need for more approaches, instruments, and metrics to evaluate various R-strategies (Alamerew et al., 2020). As highlighted by Droege et al. (2021), the development of indicators and tools encompasses a spectrum of variables, ranging from what should be evaluated to how the evaluation should be conducted, and involving diverse stakeholders in this process enhances the efficacy of the tools. Based on these arguments, the following proposition is presented:

> Proposition 5: Validate CE assessment tools through case studies and practical examples, demonstrating their applicability in real-world contexts. Collaborations with companies implementing R-strategies can support this process, helping refine the tools and improve their effectiveness in organizational settings.

This research is ongoing, and the subsequent phase entails the proposition of a conceptual, analytical model for appraising, focusing not only on the micro level but notably encompassing the impacts of circularity practices on the Triple Bottom Line (TBL), namely, the social, economic, and environmental dimensions of sustainability. It is recognized that only a comprehensive examination of these practices will facilitate a genuine understanding of how CE fosters sustainable development.

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CONCLUSIONS

CE assessment tools are essential for tracking its adoption and progress, particularly at the company level. This article explores the limitations and challenges associated with tools for measuring CE practices at the micro level. A quantitative and qualitative analysis was conducted using 30 documents collected from the Web of Science and Scopus databases.

The bibliometric analysis indicated that most papers were published between 2015 and 2022. The sample of the 16 most cited papers demonstrated the prevalence of European countries as the first author's affiliation. The themes of reverse logistics/waste management and supply chains were mainly addressed in the 16 most cited papers of the sample.

Theoretical contributions

In the intricate landscape where diverse realities coexist between developed and developing nations, the pursuit of standardization of tools to gauge the advancement of CE presents a formidable challenge and remains elusive. This challenge arises due to the inherent dependency of assessing this system on the contextual framework and the specific resources under evaluation. In a broader context, the research findings show the limitations of existing evaluation tools and indicators at the micro level, which have been extensively deliberated and scrutinized in prior studies. Furthermore, the research highlights researchers' burgeoning interest in this domain in recent years. Moreover, it is noteworthy that EU institutions emerge as leaders in productivity, as evidenced by the volume of documents generated.

Practices associated with CE necessitate comprehensive assessments and monitoring facilitated by metrics that encapsulate the breadth of the concept, striving to guarantee clarity and reliability in data interpretation. The tools employed to evaluate CE practices exhibit variability in terms of scope and purpose, potentially yielding inconsistent implications contingent upon the system under evaluation. The potential of CE transcends national boundaries; nevertheless, it mandates assessments and monitoring underpinned by instruments possessing the total capacity to measure its strategies and all its dimensions. Current literature still needs tools that effectively address the complexity and diverse nature of circularity.

Another consideration is incorporating the social dimension into the monitoring of CE, which necessitates enhancements, particularly regarding scope. Most assessment tools prioritize the environmental and economic dimensions, relegating social impacts to a secondary position in most proposed tools. Failure to adequately integrate this dimension into evaluation tools compromises the ability to gauge the impacts of circular strategies, given the system's interconnectedness across all implementation levels. Moreover, empirical studies are underrepresented in introducing novel evaluation methods, pivotal in identifying barriers and refining analytical strategies.

The paper provides a detailed analysis of the thematic evolution of research related to CE over the past 13 years, highlighting the growing prominence of sustainability-related themes and

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the integration of new concepts such as circularity indicators and social sustainability. These contributions collectively show the importance of advancing assessment frameworks to better align with the principles of CE and enhance their effectiveness in practice.

Managerial implications

The study's practical contributions are rooted in identifying limitations and challenges inherent in evaluating CE, signaling the necessity for enhancements in assessment tools, particularly emphasizing integrating the social dimension. These contributions possess the capacity to significantly influence CE practice by steering endeavors toward the adept evaluation of systems. The study enables companies and other stakeholders to refine their strategies and metrics, ensuring better alignment with CE principles. Moreover, the findings signal the need for enhancements in assessment tools, particularly in integrating social dimensions, which can significantly influence CE practices and help organizations refine their strategies and metrics.

In terms of public policy, it is necessary to promote the adoption of CE practices across industries or improve the assessment tools used to measure circularity through the Involvement of various stakeholders, including government agencies, businesses, NGOs, and academic institutions, to gather diverse perspectives and ensure the policy addresses the needs of all parties involved.

Policymakers should establish unified standards for CE assessment metrics to enhance comparability and reduce variability. It is also essential to ensure that the policy promotes the integration of social, environmental, and economic dimensions within assessment methodologies. Additionally, mechanisms must be established to monitor the effectiveness of both the policy and the assessment tools. By following these guidelines, policymakers can effectively address the challenges and create a comprehensive framework that supports sustainable development.

Limitations and future research agenda

The study's main limitation is that the selected keywords might unintentionally overlook significant studies that could provide valuable insights into the topic. Although still in development, this research highlights the need to advance standardized measurement methods for CE systems, which align with the propositions presented throughout this work. Future studies should develop tools encompassing a broader range of R-strategies and integrate social, environmental, and economic dimensions for a more comprehensive approach. There is also a pressing need to establish standardized indicators that can assess CE practices effectively across different levels of analysis (material, product, and organizational). Additionally, balancing comprehensive metrics with usability is essential to ensure that evaluation methods remain accessible to all stakeholders. Validating these tools through case studies and practical applications is necessary to improve their effectiveness and relevance in organizational contexts.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

AUTHORS' CONTRIBUTION

Larissa Costa: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – proofreading, and editing.

Gabriela Scur: Conceptualization; Data curation; Formal analysis; funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – proofreading, and editing.

Jorge Alfredo Cerqueira Streit: Conceptualization; Methodology; Validation; Visualization; Writing – proofreading, and editing.