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Assessing circularity at the macro-level: a systematic review of indicators

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Glossary

APCE	Action Plan for the Circular Economy, comprehensive body of legislative and non-legislative actions adopted in 2015, aimed to drive the European economy from a linear to a circular model
CCD	Circular City Diagram, framework designed to capture all the dimensions affected by the circular economy
CE	Circular Economy
CEI	Circular Economy Indicator
CG	Circularity Gap, it evaluates the extent to which materials and products are being reused, recycled, and reintegrated into the economic cycle rather than being disposed of as waste
CMU	Circular Material Use Rate
DMC	Domestic Material Consumption, it is the total amount of materials directly used by an economy
DMI	Domestic Material Input, it provides insights into the overall environmental and resource impact associated with a country's consumption patterns
EUROPE 2020	EU strategy adopted to became more sustainable by year 2020
GDP	Gross domestic product, indicator used to measure the economic performance of a Country by assessing the market value of final goods and services produced
LFI	Linear flow index, percentage of material within a system that follows a linear trajectory
MFA	Material flow analysis
MFCE	First Monitoring Framework on Circular Economy of EU
PCA	Principal Components Analysis
PM	Processed Material

PROMETHEE	Evaluation method designed to assist decision-makers in ranking and comparing various alternatives based on multiple criteria
SLR	Systematic Literature review
WTE	Waste to energy, circular strategy aimed to produce energy burning waste

Abstract

"The global impetus towards embracing the circular economy paradigm has intensified as countries worldwide deal with the urgent need to address environmental degradation while striving for economic prosperity. This strategic framework, premised on minimizing resource depletion and waste generation, emerges as a cornerstone in fostering sustainable development. However, the successful transition towards a circular economy necessitates not only a deep understanding of its principles but also the development and implementation of effective performance assessment methodologies.

This Master Thesis embarks on a comprehensive exploration of methods and indicators for evaluating circularity, specifically focusing on the macro-level perspective. Through a meticulous

systematic literature review, a vast array of global circular economy indicators are analyzed, categorized, and synthesized to construct a comprehensive taxonomy of existing performance assessment methods.

Studies will be thoroughly analyzed to understand the proper methods for gathering assessment instruments, ensuring they are neither too vague nor overlooking crucial aspects within the broader landscape.

Employing rigorous descriptive analysis, this study unveils the intricate conceptual foundations and mathematical frameworks founding these indicators, offering valuable insights into their applicability and relevance in the context of circular economy.

Furthermore, beyond the mere cataloging and analysis of existing methods, this research critically assesses their strengths, limitations, and potential areas for future improvements. By identifying gaps in the current landscape of circular economy performance assessment methodologies, this Thesis sets a roadmap for future research and innovation in this domain, thereby contributing to the advancement of sustainable practices and policies.

Through its exhaustive examination and critical evaluation, this thesis aspires to provide a definitive and exhaustive overview of circularity awareness in the literature, serving as a guide for students, researchers, and practitioners alike in their shift to accelerate the transition towards a more regenerative economic model. By fostering a deeper understanding of circular economy principles and offering actionable insights for improvement, this work aims to catalyze transformative changes towards a more sustainable and resilient future for all. "

1. Introduction

In the raise of rigorous global challenges such as climate change, resource scarcity, and environmental degradation, traditional linear economic models have been proven unsustainable (Elisha, 2020). The paradigm of circular economy, a regenerative system aimed at minimizing waste and maximizing the continual use of resources, has gained significant leverage as a potential solution.

Exploring assessment methods of circular economy at the macro-level means adopting a broader perspective on a systemic rather than focusing on individuals.

This study delves into the system as a whole entity, aiming to understand how an innovative approach as CE can be measured relying on parameters that describe a community.

From a macroeconomic standpoint, adopting circular practices ensures environmental benefits by preserving the natural resource heritage of a geographical area. Strategies such as recycling, reusing, and other circular approaches are essential in alleviating environmental pressures on virgin materials.

Economically, the macro-level considerations regarding circular economy reveal numerous positive implications. By limiting waste production within a country, significant reductions in expenses for waste management can be achieved, freeing up resources to fund educational or environmentally oriented initiatives.

Furthermore, embracing circular behaviors serves to stimulate economic growth by fostering the emergence of new business opportunities and industries centered around circular practices. These sectors have the potential to generate employment, attract funds, drive innovation, and contribute to economic diversification.

Implementation of circular economy principles holds the key to reshape the entire economies, driving sustainable development, and mitigating the adverse impacts of relentless consumption and waste generation (Eberhardt et al., 2022). This Thesis thus aims to systematically review methods and indicators to assess circularity from the macro perspective to create a comprehensive taxonomy of existing performance assessment methods to gauge CE performance. This is critical to examine the crucial role of circular economy indicators in steering nations toward a more sustainable future.

1.1. The circular economy concept and definition

The literature on circular economy has witnessed a diverse array of definitions over the years. This variability is underscored by the exhaustive study conducted by (Kirchherr et al., 2017), where they meticulously examined a wide set of existing literature to find out the most pertinent interpretations of this concept. To avoid potential confusion, all the key strategies defining the circular economy model are meticulously delineated in Figure 1 (Kirchherr & Piscicelli, 2019).

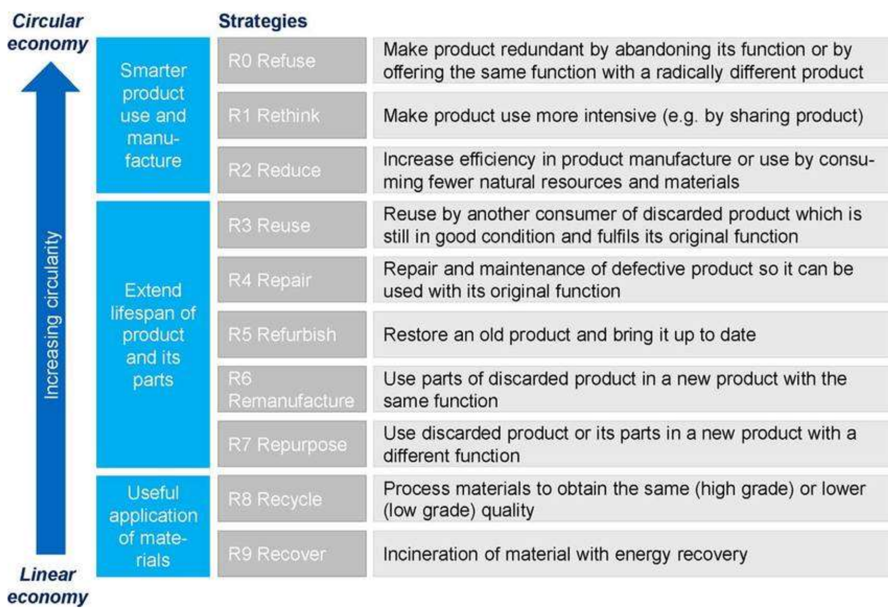

Figure 1 The 9R paradigm

(Kirchherr & Piscicelli, 2019)

It becomes evident that, given the multitude of possible combinations among these options, a definition can emerge that significantly distinguishes itself from others. A possible suitable definition can be the one that (Geissdoerfer et al., 2017) claimed to be the most prominent CE definition that has been provided. We are taking about the definition given by (Macarthur, 2017) :

"[CE] is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic

chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."

A key issue is the fact that the abundance of different CE conceptualizations can become a serious challenge for anyone trying to deal with this concept. Knowledge accumulation regarding the CE is difficult and the application of the CE has been hampered by different interpretation of its concepts, i.e. associating single strategies (Figure 1) to the concept of CE. When people lack awareness of the divergent (but still coexistent) conceptual interpretations of CE, misleading outcomes can be obtained when attempting to accumulate knowledge. (Dacin et al., 2010) state that "the current state of conceptual confusion serves as a barrier to advances in the CE field". Of those definitions examined during the paper reading the definition of circular economy, the definition proposed by (van Buren et al., 2016) was found able to include at the same time the 3R framework, the R hierarchy, a systems perspective, environmental quality, economic prosperity and social equity and so can be considered as one of the most inclusive. According to (van Buren et al., 2016):

"Unlike the current economy, which is largely based on the principle "take-make-waste" (linear economy), the focus point in a circular economy is to not unnecessarily destroy resources. This implies far more than the reduction of waste through recycling, stresses the following focal points that are listed starting from the action with the higher recovery value to the lowest in accordance with the waste hierarchy paradigm: reducing the consumption of raw materials, designing products in such a manner that they can easily be taken apart and reused after use (eco-design), prolonging the lifespan of products through maintenance and repair, and the use of recyclables in products and recovering raw materials from waste flows for example through energy creation. A circular economy aims for the creation of economic value (the economic value of materials or products increases), the creation of social value (minimization of social value destruction throughout the entire system, such as the prevention of unhealthy working conditions in the extraction of raw materials and reuse) as well as value creation in terms of the environment (resilience of natural resources)"

Instead of viewing resources as finite entities, the circular economy treats them as valuable assets that can be restored. While these principles are intuitively appealing, their effective application is not definitively given at the macro level and for that reason it requires a stable understanding of the complex interactions between industries, policies, and people behaviors (Sharma et al., 2022).

Crucial to the understanding and implementation of circular economy are the metrics and measurements represented by circular economy indicators. These indicators serve as analytical tools, quantifying the effectiveness of circular strategies within an economy. These indicators provide a comprehensive view of resource utilization, waste management, and environmental impact. In essence, they empower policymakers and stakeholders with the knowledge necessary to make conscious decisions, aligning economic growth with ecological sustainability.

When analyzed at a macro level, the impact of circular economy practices transcends environmental concerns and get in touch with economic, social, and policy domains. Economically, the circular economy stimulates innovation, promote environmental responsible entrepreneurship, and speed up the ascension of a green industries model, thereby driving economic growth while reducing environmental pressures (Kristensen & Mosgaard, 2020). Socially, it promotes inclusivity by creating job opportunities, especially in fields related to recycling, remanufacturing, and sustainable technologies (Drakulevski & Boskov, 2019). Moreover, it promotes a sense of environmental responsibility and awareness, shaping sustainable consumer behaviors (EEA, 2022) (for example through the implementation of car sharing services in urban areas).

In terms of policy, the circular economy necessitates adaptive and forward-looking regulations, incentivizing businesses and individuals to adopt innovative practices (Liu et al., 2023). Therefore, examining the implications of the circular economy requires comprehensive lens that captures its composite impacts on different sectors of society.

While the concept of a circular economy holds an untapped potential, its implementation at a macro scale is not lacking challenges. These future challenges start from the need for significant investments in green technologies to overcoming inertia within established industries and regulatory frameworks (Berto et al., 2022).

Additionally, modelling a circular mindset among consumers and stakeholders demands and extending awareness campaigns and education initiatives. Innovative financing models, cross-industry collaborations, and international partnerships can pave the way for effective circular economy adoption.

By critically examining existing circular economy indicators and proposing future research directions based on the identified research gaps, this study seeks to contribute significantly to the academic acknowledgement on circular economy. In doing so, the goal is to offer practical insights, innovative solutions, and a nuanced understanding of the transformative potential embedded in circular economy principles, shaping a sustainable future for future generations.

1.2. CE layers

This Thesis's understating of CE levels is primarily based on the division among the macro, meso, and micro circularity levels commonly applied in CE research (Kirchherr et al., 2017) with the addition of the concept of nano scale brought in the literature by (Saidani et al., 2019)

Different levels of CE are divided based on the level of analysis, from the broader one to the smaller one.

Looking at the systemic CE view provided by (Huamao & Fengqi, 2007), CE levels influence and interact with one another, meaning that the upper levels are based on the lower levels, which, in turn, orient their development.

This point of view is graphically exemplified in Figure 2.

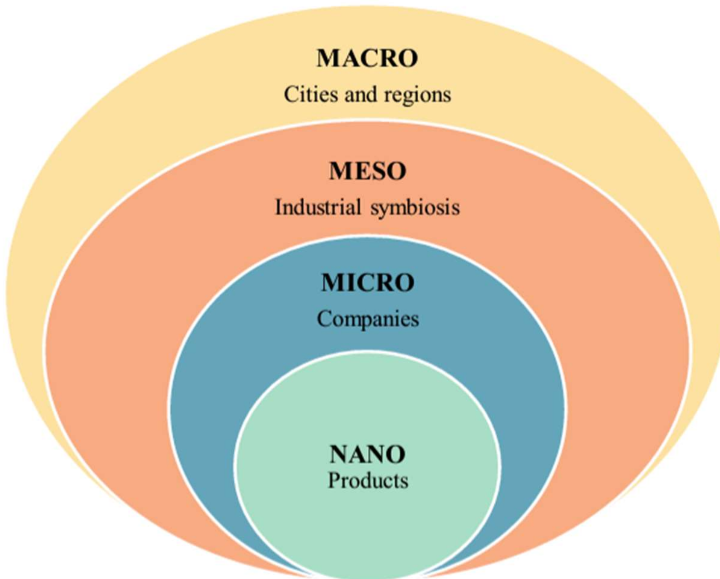

Figure 2 CE layers

(de Oliveira et al., 2021)

1.2.1. Nano level

The concept of the “nano” scale as a new product centered term to the CE context was firstly introduced by (Saidani et al., 2019). The nano level describes “the circularity of products, components, and materials, included in three wider systemic levels, all along the value chain and through- out their entire lifecycle” (Saidani et al., 2019)

This involves a comprehensive approach that considers various activities undertaken by companies to add value to a product throughout its life cycle. These activities span from the initial stages of production, through the design and marketing phase and extend to the after-sales service life cycle.

In essence, the “nano” scale within the circular economy framework emphasizes the need for a holistic perspective, ensuring that every stage of a product's journey, from its creation to its eventual disposal or recycling, aligns with durability and hence sustainability principles.

As pointed out by (Lindgreen et al., 2020), grouping all corporate operations under the same category to assess company- level circularity may be overly general and extensive. The further distinction between nano and micro circularity levels aims to dissolve the common confusion derived from a far too broad view of the smallest level.

In this context, the implementation of circularity indicators to the nano level is a way to strictly distinguish the influence of specific products and design options from the overall company circularity.

As consequence of (Huamao & Fengqi, 2007) assumptions, nano level is intrinsically present in every upper level and hence constitutes the basis for every CE consideration.

1.2.2. Micro level

At the micro level, the Circular Economy (CE) paradigm profoundly affects individuals and firms, affecting their behaviors and consumption patterns towards sustainability. This level of the CE framework focuses on the small units within society, emphasizing the importance of initiatives and individual choices in driving the transition towards a circular economy.

At the micro level, multiple firms across different industries decide to “close the loop” by implementing cleaner production and eco-design initiatives (Ghisellini et al., 2016).

Another key aspect of the circular economy at the micro level is the product and its influence on consumer behavior (Wojnarowska et al., 2022). Individuals are encouraged to adopt mindful consumption practices, emphasizing the importance of quality over quantity. Instead of constantly buying new products, consumers are urged to repair, refurbish, and reuse items, thereby extending their lifecycle.

In summary, the micro level of the Circular Economy is characterized by individual actions, community collaborations, entrepreneurial initiatives, and educational efforts. By encouraging mindful consumption, promoting community engagement and raising awareness, the circular economy at the micro level creates a foundation for a more sustainable future, where individuals and communities actively participate in the preservation of resources and the well-being of the planet.

1.2.3. Meso level

The Circular Economy at the meso level represents the dimension in which enterprises, industries, and local governments collaborate to transform their operations and supply chains through industrial symbiosis (Balanay & Halog, 2016).
This level comes as a bridge between micro-level individual actions and macro-level policy and national/ regional changes. Below, the 2 main area of interest of the Circular Economy at the meso level are presented:

- **Circular Supply Chain**
  Meso level CE initiatives emphasize the development of innovative circular supply chains. Businesses work to redesign their processes (i.e. procurement) establishing a dialogue with supplier and stakeholders (Qazi & Appolloni, 2022)with a clear intent on minimizing waste, optimizing resource use, and encouraging recycling of materials. This shift results in a more environmental impact free, efficient, and environmentally responsible approach to production and distribution.

- **Eco-Industrial Parks**
  In support of circularity, meso level initiatives often lead to the establishment of eco-industrial parks. These hubs are strategically designed to facilitate the exchange of resources and waste among companies within close geographical proximity. By co-locating businesses with complementary production processes, these parks promote interactions where one company's waste becomes another's raw material, minimizing waste generation and promoting collaboration and circularity.

In summary, the Circular Economy at the meso level is characterized by the collaborative efforts of businesses and industries to embrace circular practices. This level promotes sustainable production through circular strategies, responsible resource management, and the development of circular supply chains. By fostering circular supply chains, creating eco-industrial parks, promoting collaborative innovation, adopting circular business models, this level serves as a promoter for systemic change, facilitating the transition to a regenerative economic system.

1.2.4. Macro level

As previously introduced, circular economy at the macro level is a comprehensive and complex framework that revolves around systemic changes and the adoption of circular practices of an entire macro entity such as a City, a Region or a Country (Kirchherr et al., 2017). In a macro level circular economy, governments and national bodies implement regulations and incentives that promote waste reduction, recycling, and sustainable resource management.

For Cities, CE is considered as an approach that can decouple urban development from resource consumption thereby integrating economic welfare priorities with eradication of environmental pressures, while addressing socio-economic challenges that Cities face (Marchesi et al., 2020)

From a social perspective, promotion of national education system with the main aim to develop new working profiles able to deal with the new environmental challenges of the present and to propose solution to avoid the loss value through disposal. Investments are made in innovative technologies and sharing oriented practices (Pitkänen et al., 2023).

Education and awareness initiatives target businesses, policymakers, and the public, to benefit the raise of a culture of sustainable consumption and production. International collaboration ensures the exchange of best practices and accelerates the global transition toward a circular economic model, promoting economic growth while minimizing environmental impact.

1.3. Indicators

An indicator is a specific tool employed to assess, monitor, or gauge a particular aspect of a system, process or phenomenon.

Indicators serve as vital tools in various fields, providing measurable insights into complex systems, processes, and outcomes. At their core, indicators are designed to fulfill multiple purposes, primarily to assess performance, guide decision-making, and monitor progress towards specific goals or objectives. Their scope of use extends across diverse domains, including environmental management, economic analysis, social policy, and organizational governance.

In essence, indicators act as navigational aids, offering quantifiable metrics to evaluate the effectiveness of strategies, interventions, and policies. By distilling complex information into manageable data points, indicators facilitate informed decision-making by highlighting areas of success, identifying challenges, and guiding resource allocation.

As pointed out by (Saidani et al., 2019), an indicator can be considered as an analytical tool that simplify the information coming from observations.
The scope of indicators is broad and adaptable, allowing them to address a wide range of objectives and contexts. Environmental indicators, for instance, measure aspects such as air quality, water pollution, and biodiversity loss, providing insights into the health of ecosystems and the effectiveness of conservation efforts. Economic indicators, on the other hand, assess factors like GDP growth, employment rates, and income inequality, offering insights into economic performance and societal well-being. Similarly, social indicators gauge factors such as education attainment, healthcare access, and social cohesion, providing insights into the quality of life and societal progress.
Indicators come in various types, each tailored to specific objectives and contexts. Quantitative indicators rely on numerical data, such as percentages, counts, or rates, to measure phenomena objectively and precisely. Examples include carbon emissions per capita, unemployment rates, and literacy rates. Qualitative indicators, in contrast, capture subjective or qualitative aspects of phenomena, such as perceptions, attitudes, or experiences. Examples include stakeholder satisfaction surveys, expert assessments, and narrative descriptions of social dynamics.
Due to their flexibility, these tools find widespread applications across various domains like economy, environment, science, and social sciences, providing either quantitative or qualitative data crucial for evaluating trends and progresses.
Indicators can be used to assess performance by comparing actual outcomes against predetermined targets, benchmarks, or standards. For instance, a company may use indicators to track progress towards reducing greenhouse gas emissions by a certain percentage over a specified timeframe. By regularly monitoring and analyzing indicator data, organizations can identify trends, detect deviations, and implement corrective actions to improve performance and achieve desired outcomes.

1.3.1. Sustainability Indicators

Sustainability indicators serve as tools for measuring the success of a company or institution's strategies. These strategies are outlined in a sustainability plan and are linked to specific targets, such as reducing carbon footprint or waste during production. Their implementation allows for assessing whether progress is being made in the desired direction (Aplanet, 2023).
The primary purpose of use for these indicators is to gauge whether someone is meeting its objectives. In the event of a deviation, corrective measures can be implemented.

In the context of sustainability, performance is defined as the ability to achieve specific sustainable targets. Thus, sustainability indicators evaluate both the company's performance and the execution of its plans. To conduct a proper performance evaluation, it becomes essential to select the right parameters closely aligned with the proposed objectives; otherwise, they may demonstrate largely ineffective.
Companies adopt sustainability indicators to prove their commitment and results in specific areas. Governments decide to implement sustainability indicators to analyze national strategy and design effective action plans to meet precise target, aiming to receive public funds or to be compliant with global requirements.
Therefore, these instruments are ideal tools for evaluating the implementation of the circular economy at different scopes.

Figure 3 3P sustainability pillars (Getty Images, 2022).

According to the 3P Sustainability model (showed in Figure 3), Sustainability indicators belong to three different areas:

- **Environmental Indicators (Planet)**

  They measure the environmental impact of human activities, encompassing consideration as air and water quality, greenhouse gas emissions, biodiversity, energy consumption, and waste generation. Environmental indicators help in monitoring ecosystems' health and detect potential environmental threats (Sustainability Success, 2023).

- **Social Indicators (People)**

  These instruments focus on individual and community well-being, including factors like education access, healthcare, employment opportunities, poverty rates, and social equity. They evaluate quality of life and social inclusion within society (Sustainability Success, 2023).

- **Economic Indicators (Profit)**

  They measure green financial performance, involving factors such as economic growth, income distribution and resource efficiency. Economic indicators assess the economic viability of long-term development strategies (Sustainability Success, 2023).

Circular economy transition has significant consequences on the three sustainability pillars (Figure 3) and it is essential to understand sustainability indicator's role.
As industries and societies increasingly embrace circularity, the implications resound across environmental, social, and economic dimensions. From mitigating resource depletion and minimizing waste to fostering social equity and driving economic resilience, the circular economy paradigm permeates every facet of sustainable development.
The heart of this transition lies in the need for robust metrics and indicators to gauge progress and inform decision-making. Sustainability indicators serve as compass points, providing valuable insights into the effectiveness of circular initiatives.
Understanding the intricate interplay between the circular economy and sustainability indicators is the key to define a benchmark to measure the real influence of Circular Economy on the society.

1.3.2. Scope

In essence, indicators work as support for decision makers, enabling individuals, organizations, or policymakers to observe changes, set objectives, and measure the effectiveness of interventions or policies. They provide valuable insights and enable benchmarking, making information more comprehensible and manageable.
Quantitative indicators serve as tools that indicate whether planned activities are being executed as intended. They offer measurable data, such as numbers, ratios, or percentages, enabling decision makers to track direct

outputs of their activities. Examples of quantitative indicators include number of people that attend University courses, volume of wasted water or unemployment rates categorized by age, gender, or occupation (Pitkänen et al., 2023).

These indicators do not only monitor values in precise moment, but they are able to reveal improvements or outcomes resulting from changes if compared between each other in different instant of time.

Sometimes it becomes essential to assess variation of parameters, whether positive or negative, brought about by actions or strategies.

On the other hand, qualitative indicators gauge the impact of initiatives by capturing changes on people's perception. Unlike quantitative indicators, qualitative indicators do not rely on numerical data but instead focus on opinions, and feelings. These indicators can measure aspects that lack numerical evidence. Qualitative data, derived from people's viewpoints, offers a refined understanding of progress toward specific goals. Examples of qualitative indicators include assessing the ease of access to instruction or evaluating satisfaction levels with respect to national policies. These indicators, grounded in people's experiences and perceptions, provide insights into the direction and impact of programs and initiatives.

Differently, hybrid indicators are measurement tools that combine both quantitative and qualitative data to assess a specific phenomenon, process, or system. Unlike purely quantitative or qualitative indicators, hybrid indicators provide a more comprehensive understanding by integrating numerical data with qualitative insights.

In practical terms, hybrid indicators often involve the use of numerical data to quantify certain aspects of a phenomenon and qualitative data to provide context, explanations, or deeper understanding. By incorporating both types of information, hybrid indicators offer a richer analysis and enable a more thorough evaluation of the subject matter.

2. Methodology

The following literature review is conducted in accordance with the extended and systematic literature review (SLR) methodology proposed by (Sauer & Seuring, 2023) for its relevance.
After defining the aim of the research and the fundamental questions that constitute the foundation of the work (2.1), it will follow the definition of the criteria used to filter the available resources hence to obtain a depurated sample of instruments to perform the analysis (2.2).
At this point, it will be defined the database where researching documents and the string of research used in the database to obtain the most appropriate group of contents (2.3).
When the starting set of articles is created, it's refined according to the exclusion principles (2.4).
The process of exclusion will be divided in three main stages:

1 Exclusion of contents according to the principals set during 2.2.
2 Exclusion after reading of the abstract
3 Exclusion after a complete reading of the remaining articles

From this moment on, the author will analyze the remaining articles according initially to a predefined coding scheme and then to an axial and open one (2.5).
The process terminates with the presentation of results found in the articles during 2.6.
As Figure 4 shows, SLR is mainly composed by 6 fundamental steps.

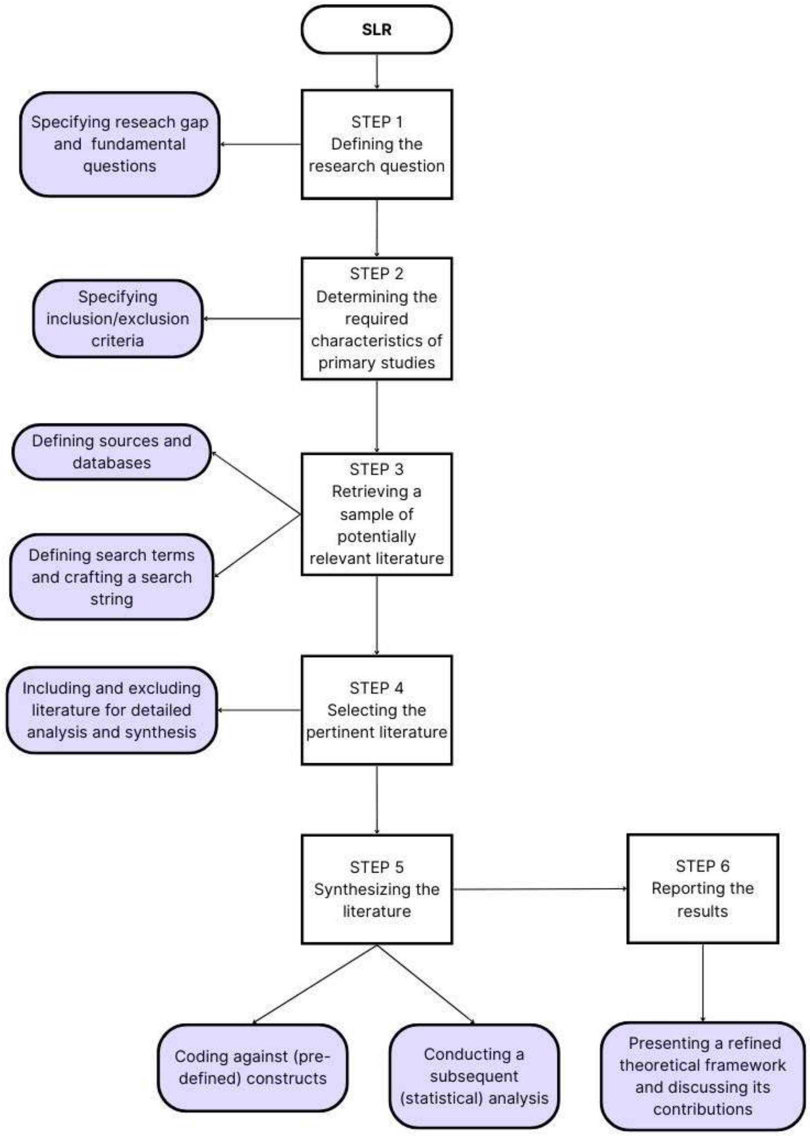

Figure 4 SLR 6 steps

2.1. Step 1: Fundamental questions

To bridge the gap in scientific knowledge and accomplish the objective of this article, two fundamental research questions were formulated and investigated throughout the course of this study.

"Which circularity indicators/circularity performance assessment methods/circularity performance indicators exist at the macro level?"

Surely this first question represents the dominant theme of the entire work. The query deep dive into the comprehensiveness and sufficiency of the tools and methods identified through research for assessing the circularity degree. This inquiry highlights the need to critically evaluate the suitability and thoroughness of the analytical instruments in capturing the circular economy practices. It underscores the importance of achieving a comprehensive overview of the existing tools, enabling researchers and policymakers to make informed assessments and decisions in various geographic context exploiting analyzed instruments.

"Can the three sustainability pillars be assessed by circularity indicators?"

The question suggests an exploration into the compatibility between circularity indicators and the fundamental aspects of sustainability: economic, environmental, and social pillars (Figure 3).
Examining this question is pivotal to understand whether the metrics and indicators employed to measure circularity can effectively embed the entire sustainability framework. By studying circularity indicators in this context, the author aims to assess not only the economic viability but also the environmental consciousness and societal implications of circular practices.
It challenges to ascertain if the indicators utilized can truly capture the complex balance required for a sustainable future.

2.2. Step 2: Exclusion criteria

In accordance with the boundaries set at the beginning of the research, specific inclusion and exclusion criteria are applied to create the analysis sample.

Every paper wrote in languages different from the English is excluded.

A 14 years' time range (2010 – 2024) is set for articles to be considered.

Articles too distant in the past might address subjects that have significantly evolved and reshaped in subsequent years due to the continuous evolution experienced by circular economy. The idea is to focus on recent pieces of work which highlight latest research developments.

As expectable, all the papers that do not elaborate Circular indicators of performance are rejected due to the inconsistence with the core of the research and to the lack of contribution to the scope of the work.

Finally, the last exclusion principle set to articles is the Circular scope.

Only articles focused on macro circularity assessment are considered.

2.3. Step 3: Definition of database and research keywords

One of the most crucial phases in conducting a systematic literature review involves selecting appropriate keywords and choosing relevant databases to support the investigation.

It is decided to proceed initially with a singular database of article, "Scopus".

Scopus is considered the most comprehensive database of peer-reviewed articles in the areas of engineering and management and for this reason was considered to be widely enough in terms of results.

Other sources of article like "Science Direct" or "Google Scholar" were left aside, to be used as backup sources in the case the scarcity of results was such that no solid literature review would have taken place.

Given that the subject matter does not involve dimensions of Circular Economy beyond the macro level, it is decided to isolate as a first word of the string the term "macro", in addition with other terms that delineate the macro scope ("Macro" OR "Cit*" OR "Region*" OR "Countr*").

The first selection has been coupled with a second set of words focused on the circular dimension, namely ("Circular*" OR "Circular Economy "). The necessity in this case is to express in the coding creation the concept of circularity avoiding any possible misleading article based on different topics.

Finally, the third component of the string is defined with the aim to express the concept of "instrument able to assess performance". Due to the large perimeter of action, many different words are employed ("Method*"

OR “Model*” OR “ Indicator*” OR “Assessment*” OR “Metric*” OR “Tool*” OR “Index*” OR “Measure*” OR “ Analysis”).

As shown in Figure 5, the result of the research string is presented.

((‘Macro’ OR ‘City’ OR ‘Region’ OR ‘Country’) AND (‘Circular’ OR ‘Circular Economy’) AND (‘Method’ OR ‘Model’ OR ‘Indicator’ OR ‘Assessment’ OR ‘Metric’ OR ‘Tool’ OR ‘Index’ OR ‘Measure’ OR ‘Analysis’))

Figure 5 Search string

2.4. Step 4: Detailed papers analysis

As depicted in Figure 6, 387 results were obtained from the combinations of words generated by the string.

The previously cited exclusion criteria have allowed to depurate the sample from irrelevant articles.

At the end of this passage (STAGE II), the remaining set counts 115 different articles.

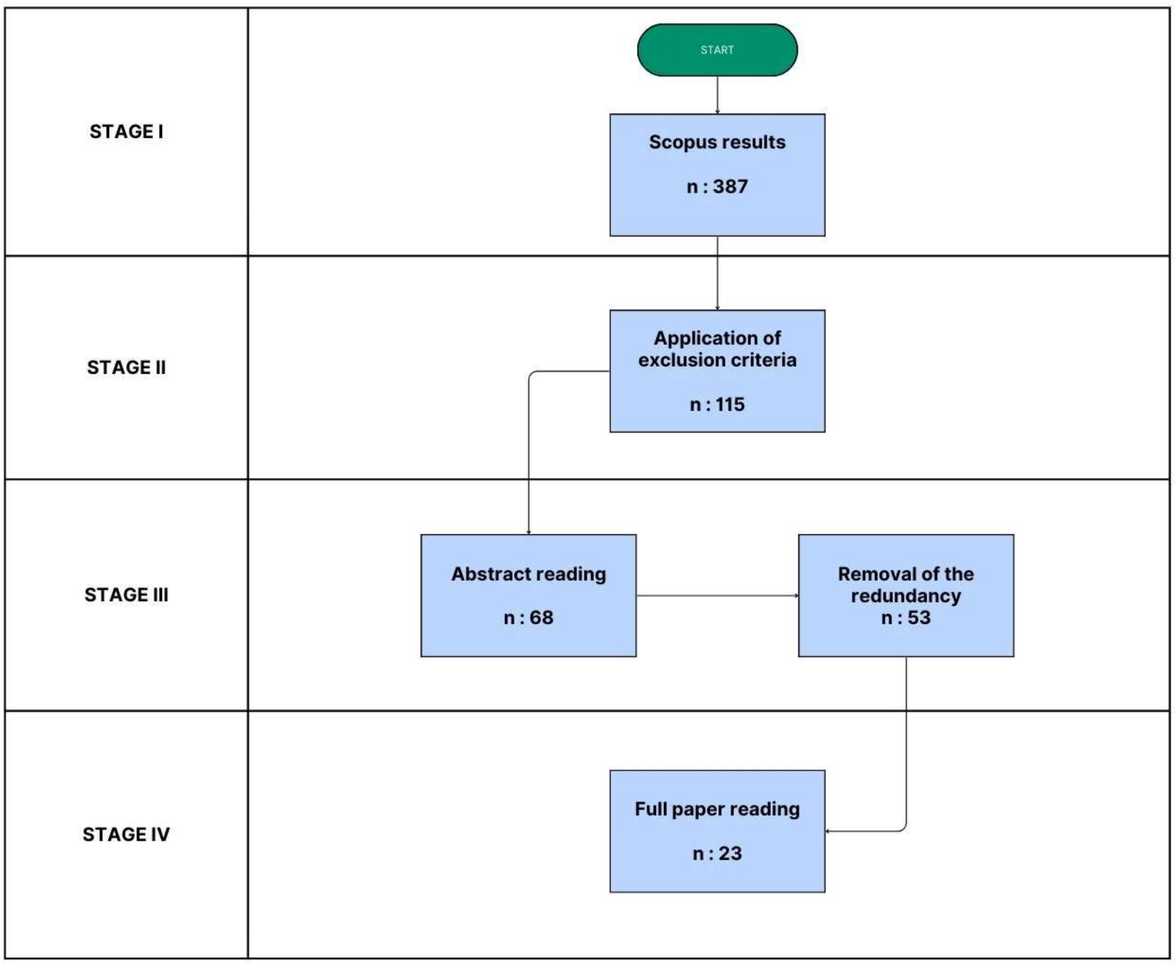

Figure 6 Papers exclusion process

Then, a more selective process (STAGE III) is observed aiming to secure a selection of the most relevant papers. This is obtained reading the full abstract of the articles. By doing this, it becomes clearer which documents can provide the most valuable and precious contents to the research.

68 articles remain after the analysis after abstract reading.

To this end it's useful to precise that within this remaining amount, many paper articles are found redundant in terms of contents.

For instance, articles perfectly aligned with the inclusion criteria but too similar in term of indicators considered or industry studied were excluded due to the poor value contributed by individuals.

For that reason, a manual cross-checking process is conducted to eliminate redundant results. The sample after this procedure counts 53 searching result.

The last step performed can be considered as an additive check following the first abstract reading.

That is accomplished through the complete reading of the articles and identification of the main indicators argued. This passage results to be indispensable since a marginal component of the list was deviating from the expected topic coverage.

An example of final exclusion can be experienced in articles that present and explore indicators used to define how much a system is ready for a Circular economy model application. Readers may readily observe a significant divergence from the literature review's focus, as it lacks concrete tools for measuring actual circularity condition, a consideration that was not achievable after a simple examination of the abstract.

The final number of papers selected for the analysis is 23.

2.5. Step 5: Coding scheme

Following the extraction of the selected papers to be fully read, these were tabularized in a spreadsheet (Table 1).

AUTHORS	TITLE
(Avdiushchenko & Zajaç, 2019)	"Circular Economy Indicators as a Supporting Tool for European Regional Development Policies"
(de Ferreira & Fuso-Nerini, 2019)	"A Framework for Implementing and Tracking Circular Economy in Cities: The Case of Porto"
(de Souza et al., 2024)	"A Multi-level Resource Circularity Index based in the European Union's Circular Economy Monitoring Framework"
(Gao et al., 2021)	"Evaluating circular economy performance based on ecological network analysis: A framework and application at city level"
(Gatto, 2023)	"Quantifying management efficiency of energy recovery from waste for the circular economy transition in Europe"
(Geng et al., 2012)	"Towards a national circular economy indicator system in China: an evaluation and critical analysis"
(Haas et al., 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"
(Heshmati & Rashidghalam, 2021)	"Assessment of the urban circular economy in Sweden"
(Kakwani & Kalbar, 2022)	"Measuring urban water circularity: Development and implementation of a Water Circularity Indicator"
(Karman & Pawłowski, 2022)	"Circular economy competitiveness evaluation model based on the catastrophe progression method"
(Manea et al., 2021)	"CIRCULAR ECONOMY AND INNOVATIVE ENTREPRENEURSHIP, PREREQUISITES FOR SOCIAL PROGRESS"
(Martínez Moreno et al., 2023)	"A global and comparative assessment of the level of economic circularity in the EU"
(Mazur-Wierzbicka, 2021)	"Circular economy: advancement of European Union countries"
(Musyarofah et al., 2023)	"Developing a Circular Economy Index to Measure the Macro Level of Circular Economy Implementation in Indonesia"
(Nurdiana et al., 2021)	"How Shall We Start? The Importance of General Indices for Circular Cities in Indonesia"
(Pitkänen et al., 2023)	"How to measure the social sustainability of the circular economy? Developing and piloting social circular economy indicators in Finland"
(Yang et al., 2011)	"Study and Integrative Evaluation on the development of Circular Economy of Shaanxi Province"
(Silvestri et al., 2020)	"Regional development of Circular Economy in the European Union: A multidimensional analysis"
(Smol, 2023)	"Inventory and Comparison of Performance Indicators in Circular Economy Roadmaps of the European Countries"
(Stanković et al., 2021)	"An integrated approach of PCA and PROMETHEE in spatial assessment of circular economy indicators"
(Tong et al., 2021)	"Using weighted entropy to measure the recyclability of municipal solid waste in China: Exploring the geographical disparity for circular economy"
(Vranjanac et al., 2023)	"Modeling circular economy innovation and performance indicators in European Union countries"

(Wang et al., 2018)	"Evaluation of Urban circular economy development: An empirical research of 40 cities in China"

Table 1 Final papers sample

The Thesis then proceeds with a preliminary analysis stage, leveraging the distinctive characteristics of various papers to compare articles after the selection process. This passage is even known as Bibliometric analysis. Table 2 shows the 3 main shared levels of analysis:

Bibliometric levels of analysis
Geographical Area
Date of Publication
Journal of publication

Table 2 Bibliometric levels of analysis

The selection of these primary coding dimensions is made accordingly to the different SLR found in the literature.

Examining the geographical distribution of papers allows to gain a global perspective on the topic of interest. It helps in understanding how research and knowledge are distributed across different regions and countries. This can be crucial for identifying trends, disparities, and areas of focus in different parts of the world.

Different regions and countries may have unique cultural, social, economic, and political contexts that can influence research findings. Analyzing the geographical distribution helps researchers to recognize these variations and to consider the impact of cultural and contextual factors on the outcomes of studies.

Nevertheless, understanding where studies have been conducted can provide insights into the applicability of findings. Research conducted in specific geographical locations may have implications for those regions, and researchers need to consider the extent to which findings can be applied to other settings.

Examining the temporal distribution allows to identify trends and patterns in the development of a particular topic over time. It helps to understand how literature has evolved, what key milestones or breakthroughs have occurred, and how the focus of studies may have shifted over different periods.

It allows to observe the progression of ideas and innovations, providing insights into when certain concepts gained prominence or when new technologies became influential in a particular field.

This thesis can gain a better understanding of the maturity and stability of a topic by considering the frequency and distribution of publications over different time periods.

The final step of investigation is created to show to the readers which are the main sources (journals) that helped to populate this research.

The following stage of the work involves coding against personal constructs, as proposed in figure 7, providing additional analysis instruments.

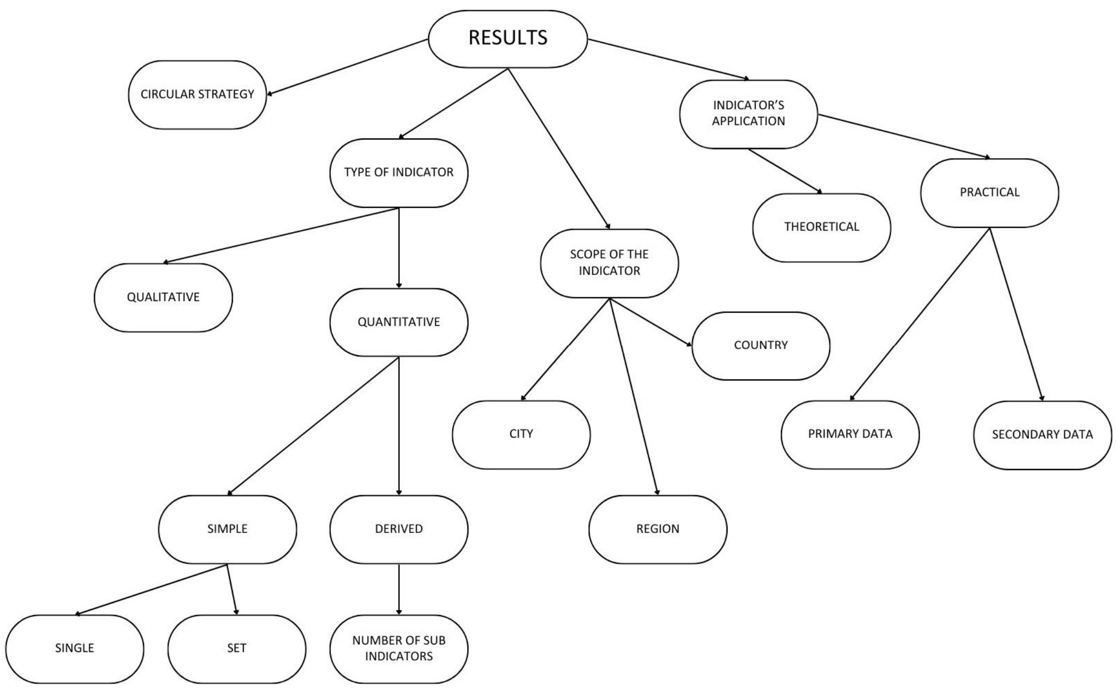

Figure 7 Axial coding scheme

2.5.1. Circular Strategy

It's useful to underscore which type of circular strategy has been mainly followed to measure circularity level of geographical areas.

Strategies considered are the ones presented in Chapter 1, Figure 1.

This part of the work will be very useful especially in a few pages, where potential gap found in the literature will be discussed.

2.5.2. Type

While the difference between qualitative and quantitative has been already presented in Section 1.3.2 indicators can be further classified into:

- Simple indicators

"Uncomplicated measures that provide direct information about a specific aspect or variable "

- Derived indicators

"Composite measures created by combining multiple simple indicators or variables. They are designed to provide a more comprehensive view or insight into a complex phenomenon "

In chapter 3, readers will observe that not all researchers decide to use derived indicators.

Sometimes it becomes useful to exploit a set of simple indicators to be used "in parallel" to not contaminate the value added, in term of contribution, by the single figures.

Doing so, we can provide a complete overview for performance assessment without compromising the influence of a single indicator, typical caused by the weighting process during derived indicators creation.

2.5.3. Scope

The scope of the instruments represents the geographical area of application for assessment tools.
It's important now to understand statistically which type of scope is more common.
This information allows to make precious consideration about common literature trend.
Additionally, it helps to understand which is the more suitable perimeter of action for circularity assessment.
It's important to highlight that not every assessment approach will be strictly suited for a specific geographical dimension. Sometimes certain indicators will be suited for multiple applications at different scopes.
On the other side, the more tailored is a methodology is, the higher the detail supplied to the research.

2.5.4. Application

An essential aspect of analysis revolves around the practical application of indicators. Delving deeper into the contents, readers will observe that numerous studies draw strength from practical case studies, enhancing the validity of their findings.
In this case, data employed to validate the assumptions can be acquired directly through socio/geographic questionnaires ("primary data") or sourced from public databases ("secondary data").
Conversely, a smaller portion of the sample lacks integration with real-world scenarios in their computations.
Consequently, this subset remains a theoretical approach to circularity evaluation.

2.6. Step 6: Results

The conclusive phase of a Systematic Literature Review entails the presentation of analytical findings extracted from the reviewed papers.
Chapter 5 illustrates the main findings of the systematic literature review and serves as a pivotal figure in the overall structure of the research document.
The results chapter presents the outcomes of the investigation. It provides a detailed account of the data collected, the statistical analyses performed, and the patterns / trends identified. This section allows readers to understand the empirical evidence and it allows to explain the significance of finding.

Regarding the initial research questions, the results chapter provide the contents to answer the fundamental queries that inspired this work, contributing to the overall argument and significance of the study.

3. Results

3.1. Bibliometric analysis

3.1.1. Temporal distribution

Publication year investigation clarifies when CE exploration has become an undeniable necessity and when academic awareness has started to gain relevance in the literature.

Looking at Figure 8, the bibliometric analysis unmistakably reveals a growing enthusiasm in the field. Papers publication has experienced a notable increase since 2018.

The highest number of articles (7) have been published in year 2021 (Figure 8).

One Reason that can explain this tendency is the increasing environmental concern that raised in the recent years. The introduction of this innovative concept has captured the attention of many researchers. Moreover, this kind of knowledge and academic background is highly demanded by national authorities and businesses striving to enhance their sustainable practices.

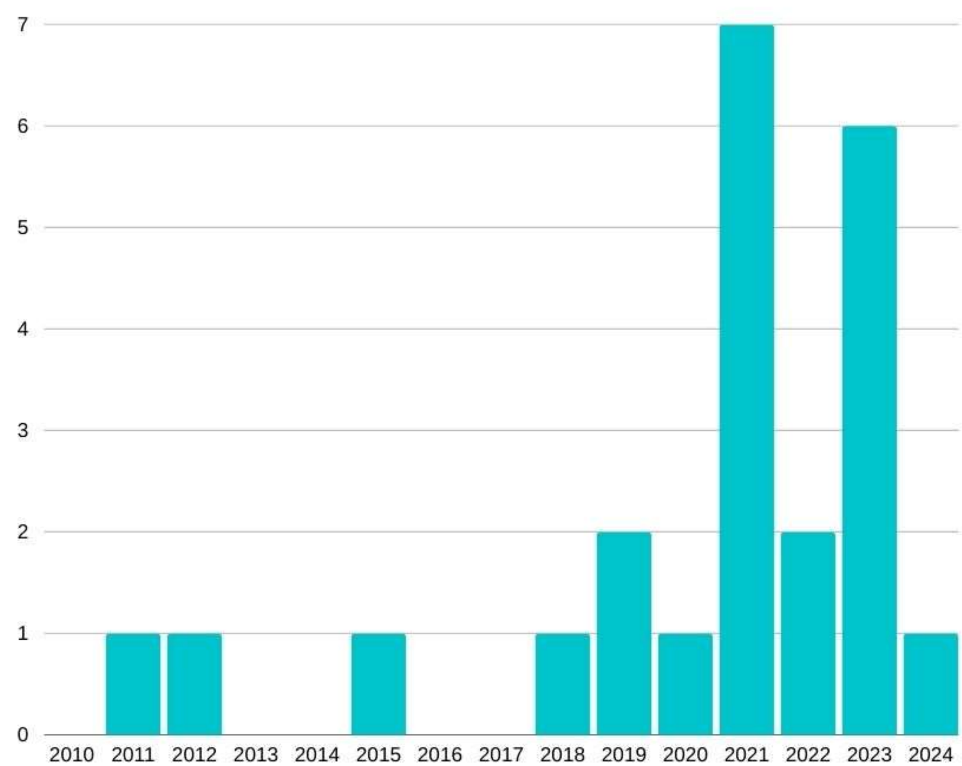

Figure 8 Papers distribution over time

3.1.2. Geographical Distribution

When examining the geographic concentration of research, it becomes clear that China and Europe emerge as frontrunners, collectively contributing with more than 15 publications in the current sample.
China, a nation with a strong establishment, found it difficult to overlook such a compelling opportunity, especially given the ongoing ecological challenges that has encountered over the last fifty years.
Figure 9 illustrates the residuals distribution.
There is a notable dearth of research papers originating from the African region. This lack underscores the inextricable link between sustainable research endeavors and the level of economic development.
It emphasizes the necessity for a more inclusive and equitable approach for research to address global sustainability challenges comprehensively.

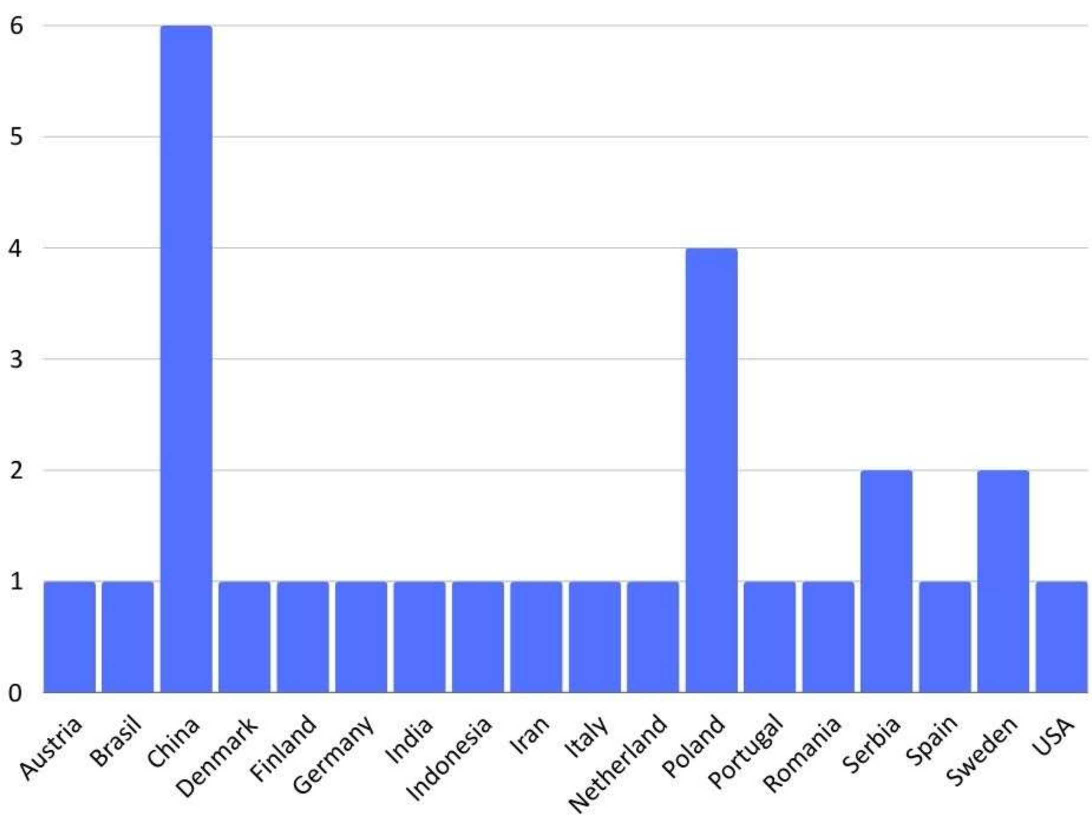

Figure 9 Papers geographical distribution

3.1.3. Journal Distribution

All referenced sources used for this study were drawn exclusively from published articles, hence excluding the Thesis, conference proceedings, or grey literature.

As observable, provenience of papers is depicted in Figure 10.

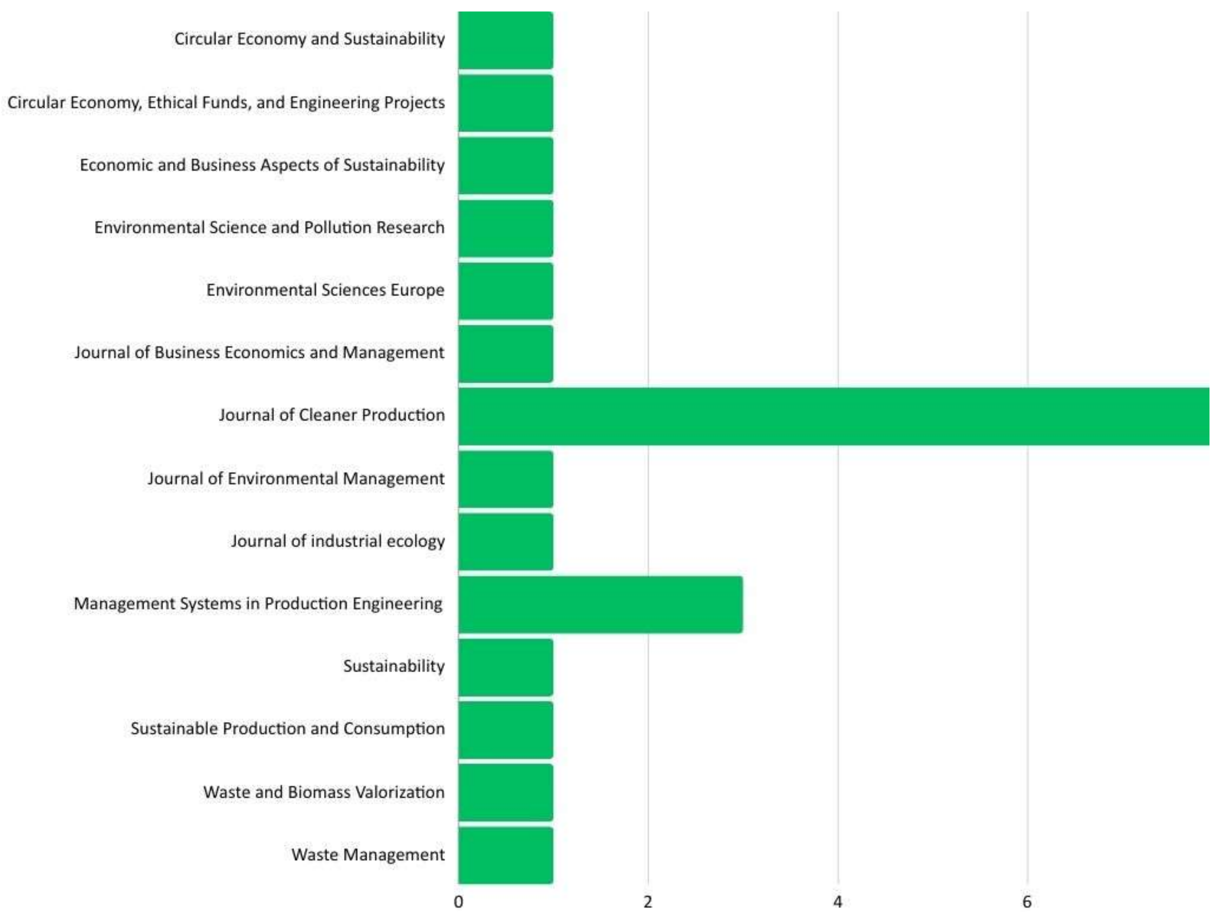

Figure 10 Journal provenience of papers

The larger portion of articles have been published in sustainability-oriented journals like “Journal of Cleaner Production”, marginal contributions are supplied by other journals.

This trend is comprehensible since CE in not considered as one of the priorities, for example, by economic researchers, even if financial benefits of CE are undebatable.

3.2. Analytic findings

This section describes the assessment methods prosed by researchers in the papers, including their underlying analytical and mathematical foundations.

To facilitate the comprehension, the contents are divided per category to display in a more organized way the findings, starting from the Eurostat based indicators (Section 3.2.1). Then chapter will proceed analyzing waste oriented (Section 3.2.2) and social circularity indicators (Section 3.2.3).

It will follow Section 3.2.4, based on MFA oriented methods to assess circularity, Section 3.2.5 based on national circularity indicators and finally section 3.2.6, based on circularity indicators at the municipal level.

3.2.1. Eurostat based Indicators

The first category of circular assessment models is related with the European system of measurement of circularity. These studies are brought together by their relationship with the Eurostat.

Eurostat is the statistical office of the European Union that provides the EU with statistics at a European level that enable comparisons between countries. The values of CE indicators are an integral part of the European way of life and show the progress of EU countries towards the CE. For research purposes, Eurostat indicators are used within the area of monitoring framework, and they are classified into 3 main thematic areas:

1. Production and consumption
2. Waste management
3. Secondary raw materials

(Vranjanac et al., 2023) aims to explore the connection between Circular Economy innovations and performance in EU countries, using indicators from the Eurostat CE indicator set.

The study uses average indicators for EU27 countries from the period 2018-2021, including measures such as resource productivity, recycling rates of municipal waste, circular material use rate, private investments, jobs, and gross value added related to CE sectors, patents related to recycling and secondary raw materials, recycling rates of all waste excluding major mineral waste, and generation of municipal waste per capita. This applied research seeks to illustrate a decoupling between economic growth and resource use, contributing to the understanding of transition towards a CE in the EU.

(Manea et al., 2021) proposes the identification of a circular economy indicator (CEI) to investigate the complexity of circular economy in EU countries.

CEI relies on 14 Eurostat proposed sub-indicators, divided into Production and consumption, Waste management, Secondary raw materials, and Competitiveness and innovation areas.

For the construction of the composite index, the PCA method was exploited.

Assumed a not negligible correlation between variables, this method combines metrics to reduce redundancy while capturing the maximum amount of variance of the data.

To do so, groups of indicators called "principal components" are created. Indicators are gathered in groups depending on their variability.

The weight used for the formulation of the final derived indicator depends on the individual variance following the general rule: "the higher the variance, the higher the contribution in the final index".

The study analyzes statistical secondary data at the EU country level in 2019.

The study of (Mazur-Wierzbicka, 2021) utilizes Circular Economy monitoring indicators proposed by the European Commission, focusing on the macro-level analysis of 28 EU member states (EU-28) in the timeframe between 2010 to 2018. The research process involves statistical analyses conducted using "PQStat" and "GradeStat" software. Thirteen CE indicators are identified from the original Eurostat set, considering partial indicators, aggregated data (self-sufficiency for raw material, contribution of recycled material to raw materials demand), and undeveloped statistics (Green Public Procurement, Food waste).

In Table 3 the selection is presented.

	INDICATOR	INDICATOR TYPE
1	Generation of municipal waste per capita	EUROSTAT indicator
2	Generation of waste excluding major mineral wastes per GDP unit	Aggregated indicator
3	Generation of waste excluding major mineral wastes per domestic material consumption	Aggregated indicator
4	Recycling rate of municipal waste	EUROSTAT indicator
5	Recycling rate of all waste excluding major mineral waste	EUROSTAT indicator
6	Recycling rate of packaging waste by type of packaging	EUROSTAT indicator
7	Recycling rate of e-waste	Aggregated indicator
8	Recycling of bio-waste	Undeveloped indicator
9	Recovery rate of construction and demolition waste	Aggregated indicator
10	Circular material use rate	EUROSTAT indicator
11	Trade in recyclable raw materials	Undeveloped indicator
12	Private investments, jobs and gross value added related to circular economy sectors	EUROSTAT indicator
13	Patents related to recycling and secondary raw materials	EUROSTAT indicator

Table 3 (Mazur-Wierzbicka, 2021) indicators type

Countries are then divided in 2 clusters of analysis (based on proximity) and the results are compared with respect to the selected variables.

Like all the indicators system belonging to the "Eurostat category", secondary data employed to support the analysis were extracted from the Eurostat dataset for a period ranging from year 2010 to 2018.

(Silvestri et al., 2020) mainly aim to discuss the CE performance of 169 European regions by building two composite indicators - the Circular Economy Static Index (CESI) and the Circular Economy Dynamic Index (CEDI) that permitted both a static and a dynamic evaluation of the CE performance of European regions.

11 variables were chosen within the set of available items in Eurostat database, to reflect the adopted definition of CE and hence covering the fields of recycling ("the value of products, materials and resources is maintained in the economy for as long as possible"), waste management (minimized waste generation), low carbon and resource efficient orientation (resource efficient economy), sustainability and competitiveness (obtaining competitive advantage from innovative CE approach).

Figure 11 shows the selection of metrics that characterize the CESI indicator. A particular attention must be kept on the weight and contribution assigned to each one.

These aspects become essential when statistics are gathered throughout a weighted average with the objective to obtain a unique figure advantageous to make comparisons between region of EU.

Variables included in each CE dimension	Contribution in the calculation of the Index
SOCIO-HEALTH DIMENSION (weight 1/3)	
Life expectancy 2015	(+)
Diseases of the circulatory system (rate) 2015	(−)
Malignant neoplasms (rate) 2015	(−)
Transport accidents (rate) 2015	(−)
ECONOMIC DIMENSION (weight 1/3)	
GDP at current market prices (euro per inhabitant) 2015	(+)
Total intramural R&D expenditure (euro per inhabitant) 2013	(+)
Total amount of fractional patents inv. per year 2013	(+)
ENVIRONMENTAL DIMENSION (weight 1/3)	
Waste generated (tonnes per inhabitant) 2011	(−)
Waste recycling - composting and digestion (tonnes per inhabitant) 2011	(+)
Artificial land (percentage) 2015	(−)
Estimated soil erosion by water (tonnes per hectare) 2012	(−)

Figure 11 CESI indicator composition

(Silvestri et al., 2020)

In a similar way, Figure 12 shows the composition of CEDI indicator.

Variables included in each CE dimension	Contribution in the calculation of the Index
SOCIO-HEALTH DIMENSION (weight 1/3)	
Growth rate life expectancy 2012/2015 (%)	(+)
Growth rate diseases of the circulatory system 2012/2015 (%)	(−)
Growth rate Malignant neoplasm 2012/2015 (%)	(−)
Growth rate Transport accidents 2012/2015 (%)	(−)
ECONOMIC DIMENSION (weight 1/3)	
Growth rate GDP at current market prices 2012/2015 (%)	(+)
Growth rate Total intramural R&D expenditure 2011/2013 (%)	(+)
Growth rate Total amount of fractional patents inv. per year 2010/2013 (%)	(+)
ENVIRONMENTAL DIMENSION (weight 1/3)	
Growth rate waste generated 2010/2011 (%)	(−)
Growth waste recycling per inhabitant - composting and digestion 2010/2011 (%)	(+)
Growth rate artificial land 2012/2015 (%)	(−)
Growth rate estimated soil erosion by water 2000/2012 (%)	(−)

Figure 12 CEDI indicator composition

(Silvestri et al., 2020)

(Silvestri et al., 2020) choose to distinguish between Static and Dynamic assessment instruments.

Due to the dynamic nature of the variables, CEDI index is enrolled with the aim to capture the variation between parameters over time, reflecting the relative Circular Economy performance improvements. CEDI awards regions with the highest improving rates for CE variables. This perspective captures advancements, even if the absolute levels achieved might appear weak, a factor evaluated by the previous Index, CESI.

An alternative approach is proposed by (de Souza et al., 2024), who avoid selecting multiple circularity-oriented metrics to be combined and focus on a single analytic computation centered on the measurement of circulation of refurbished material within the perimeter of a Country.

This evaluation can be made thanks to the MCU index.

Figure 13 visually describe the concept of Circularity gap (CG), from which MCU index comes from.

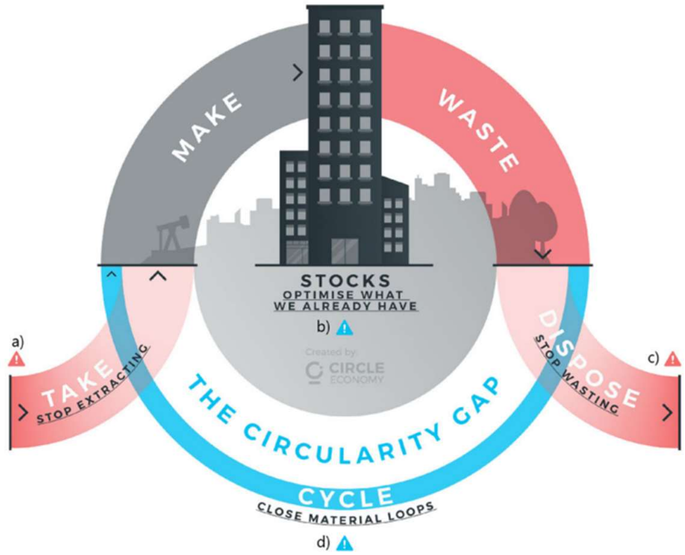

Figure 13 The Circularity Gap (CGRi powered by Circle Economy Foundation, 2018).

National CG is determined with the expression (equation 1):

$$\mathrm{NCG} = 1 - \mathrm{CMU}$$

Equation 1

CMU is the 'Circular Material Use Rate'. The CMU of a country of EU28 can be estimated as ration of share of Secondary Material (SM) on Overall Material Used (equation 2). SM is the sum of waste recovered locally (RCVR) and waste exports (EXPW) trimmed by imports of waste (IMPW). DMC stands for Domestic Material Consumption and it's the total amount of materials directly used by an economy. These figures are normally expressed in [Kt] per year, while the CMU is reported bi-yearly.

$$CMUc = \frac{SMc}{OMUc} = \frac{(\ RCVr + EXPw + IMPw\ )c}{DMCc + (\ RCVr + EXPw - IMPw\ )c}$$

Equation 2

The paper applies the proposed method, evaluating the CMU index for every European member state and CMU index for national regions (16 NUTS-1 regions of Germany were taken as reference for the CMU regional consistency demonstration).
MCU uses secondary data supplied by Eurostat.
it seems to be well suited with the objective of the research even if a significant limitation can be observed. The SD and the CMU parameters consider only recycled materials as secondary materials. Preparation for Reuse (PfR), consisting of the activities like repair, repurpose, refurbishing and remanufacturing, is currently not accounted for.
This limitation can lead to unintended or incomplete assessments of circularity if we consider countries where the PfR works as a preferred way to “close” the material circularity loop.
Another indicator is the one proposed by (Martínez Moreno et al., 2023) labelled CECI (Circular Economy Composite Index). It is a comprehensive measure devised for the European Union and its Member States to gauge progress following the implementation of the first Action Plan for the Circular Economy (APCE) spanning 2014–2020. This index evaluates the effectiveness of recycling and “downcycling”. It achieves this through the straightforward and easily interpretable calculation method previously called Principal Component Analysis (PCA).
CECI is based on a set of 22 indicators included in the MFCE (First Monitoring Framework on Circular Economy of EU) and relies on secondary data from Eurostat.
In Figure 14 the composition of CECI is highlighted.
Secondary data exploited depict the performances of 27 EU members and UK in 4 different years of the previously introduced timespan.
More precisely the work of (Martínez Moreno et al., 2023) has selected as reference:

- 2014: Year prior to the publication of APCE
- 2018: Year of publication of APCE
- 2019: First year after publication
- 2020: Most recent year for available data

INDICATOR	SUB-INDICATOR
1. EU self-sufficiency for raw materials	
2. Green public procurement	
3. Waste generation	3.1. Generation of municipal waste per capita
	3.2. Generation of waste excluding major mineral waste …
4. Food waste	
5. Recycling rates	5.1. Recycling rate of municipal waste
	5.2. Recycling rate of all waste excluding …
6. Recycling/recovering for specific waste streams	6.1. Recycling rate of overall packaging
	6.2. Recycling rate of plastic packaging
	6.3. Recycling rate of wooden packaging
	6.4. Recycling rate of e-waste
	6.5. Recycling rate of biowaste
	6.6. Recovery rate of construction and demolition waste
7. Contribution of recycled materials to raw material s demand	7.1. End-of-life recycling input rates (EOL-RIR), aluminium (%)
	7.2. Circular material use rate
8. Trade in recyclable raw materials	8.1. Trade in recyclable raw materials: Imports from non-EU countries
	8.2. Trade in recyclable raw materials: Exports to non-EU countries
	8.3. Trade in recyclable raw materials: Intra EU trade
9. Private investments, jobs, and gross value added	9.1. Gross investment in tangible goods
	9.2. Employees
	9.3. Value added at factor cost
10. Patent related to recycling and secondary raw materials	Number of patents related to recycling and secondary raw materials

Figure 14 CECI indicator composition

(Martínez Moreno et al., 2023)

The aggregation of the sub-indicators for the construction of the CECI index is carried out linearly according to Equation 3, expression appliable for every year of inspection:

$$CECI = \sum wi \ x \ Ii$$

Equation 3

Ii *: values of the one-dimensional sub-indicators chosen*

wi *: weights of each indicator*

(Stanković et al., 2021) selected a wide range of indicators to evaluate the level of circularity of European countries pointing on different evaluation perspective and applying the PROMETHEE II approach to estimate which alternative, defined as a cluster composed by a certain number of countries, is better between the options.

PROMETHEE II allows decision-makers to assess alternatives against criteria in varying circumstances (i.e. the year considered) in order to determine a preference direction that leads to the optimal condition.

The preference between two alternatives can be determined starting from quantitative or qualitative input, depending on the nature of the criteria. Every criterion is linked with a specific weight according to the specific order of relevance in the assessment. PROMETHEE II then processes this information to generate a ranking of the alternatives.

The preference function evaluation is carried on between alternatives (clusters).

(Stanković et al., 2021) employed the following metrics (Figure 15):

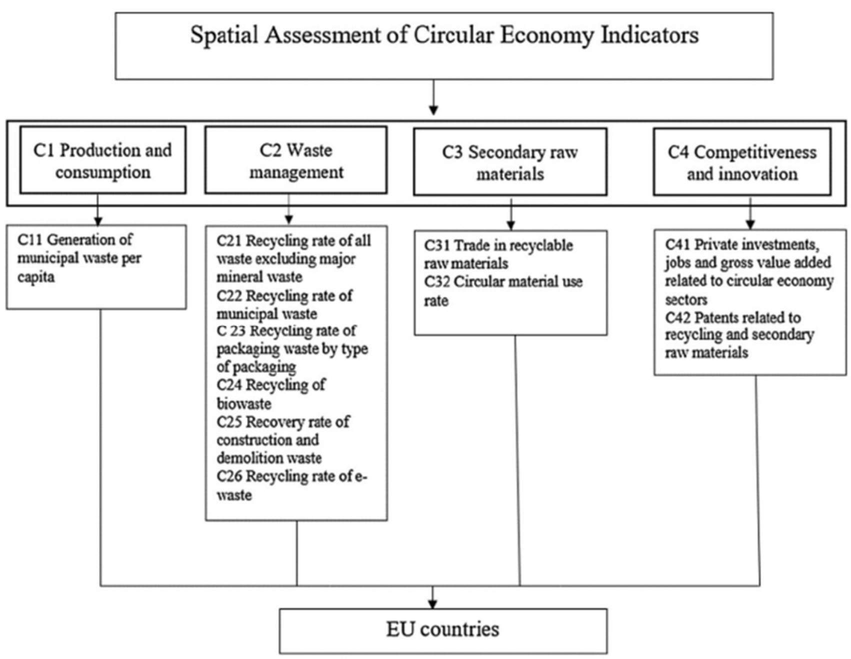

Figure 15 Stankovic circularity indicator composition

(Stanković et al., 2021)

(Karman & Pawłowski, 2022) instead introduced a methodology known as the Composite Economic Circularity Index (CECI). To create CECI, a comprehensive set of 30 fundamental indicators was curated, forming the basis of the analysis. These indicators were then grouped into groups, each representing a distinct theme within the circular economy landscape. These themes were further subdivided into macro pillars, refining the categorization process to capture nuanced aspects of circularity. The totality of the pillar defines the final comprehensive index (Figure 16).

Main index	Pillar	Theme	Indicator
CE Competitiveness index	Social behaviours	Waste households	Food waste
			Generation of municipal waste per capita
			WEEE waste collected from households
			The volume of sewage from households
		Energy and Material Consumption households	Energy consumption per household
			Domestic material consumption/ per capita
			Water consumption per household
	Business operations	Energy and Material Consumption industry	Energy consumption per industrial sector
			Direct material input
		Waste industry	GHG emission from industrial sectors
			Waste from industrial sectors
	Resource management	Recycling	The recycling rate of municipal waste, perc
			The recycling rate of all waste excluding major minerals waste, perc
			The recycling rate of packaging waste by type of packaging, perc
		Recycling spec	Recycling rate of e-waste, perc
			The recycling rate of plastics
			The recycling rate of biowaste
		Recovery	The recovery rate of construction and demolition waste
			Energy recovery per capita
		Circularity	Circular material use rate
			Resource productivity
			Amount of treated sewage per capita
			Share of renewable energy in gross final energy consumption
	Innovativeness	Eco Innovation Index	Eco-innovation index
		Investment	Patents related to recycling and secondary raw materials
			Private investment, cost factor related to circular economy sectors
			Private investment, jobs related to circular economy sectors
			Waste protection investment in mln Euro
		Green economy	Labour productivity
			Trade in recyclable raw materials

Figure 16 Karman circularity indicator composition

(Karman & Pawłowski, 2022)

To ensure consistency across various measurement scales, data underwent normalization, preventing discrepancies arising from different measurement units. In (Karman & Pawłowski, 2022) study, averages were calculated based on data from different years within a predetermined timeframe.

Following this step, the weights for the primary categories were calculated by summing the weights of the respective sub-indicators. It is important to note that these weights are inherently relative in nature. After a conversion of these relative weights into absolute values, the weighted sum aggregation method is applied to compute the Circular Economic Circularity Index (CECI) for each country.

(Avdiushchenko & Zajaç, 2019) also suggest a set of potential indicators to assess the advancement of the circular economy (CE) on a regional scale within European Union nations. This was achieved by firstly conducting a deep research the existent Eurostat CE indicators and monitoring methods proposed by the different European policies like EUROPE 2020, Sustainable Development Strategy (from 2005 to 2015) and Sustainable Development Goals (since 2016), Euro-indicators and European Pillars of Social Right. Every one of them has been defined with the clear intent to monitor CE implementation at the national level. The scope of the work was to model these existing frameworks and explore the feasibility of adapting these methods to European regions.

(Avdiushchenko & Zajaç, 2019) extracted indicators from the existing European monitoring framework and added additional metrics obtaining a final set of 130 circular measurement tools. After the exploration phase was completed, they summarized this complex amount of metric and proposes a set of 25 quantitative indicators divided in 7 main thematic classes (figure 17).

The combination of these indicators is delegated to the individual application, although a conventional weighted average appears to be the customary compromise between computational simplicity and mathematical significance.

Dimensions	No.	Indicators	Units
Economic prosperity economy	1.1	GDP	per capita, fixed prices, PLN
	1.2	Average life expectancy at birth for men	years
	1.3	Registered unemployment rate	%
	1.4	At-risk-of-poverty rate	%
Zero-waste economy	2.1	Municipal waste collected selectively in relation to the total amount of municipal waste collected	%
	2.2	Municipal waste collected per one inhabitant	tons/person
	2.3	Industrial and municipal wastewater purified in wastewater requiring treatment	%
	2.4	Outlays on fixed assets serving environmental protection and water management related to recycling and utilization of waste	per capita, fixed prices, PLN
Innovative economy	3.1	Expenditures on research and development activities	per capita, fixed prices, PLN
	3.2	Average share of innovative enterprises in the total number of enterprises	%
	3.2	Adults participating in education and training	%
	3.4	Patent applications for 1 million inhabitants	
Energy-efficient and renewable energy-based economy	4.1	Share of renewable energy sources in total production of electricity	%
	4.2	Outlays on fixed assets serving environmental protection and water management related to electricity saving	per capita, fixed prices, PLN
	4.3	Electricity consumption	kWh/person
Low carbon economy	5.1	Carbon dioxide emission from plants especially noxious to air purity	tons/person
	5.2	Emission of particulates	tons/1 km^2
	5.3	Passenger cars	Cars/1000 population
	5.4	Pollutants retained or neutralized in pollutant reduction systems in total pollutants generated from plants especially noxious to air purity	%
	5.5	Outlays on fixed assets serving environmental protection and water management related to protection of air and climate	per capita, fixed prices, PLN
Smart economy	6.1	Households with personal computer with broadband connection to Internet	%
	6.2	enterprises with access to the Internet via a broadband connection	%
Spatially effective economy	7.1	Forest cover indicator	%
	7.2	Street greenery and share of parks, lawns and green areas of the housing estate areas in the total area	%
	7.3	Urbanization rate	%

Figure 17 Avdiushchenko circularity indicator composition

(Avdiushchenko & Zajaç, 2019)

Consequently, the developed tool is exploited in an authentic case study focused on Malopolska, a Polish region located in the south-east of the country.

Leveraging secondary data sourced from the internal databases of the Malopolska Regional Statistical Office and the Environmental Department of the “Malopolska Marshal Voivodeship Office”, the goal was achieved.

3.2.2. Waste oriented Indicators

This section investigates the research that acknowledge waste generation and the related environmental burden as vital in the assessment of circularity.

One of the most significant contributions to this section is supplied by the work of (Gatto, 2023).

The main center of this analysis is the Waste to Energy sector (WtE). WtE is the process by which waste is incinerated with energy recovery, providing a beneficial service to communities by treating residual waste that cannot be prevented or recycled (https://www.covanta.com/what-we-do/waste-to-energy).

Even if it is still utopic to think of the WtE sector as capable to cover a large share of the electricity demand of a modern city, this field is crucial for EU policies to facilitate the CE transition. The following indicator provides a clear estimation of the effective efficiency of this sector in European Countries.

To assess the efficiency of Waste-to-Energy (WtE) practices in alignment with Circular Economy principles and existing research, this study introduces the composite indicator EIMEERW. The composite indicator serves as comparative tools for national performance, and it is valuable in policymaking due to its low subjectivity and huge comparability over time, enhancing communicative effectiveness.

In this study, an initial sub-index was created by selecting and processing 14 energy-related variables.

This information becomes the foundation to obtain the 3 sub-indicators that composes the EIMEERW final indicator, as shown in Figure 18.

Variable	Composition	Composite Indicator
Domestic waste-based power production	% of domestic waste based power production	
Production efficiency of WtE.plants	waste-based power production divided by the amount of waste treated	EIMEERW
Average production capacity of WtE plants	total amount of waste treated divided by the number of plants	

Figure 18 EIMEERW indicator composition

(Gatto, 2023)

The initial aspect focuses on the country's proportion (expressed as a percentage) of power generation derived from waste, indicating a potential cost advantage of Waste-to-Energy (WtE) facilities over conventional energy production. This dimension captures factors such as stringent environmental regulations and public subsidies supporting WtE operations. The second aspect evaluates the efficiency of WtE plants, calculated by dividing waste-based power production by the volume of waste processed. This factor accounts for the technological sophistication of the production process and the quality of incoming waste in terms of latent energy content. The third dimension measures the average production capacity of WtE plants. This value is determined by dividing the total treated waste volume by the number of plants, illustrating the principle of economies of scale in production. It is important to note that, for purpose of illustration, the study assumes all WtE plants operative at maximum capacity, an assumption that may not hold in operational contexts.

These sub-variables are than computed for each EU Country and then the results are assembled according to mathematical weighted average. This final aggregation step is made only after applying the principal of Min_max normalization in order to work with comparable data (keeping values between 0 - 1).

(Tong et al., 2021) introduced an indicator called the Entropy-Weighted Recyclability Index (EWRI). This indicator is designed to assess the recyclability of Municipal Solid Waste (MSW) in Chinese prefectural cities. It achieves this by incorporating road transportation density and regional recycling capability into the classifications of waste physical components. The goal is to measure the cost-effectiveness of delivering waste from its sources to recycling conversion sites.

Firstly, the recyclable waste is divided into material categories. (Tong et al., 2021) proposes 6 primary categories:

- Paper
- Plastic and Rubber
- Textile
- Wood
- Metal
- Glass

Then, the recyclability rate is computed (Equation 4):

$$Qij \; = \; Cij \; x \; Rij \; x \; Tij$$

Equation 4

Where:

- Cij: estimated quantity of physical component “j” in city “i”
- Rij: regional recycling capacity

- For recycling waste as glass and wood, Rij is the non-metal recycling enterprises density of the province
- For recycling waste as paper, plastics, textile, Rij is the non-metal recycling enterprises density of the region
- For metals, Rij is the metal recycling enterprises density of the region

- Tij: transportation factor:
  - For local recycling waste as glass and wood, Tij is the road density of the city
  - For long-distance recycling waste as paper, plastics, textile and metals, Tij is the road density of the region that city "i" lies in

Pij, a normalized value of recyclability index Qij, can be computed as in Equation 5.
A is a small off-set value to avoid $log2\ (0)$

$$Pij = \frac{Qij + A}{\sum_{i=1}^{n}(\ Qij + A\ )}$$

Equation 5

The next step is represented by the normalization of the recyclability factor.
Entropy (Ej) is hence calculated (Equation 6):

$$Ej = -\frac{1}{log2\ (\ n\ )}\ x\ \sum_{i=1}^{n} Pij\ x\ log2\ (\ Pij\ )$$

Equation 6

The weight of every entropy, proper of every city, is obtained dividing $1 - ej$ by the sum of $(\ 1\ -\ ej\ )$ considered for every variable (waste category).
Finally, the EWIRI concept is computed (Equation 7).

$$EWRI = \sum_{j=1}^{n} Wj\ x\ Qj$$

Equation 7

The Entropy weighted recyclability index was calculated for 339 prefectural cities in China to classify them as "best, good, normal, and difficult" from the recyclability of local MSW perspective.

3.2.3. Social Circularity indicators

Social circular indicators are metrics capable to catch the social impact and benefits of circular economy practices. These indicators provide knowledge into how circular economy initiatives influence communities, employment opportunities, social equity, and overall well-being. By measuring aspects such as job creation, community engagement, skill development, and improved living standards, social circular indicators help policymakers to evaluate the positive societal outcomes of adopting circular approaches.

A robust example can be found in the research of (Pitkänen et al., 2023) that outline the creation of a metric for Circular Economy Jobs (CE jobs). By using employment/education and service accessibility figures as sub-factors, this measure provides cities with a reliable numerical representation of their advancement in the circular economy. As a matter of facts, 11 indicators were selected as monitoring framework for the research. The first subset is composed by metric referred to the employment condition and includes volume and quality of employment, average income in CE sector jobs (considering at the same time 3 of the main CE working field like recycle, repair and reuse), job distribution across different educational backgrounds (university, high school and secondary instruction) and employment opportunities for vulnerable groups within the CE sector. A vulnerable group can be defined as a part of population within a country that has specific characteristics that make it at a higher risk of needing humanitarian assistance than others or being excluded from financial and social services (Kuran et al., 2020).

These metrics provide clarifications about both the quantity and social distribution of jobs created by the CE initiatives (Figure 19).

Indicator (unit) [impact/ change indicator]	Data sources and data collection methods (reference)	Calculation method
Employment: number of workplaces and their personnel in the CE industries (number of workplaces or personnel) [impact]	Annual statistics of businesses and financial statements, structural business and financial statement statistics (Statistics Finland)	$\sum \substack{\textit{workplaces}\\(\textit{CE industries})} \sum \substack{\textit{personnel}\\(\textit{CE industries})}$
Employment: the pay level in the CE industries (EUR per month) [impact]	Annual statistics of the structure of earnings in the CE-related branches (Statistics Finland)	Median (monthly pay)
Employment: the educational background of persons employed in the CE industries (number of employees) [impact]	Annual statistics on transition from school to further education and work in the CE industries (Statistics Finland)	$\sum \substack{\textit{employed from}\\\textit{vocational school}} \sum \substack{\textit{employed from university}\\\textit{of applied sciences}} \sum \substack{\textit{employed from}\\\textit{upper secondary school}} \sum \substack{\textit{employed}\\\textit{from university}}$
Employment: subsidised employment of vulnerable groups in recycling (% of refuse sorters in subsidised employment) [impact]	Employment service statistics (Ministry of Economic Affairs and Employment of Finland, register data, annual updates)	$\frac{\sum \textit{refuse sorters}}{\sum \textit{all subsidised emloyed}} \times 100\%$

Figure 19 CE jobs indicator composition work-oriented

(Pitkänen et al., 2023)

The second subset of assessment indexes is represented by ‘CE education offerings of universities of applied sciences examined as the number of credits of university career path directly dedicated to the CE acknowledgment.

The third set gathers 4 indicators belonging to both waste management infrastructure and recycling sites accessibility categories. Figure 20 accurately describes this composition.

Accessibility of waste infrastructure: plastic packaging bring sites (% of citizens living within a certain distance from the bring site) [impact]	Spatially referenced annual, partially open online data on bring sites (Finnish Solid Waste Association (KIVO)), data on residence (Statistics Finland), data on road network (Finnish Transport Infrastructure Agency)	Modelling of the average distances of citizens from home to the bring sites via road network
Accessibility of waste infrastructure: reusable textiles bring sites (% of citizens living within a certain distance from the bring site) [impact]	Spatially referenced annual, partially open online data on bring sites (KIVO, UFF, Fida and the Finnish Red Cross (SPR)), data on residence and road network	Modelling of the average distances of citizens from home to the bring sites via road network
Accessibility of waste infrastructure: WEEE bring sites (% of citizens living within a certain distance from the bring site) [impact]	Spatially referenced annual, partially open online data from KIVO, AC Nielsen retail register, Statistics Finland business register, data on residence and road network	Modelling of the average distances of citizens from home to the bring sites via road network
Accessibility of recycled resources: biomethane vehicle fuel stations (% of citizens living within a certain drive-time from the station) [impact]	Spatially referenced annual, partially open online data on methane gas fuel stations (Gasum Ltd), data on residence and road network	Modelling of the average drive-times of citizens from home to the fuel station via road network

Figure 20 CE jobs indicator composition waste-oriented

(Pitkänen et al., 2023)

Every indicator is related to a distance measurement from different types of waste disposal site.

Enhancing practices related to waste sorting plays a vital role in facilitating the transition toward a Circular Economy and achieving ambitious recycling goals. These efforts imply a broader social commitment for a shift towards a more circular society. Household waste sorting behavior is significantly affected by the presence and accessibility of recycling and waste collection infrastructure as well as by factors such as the convenience and proximity to waste disposal sites.

The fourth subset is related to the development state of services aimed to reduce the necessity for consumption of material via, for instance, products utilization extension such as bike sharing and library loans of book. In both cases the representative metric is the ratio between, respectively, sharing intended bike and book loaned, and people.

The method was employed to formulate experimental pilot indicators tailored to Finland case. Leveraging secondary data sources for their development, these indicators aimed to encompass various social implications and Circular Economy principles.

(Yang et al., 2011) provide practical tools that comprehensively address all three key facets of Circular Economy – recycling, reduction, and reuse. Notably, the proposal strives to prevent redundancy by avoiding the overlap of similar indicators, enhancing its utility. Another noteworthy feature contributing value to the proposal is the authors' acknowledgment of data availability limitations. This awareness prompts careful metric selection, prioritizing those with abundant historical data records.

A key strength point of the discovery lies in its commitment to authenticity, opting for a more tangible and realistic presentation despite the potential loss of measurement precision, in favor of result transparency. Additionally, (Yang et al., 2011) acknowledges the inherent limitations of the indicator system and the challenge of encapsulating the entire circular model within a framework that inherently cannot fully veil the complexity of this paradigm.

The framework arranges 26 different quantitative indicators attributed to the following main area of circular concern:

- Social and Economic development (9)
- Resource efficiency (3)
- Resource recycling and reuse (3)
- Environment protection (6)
- Pollution reduction (5)

The main reason why (Yang et al., 2011) has been placed in this section of Chapter 3.2 It's the significant inflection for social category.

Within (Yang et al., 2011) paper, many social assessment instruments can be found. Here a few examples:

- Spending on Education Total as % of GDP
- Unemployment Rate

Data were then normalized and aggregated with SPSS statistical software to generate a single composite indicator that was tested at the regional level over a period of 5 years exploiting secondary data coming from China Economic Net, China Energy Statistical Yearbook, Shaanxi Statistical Yearbook, Environmental status bulletin of Shaanxi Province.

On the other side, we want to present a couple of Chinese frameworks that differently from the one analyzed before, designed to evaluate the CE development at different scope from the regional one.

3.2.4. MFA oriented indicators

MFA is a comprehensive methodology employed to meticulously quantify and scrutinize the movement of materials within a defined system, whether it is a nation, a region, or a specific industrial sector. Through the systematic examination of material flows, MFA offers invaluable insights into the entire lifecycle of materials, encompassing their production, consumption, utilization, and eventual disposal or recycling.
MFA enables to identify inefficiencies in resource usage, identify environmental impacts and opportunities for enhancing resource management practices and fostering the transition towards a more sustainable and circular economy.
The study of (Kakwani & Kalbar, 2022) aligns with the approach proposed by (de Souza et al., 2024) and (Tong et al., 2021), with a substantial difference in the goal. The shared intent is to formulate a mathematical equation, derived from single indicators, that captures the complexity of a specific aspect of the CE.
It draws inspiration from the research MacArthur Foundation of about Material Circular indicator (MCI) (Ellen MacArthur Foundation, s.d.) and introduces a metric termed 'Water Circularity Indicator' (WCI) designed to evaluate and oversee the circularity of urban water systems through the principle of Material Flow Analysis approach (MFA).
WCI is crafted to suit the singular dynamics of water flows within urban settings.
The definition of this indicator starts from the definition of consumed water in a system. The consumed water (C) is computed as the difference between the total supply of water (S) reduced by the amount of water that is returned to the system ($Frs\ x\ C$). The total supply (S) is calculated as Population times unitary demand (in volume unit). Observing now the system from the input side, the total virgin water consumed (VC) can be computed with the following Equation 8:

$$VC\ =\ C\ x\ (\ 1 - Fru - Fre - Frc\ )$$

Equation 8

Where:

Fru: Fraction of water reused.

Fre: Fraction of water recycled from wastewater treatment facilities.

Frc: Fraction of water reclaimed from wastewater treatment facilities.

Then:

$$Wo = C\ x\ (\ 1 - L -\ Cru - Cre - Crc - C\ rst\ )$$

Equation 9

W0: Volume of untreated water generated.

L: Fraction of total volume of water lost = 0.20

CRu: Fraction of water collected for reuse.

CRe: Fraction of water collected for recycling.

CRc: Fraction of water collected for reclamation.

CRst: Fraction of water collected for restoration.

Considering that every circular application is unavoidably linked with a not negligible efficiency, part of the water handled for regenerative value application is lost as waste.

The total volume of water discharged and released outside the system (Equation 10) is hence the water initially lost (W0) added to the waste associated with recycling, reclamation and restoration, as in the formula:

$$W\ =\ W0\ +\ WRe\ +\ WRc\ +\ WRst$$

Equation 10

WRe: Volume of water wasted in recycling.

WRc: Volume of water wasted in reclamation.

WRst: Volume of water wasted in restoration.

Moving to the output side, F(Rst) is considered as the portion of water leaving the system boundary for groundwater recharge or to rejoin river and lakes. Rst represents this total amount and is calculated as the product between C and F(Rst).

This quantity of water is also required to be deducted from the virgin water consumed (Vc). Therefore, virgin water "V" can be calculated as in Equation 11:

$$V\ =\ Vc - Rst$$

Equation 11

Following, the determination of the Linear Flow Index (LFI) takes place. The LFI characterizes the percentage of material within a system that follows a linear trajectory (originating from virgin resources and ultimately ending up in landfills or remaining unrecovered). Applying a parallel analogy to the urban water sector, the LFI assesses the portion of water adhering to a linear approach in contrast to the application of the circular strategies. Specifically, it represents the ratio of water flowing to the total water consumption in the defined system boundary. The calculation is expressed as follows (Equation 12):

$$\mathrm{LFI} = (\mathrm{V} + \mathrm{W}) / 2\mathrm{C}$$

Equation 12

The WCI can be finally calculated as suggested by Equation 13:

$$WCI = 1 - LFI$$

Equation 13

The previously mentioned metric is crafted for application in urban areas or cities, intending to delineate the involvement of a circular economy within an urban setting.
To test its consistency, WCI undergoes initial validation through the exploration of 100 fictitious scenarios, systematically considering variations in the 5Rs: reduce, reuse, recycle, reclaim, and restore.
However, the application of (Kakwani & Kalbar, 2022)'s work has yet to be implemented in a real-world scenario.
(Haas et al., 2015) propose in their elaboration a quantification of the different material flows, that permits to execute an assessment of circularity of the global economy at the turn of the twenty-first century.
As we can notice in Figure 21, the metrics that are employed guarantee the coverage of different types of material from fossil fuel to biomasses.

Indicator	*Unit*
PM	Gt t/cap
Net addition to stocks as share of PM	%
Recycling within the economy as share of PM	%
Biomass as share of PM	%
Domestic processed output as share of PM	%
Flows either biodegradable or recycled in economy as share of PM	%
Fossil energy carriers as share of PM	%
Material for energetic use as share of PM	%
Material for material use as share of PM	%
Waste rock as share of PM	%
Short-lived products as share of PM	%
EOL waste as share of PM	%
Recycling as share of EOL waste (overall recycling rate)	%

Figure 21 Haas circularity indicator composition

(Haas et al., 2015)

We delineate domestically processed materials (PM) as the aggregate of apparent domestic consumption of materials (DMC), which includes extraction plus imports minus exports, along with recycled materials.
In contrast to earlier findings, in this specific scenario, data (input information) are not collected to create a singular derived metric. Instead, they remain unaltered to facilitate a more precise assessment. This approach recognizes that aggregation often leads to a more effective and concise outcome at the expense of a less precise overview.
This distinctive framework has been utilized to conduct a practical comparison between European countries and the rest of the world. Notably, secondary data on material flows were utilized, employing a European average measurement for each presented indicator.
(Gao et al., 2021) considers 16 cities of a Chinese province and apply to them 3 different types of circularity indicator that relies on the concept of Material Flow Analysis:

- RP (value added per unit of material in input): it estimates the output value created by unit resources and it links resource utilization to the results of economic activities (Equation 14)

$$RP = \frac{GDP}{DMI}$$

Equation 14

Where:

GDP: gross domestic product

DMI: Domestic Material Input

- RR (portion of secondary materials that re-enter the system through recycling): examines the proportion of secondary materials that re-enter the socioeconomic system through recycling (Equation 15):

$$RR = \frac{MR}{MR + DMI}\ x\ 100\%$$

Equation 15

Where:

MR is the quantity of material recycling, encompassing recycled grain crops, recycled industrial solid waste, recovery of waste pressure and heat, recycled construction waste and kitchen waste, and primary secondary resources.'

- WDA (final waste disposal of urban system): it examines the waste disposal pressure (Equation 16)

$$WDA = WDA\,(Agr) + WDA(Mi) + WDA\,(En) + WDA\,(Ma) + WDA\,(Rec) + WDA\,(Hou) + WDA\,(Con) + WDA\,(Tran)$$

Equation 16

Where:

WDA is the final waste disposal amount of the urban system as a whole. Agr, Mi, En, Ma, Rec, Hou, Con and Tran represent agriculture, the mining industry, energy conversion, manufacturing, recycling, household, construction and transportation, respectively.

Even in this case material flow accounting data were derived from the China City Statistical Yearbook 2018, the Shandong Statistic Yearbook 2018 and the 16 city's statistical yearbooks.

3.2.5. National indicators

The European Union is currently transitioning to a circular economy, aiming for a regenerative growth model that restore more than what it depletes. Member States play a crucial role in this transformation, developing internal strategies (roadmaps) alongside the EU Action Plan.

(Smol, 2023) surveys performance indicators outlined in some national CE strategies, emphasizing the need for different monitoring vision for different national objectives since the diversity among countries prevent a universal indicator for national CE transformation.

According to the Belgian strategy, circular economy-related indicators are aligned with the Europe 2020 strategy and existing European indicators. They encompass two main aspects (productivity of resources and domestic consumption of materials), eight indicators relating to land–water-carbon and twenty complementary indicators. In the Czech Republic and in Denmark, the CE strategy lacked specific information on CE indicators or monitoring frameworks, with ongoing public consultation on the roadmap. The strategy urged better circularity measurement but did not provide specific CE indicators. Finland's strategy highlighted the importance of CE development, with the extent to be a pioneer in CE indicators within the EU. The indicators were expected to cover multiple perspectives of the CE, including sharing economy, resource loops, systemic changes, and innovations.

The French government has introduced the "reparability index" to inform consumers about a product's reparability, aiming for a 60% repair rate for electronic items within five years. This index, displayed as a score out of 10 on the product or its packaging at the point of sale. France intends to lead the development of this index as a harmonized European obligation, emphasizing the role of regional authorities in monitoring progress, especially in resource flows, waste management, and job creation. In 2016, the Monitoring and Statistics Directorate of France has provided CE indicators aligned with the seven European pillars (Figure 22).

Circular economy pillar	CE indicator	Unit
Extraction/operation and sustainable supply chains		
	Domestic material consumption per capita	Mg/capita
	Resource productivity	EUR/kg
Eco-design (products and processes)		
	Ecolabel holders	piece
Industrial and territorial ecology		
	Industrial and territorial ecology projects	piece
Functional Economy		
	Car-sharing frequency rates	%
Responsible Consumption		
	Waste quantities	kg/capita/year
Extension of product lifespan		
	Household spending on maintenance and repair	%
Recycling (materials and organic matter)		
	Waste sent to landfill over time	%
	Use of secondary raw materials	%
7 pillars as a whole		
	Employment in the circular economy	piece

Figure 22 French circular assessment indicators

(Smol, 2023)

The German government emphasizes the need for economic indicators to monitor resource efficiency, proposing a regular market monitoring system and introducing specific indicators for recycling and recovery of raw materials. Greece's strategy recommends measurable indicators for circular economy incorporation in investment plans, covering economic, environmental, and social aspects. Ireland's strategy focuses on waste data and monitoring transformation progress, utilizing the National Waste Statistics web resource. Italy aims to develop a "circularity index" and specific CE indicators, involving various sectors and adopting key performance indicators. Luxembourg highlights the importance of measuring data flow and introduces the concept of product potential certification. The Netherlands has a Material Flows Monitor and plans to develop Key Performance Indicators for CE progress that currently are still under revision. Poland's roadmap includes plans for CE indicators and monitoring, with a total of 12 proposed indicators categorized into main, auxiliary, and contextual types (Figure 23)

Type of indicators	CE indicator	Unit
Main indicators		
	Resource productivity	GDP/DMC
	Share of renewable energy in the gross final energy consumption of enterprises	%
	Expenditure on R&D in relation to GDP	%
Auxiliary indicators		
	Productivity of water resources	%
	Amount of industrial waste generated in relation to GDP	%
	Share of produced secondary raw materials in total production	
	Greenhouse gas emissions from industrial activities in CO_2 equivalent	CO_{2e}/year
	Number of e-state services for entrepreneurs	Piece
	Number of environmental certificates	Piece
Contextual indicators		
	Share of expenditure on fixed assets for environmental protection in investment expenditure of the economy	%
	Share of full-time jobs in entities related to the activity of the CE in relation to total employment	%
	Value of public circular procurement in public procurement in total	%

Figure 23 Poland circular assessment indicators

(Smol, 2023)

While Irish and Portuguese governments demonstrate a lack of promptness in ensuring proper instruments for circularity analysis, Spanish authorities have promoted the adoption of transparent and accessible indicators for assessing the implementation of the circular economy (CE), focusing on social and environmental impacts. They utilize European CE indicators and an additional indicator on greenhouse gas emissions at the national level. This set of 28 quantitative indicators evaluates the transition process, public policy effectiveness, sustainability and circularity adoption by the productive sector, and consumer choices based on sustainability criteria.

In Sweden, advancements toward achieving the circular economy (CE) model's broad objective are monitored using established indicators that correspond to specific goals and objectives. These objectives include sustainable production and product design, CE implementation through sustainable consumption practices, and the utilization of non-toxic and circular material cycles.

China created a measurement instrument that contemplates a multidimensional set of 22 indicators divided in 4 main classes as shown in Figure 24, two indicators are listed for resource output, seven are listed for resource consumption, nine are listed for resource integrated utilization and four are listed for waste disposal and pollutant emission (Geng et al., 2012).

Groups	NO.	Indicators
1. Resource output rate	1.1	Output of main mineral resource
	1.2	Output of energy
2. Resource consumption rate	2.1	Energy consumption per unit GDP
	2.2	Energy consumption per added industrial value
	2.3	Energy consumption of per unit product in key industrial sectors
	2.4	Water withdrawal per unit of GDP
	2.5	Water withdrawal per added industrial value
	2.6	Water consumption of per unit product in key industrial sectors
	2.7	Coefficient of irrigation water utilization
3. Integrated resource utilization rate	3.1	Recycling rate of industrial solid waste
	3.2	Industrial water reuse ratio
	3.3	Recycling rate of reclaimed municipal wastewater
	3.4	Safe treatment rate of domestic solid wastes
	3.5	Recycling rate of iron scrap
	3.6	Recycling rate of non-ferrous metal
	3.7	Recycling rate of waste paper
	3.8	Recycling rate of plastic
	3.9	Recycling rate of rubber
4. Waste disposal and pollutant emission	4.1	Total amount of industrial solid waste for final disposal
	4.2	Total amount of industrial wastewater discharge
	4.3	Total amount of SO_2 emission
	4.4	Total amount of COD discharge

Figure 24 Chinese circular assessment indicators

(Geng et al., 2012)

The primary emphasis of the study lies in the management of resources and the end-of-life handling of water. However, a notable drawback of this model is its limited focus on the multifaceted implementation of Circular Economy (CE), which encompasses environmental, economic, and social dimensions. The prevailing Chinese national CE standards predominantly concentrate on economic and environmental indicators, neglecting social aspects. To bridge this gap, additional indicators, such as those introduced by (Yang et al., 2011) in section 3.2.3, become indispensable to include social considerations within CE and offering a comprehensive national overview.

3.2.6. Circularity at the municipal level

Most indicators discussed from Section 3.2.1 to Section 3.2.5 were mostly focused on the national dimension. Marginal applications at the regional level were made but still did not represent the wider contribution to the research. This inclination is likely driven by the need for governments and policymakers to gain a comprehensive understanding of the circular economy's progress while the effort in achieving the same transition at the city level is lower. Anyway, different studies have been conducted on a smaller scale with the aim of shifting the focus to cities.

The analysis of (Wang et al., 2018) introduces a unique perspective, presenting the concept of the Urban Circular Development Index (UCDI).

This study extended prior research efforts by creating a singular indicator system. It involved consolidating relevant and accessible data related to city production, consumption, and lifestyles, adhering to the recycling, recovery and reutilization principles and draws inspiration from established indicator systems. The system comprises 17 distinct indicators organized into four primary criteria: Resource output, industrial circularity, residential circularity, and mechanisms and culture. The individual indicators are combined using a weighted sum to acquire the overall UCDI snapshot.

As readers can notice in Figure 25, almost all indicators are quantitative except for the last one (Creative culture of CE) that adopts a binary logic.

Goal	Criteria	Sub-criteria
UCDI	Resource output	Resource productivity (yuan/ton)
		Energy productivity (yuan/ton)
		Water resources productivity (yuan/ton)
	Industrial circularity	Audit rate of cleaner production[a] (%)
		Utilization coefficient of agricultural irrigation water (%)
		Utilization rate of crop straw (%)
		Fecal resource utilization of livestock and poultry farms (%)
		Comprehensive utilization rate of industrial solid waste (%)
		Industrial water recycling rate (%)
	Residential circularity	Recovery rate of major renewable resources (%)
		Construction waste recovery rate (%)
		Harmless treatment rate of urban municipal garbage (%)
		Urban green building standards implementation rate (%)
		City restaurant waste recycling rate (%)
		Urban reclaimed water utilization rate (%)
	Mechanism and culture	Green products purchasing rate of government (%)
		Creative culture of CE (Yes or no)

Figure 25 UCDI indicator composition

(Wang et al., 2018)

The process of weights assignation is made possible thanks to the application of an enhanced entropy method. This method objectively captures the implicit information within the data, boosting the resolution and differentiation of the index. The fundamental principle is that the greater the disparity among the evaluation values, the higher the corresponding weight.

The effectiveness of the instrument is validated by applying this concept to a set of 40 cities.

Reliable secondary data coming from the specific city's implementation plan were employed.

Statistical data on national CE model cities were collected from 2012 to 2016, with most of the data coming from each city's implementation plan. In this study, cities were further grouped into six types basing on the main economic drivers in each city:

- Industry oriented
- Resource – based
- Resource – depleted
- Compounded industrial and agricultural
- Renewable resource – driven
- Balanced development

The study of (Heshmati & Rashidghalam, 2021) introduces a comprehensive benchmark for the urban circular development and calculates a multidimensional parametric index comprising eight sub-components.
The researched framework utilizes multiple indicators to assess and attribute levels of circularity to cities. This framework entails developing a comprehensive set of indicators for each key area of sustainability concern. Every area contemplates different sub-metrics unequivocally related to the specific field. Eight areas exist. For sake of illustration, we aim to demonstrate the construction of one of these pillars. Figure 26 facilitates a clearer comprehension of the composition of each category.

Collected waste	CW_1	Collected coarse waste, kg/inhabitant
	CW_2	Total household waste collected, kg/inhabitant
	CW_3	Collected hazardous waste (incl. Electrical waste and batteries), kg/inhabitant
	CW_4	Collected food and residual waste, kg/inhabitant

Figure 26 Heshmati circular category composition

(Heshmati & Rashidghalam, 2021)

As observed by the readers, the class consists of 4 items. Each of these assumes a noticeable relevance in the full picture of the waste management approach of urban districts.
For the examination and comparison of circular economy (CE) practices across various municipalities in Sweden, (Heshmati & Rashidghalam, 2021) has leveraged data sourced from “Kolada”, which is a database containing indicators for activities conducted by county and municipality councils. The management of “Kolada” falls under the purview of the Council for the Promotion of Local Analyses (RKA), jointly owned by the Swedish State (50%) and the Swedish Association of Local Authorities and Regions (SALAR) (50 percent).
Another significant contribution to this section is the work of (Musyarofah et al., 2023).
The singular aspect about this contribution is the definition of the final derived index for circularity assessment.
The most influent metrics for circularity evaluation are defined:

- Value added to Economy
    i) Material value added in prices (%)
    ii) Percentage of the number of unemployed to the total labor force
- Human development index (longevity)
- Energy consumption per capita
- The volume of municipal waste generated per capita to the land.
- Water consumption per capita
- Emission per capita

The Economic indicator (Value added to Economy) is composed by two sub-indicators which are averaged to obtain a unique indicator.
Every indicator is associated with a specific weight.
At this point, since indicators have different units, the final derived indicator is created using the deprivation method, according to which the deprivation variable is equal to the difference between the higher and the lower value for every alternative.
So, the final indicator is calculated as in Equation 17:

$$CEI = \sum_{i}^{i} \mu_i \, x \, D_i$$

Equation 17

Where:

μ_i: *Indicator weight*

D_i: *Indicator Deprivation variable*

Differently from latest discoveries, the CCAF framework developed by (de Ferreira & Fuso-Nerini, 2019) is designed to embody key circular economy (CE) concepts from a city perspective adopting a multi-industry analysis to encompass the diverse sectorial characteristic within an urban context.
To create such instrument (de Ferreira & Fuso-Nerini, 2019) conducted a field-by-field analysis, firstly pointing out the most impactful industrial sectors and then proposing a comprehensive set of 13 quantitative indicators.
These methods follow the idea of the Circular City Diagram (CCD).
CCD involves a structure of three concentric circles: the inner circle, the intermediate circle, and the outer circle. The inner circle provides information on the city's circular economy, detailing the origins of various

businesses, materials, and energy flows. The intermediate circle, that can be assumed as the most crucial one in this research, delves into the industries and sectors that define each city, although it doesn't encompass the totality of relevant aspects. The outer circle is designed to capture broader fields and considerations. Each industry comprises one or more indicators intended to gauge the city's level of circularity.

Within the first circle we can find aspects like local resources statistics while intermediate circle encompasses dimensions like transport sector, food sector and for instance renewable energy applications.

Outliers group is populated by that are less affective but still not negligible for the urban circular empowerment like demographics or education.

To validate the applicability of this model, a real case study is developed taking as reference for investigation the city of Porto where available data sets, generally found in INE or PORDATA, were found.

An alternative way to select and hence create the instruments to compute the circular economy advancement is proposed by (Nurdiana et al., 2021) in their work.

The authors define a singular protocol, in contradiction with the literature, to highlight and propose suitable for cities. Thus, through interviews to a sample of 28 respondent stakeholders, the study enriched the theoretical set of circular economy indicators giving the possibility to Indonesian people to directly contribute with their perception of circularity to the definition of a successful assessment instrument.

The selection of respondents is evidently motivated by the necessity to represent in the most realistic manner the opinion of population involved in the transition, object achieved exploiting perspectives that belong to academic, industrial, governmental and non-governmental organization fields. Findings have provided a bridge between decision-makers and city stakeholders, through collaborative efforts, able to guarantee the formulation of a framework for advancing on circular city concept.

As shown in Figure 27, metrics are grouped in classes (i.e. environmental, economic). The results of the survey are highlighted in percentage of selected indicators by stakeholders.

Pillars (Theme) and Selected Indicators	Number of Selections				Quantity	
	NGOs	Industry	Government	Academic	Total	%
Economic						
Job creation in CE chain	2	1	1	3	7	25
Green investment	2	1	2	4	9	32
Material productivity				2	2	14.2
Local people involvement	3	1	1	4	9	32
Social						
Awareness	3	5	4	7	19	67.8
Community health	1	2	2	4	9	32
Education inclusion			2	5	7	25
Gender involvement in business	1	1	2	3	7	25
Environment						
Energy						
Energy per consumption per capita	1	10	1	3	15	53.6
Energy per consumption per sector	1	8	1	3	13	46.4
Renewable energy consumption per capita	1	7	2	4	14	50
Renewable energy consumption per sector	1	4	2	3	10	35.7
Land						
The volume of municipal waste generated per capita	2	7	4	7	20	71.4
The volume of industrial waste generated for disposal	3	8	3	7	21	75
Recycling rate of municipal waste	2	8	1	6	19	67.8
Recycling rate of industrial waste for specific waste stream	2	10	2	7	21	75
Total food waste generated per capita	3	7	4	7	21	75
Water						
Water consumption per capita per year	1	4	4	7	16	57.1
Water consumption per industry per year	1	6	2	6	15	53.6
The recycling rate of municipal wastewater		7	4	6	17	60.7
The recycling rate of industrial wastewater	1	6	4	6	17	60.7
Pollutant						
GHG emission per capita (included CO_2)	3	7	4	5	19	67.8

Figure 27 Nurdiana circular indicators selection

(Nurdiana et al., 2021)

This assessment paradigm must be considered by the readers as just theoretical since no application has been conducted.

3.3. Summary of axial coding

Once results have been presented, it's important to adopt the previously introduced axial coding scheme (Figure 7) to compare papers on different layers.

The initial analysis evaluated the implementation of the Circular Economy strategies within the reviewed sample of papers. To achieve this, it's examined the primary circular strategies (Figure 1) considered by (Kirchherr et al., 2023) when defining the concept of circular strategy.

The outcomes are depicted in Table 4.

Within this context, it is evident that the concept of recycling takes precedence, 92% of the sieved studies revealed a link with recycling.

Approaches such as refurbishing and remanufacturing are completely absent. This trend can be ascribed to the widespread popularity and versatile applicability of recycling across various fields.

As a matter of facts, many industries can align their policy with the principle of recycling to gain an operative and economic advantage while they struggle to follow strategies such as refurbishing, repurposing or remanufacturing.

Tissue and Food & Beverage industries are few examples of what just discussed.

AUTHOR	METHOD	Refuse	Rethink	Reduce	Reuse	Repair	Refurbish	Remanufacture	Repurpose	Recyle	Recover
AVDIUSHCHENKO	CEI									x	
DE SOUZA	MCU									x	
FERREIRA	CEI						x			x	
GAO	CEI									x	
GATTO	EWIRII										x
GENG	CHINESE NATIONAL INDICATORS				x					x	
HAAS	CEI									x	x
HESMATI	CEI									x	
KAKWANI	WCI				x						
KARMAN	CECI									x	x
MANEA	CEI									x	
MARTINEZ MORENO	CECI									x	x
MAZUR-WIERZBIKA	CEI									x	
MUSYAROFAH	CEI				x					x	
NURDIANA	CEI				x					x	
PITKÄNEN	CEJ			x						x	
SILVESTRI	CESI									x	
SILVESTRI	CEDI									x	
SMOL	FRENCH NATIONAL INDICATORS		x	x		x				x	
SMOL	POLISH NATIONAL INDICATORS		x							x	
STANKOVIC	CEI									x	
TONG	EWRI									x	
VRANJANAC	CEI				x					x	
WANG	UCDI				x					x	x
YANG	CEI			x	x					x	

Table 4 Circular strategies

After adressing Circular Strategies, the Thesis shifts its focus to sub-indicators comprising the assessment instruments. Regarding types of sub-indicators, no method exclusively relies on qualitative indicators. Instead, all analyzed papers demonstrate a clear preference for quantitative indicators. The only exception is the study made by (Wang et al., 2018), which utilized one qualitative sub-indicator alongside 16 quantitative sub-indicators.

As readers can notice in table 5, more than a half of the studies exploit derived indicators as final assessment tool to rank alternatives performance based on different circular economy criteria.

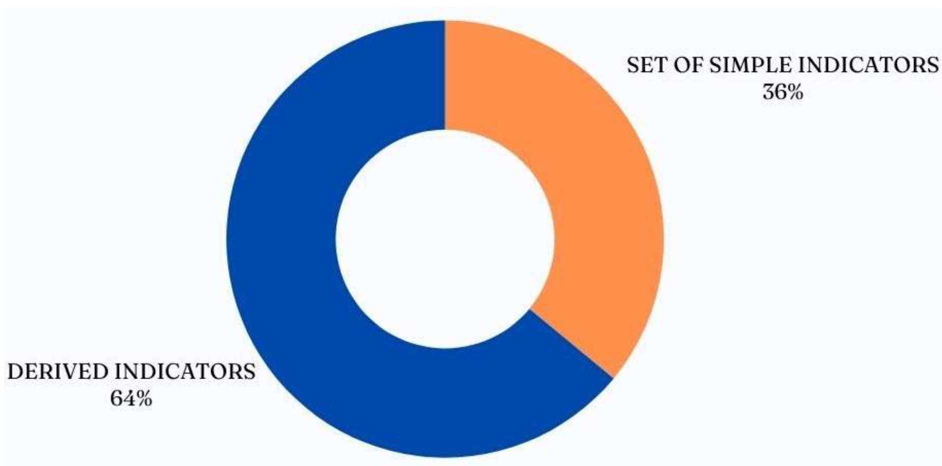

Table 5 Types of circular assessment methods

The inclination to use different indicators as benchmarks between options is comprehensible in the sense that the complexity of the target topic is such that no single or unique metric can capture all the shapes and details involved in the evaluation.

The necessity to define a ranking between alternatives following a preference direction induces authors to aggregate metrics to obtain a unique criterion to compare alternatives.

In Table 6 is presented the total number of indicators employed in each study and the total average number.

NUMER OF INDICATORS	CIRCULARITY ASSESSMENT METHOD	SUB-INDICATORS USED
7	(Vranjanac et al., 2023) CEI	• Resource productivity (GDP/DMC) • Recycling rate of municipal waste (% of recycled municipal waste in the total municipal waste) • Circular material use rate (ratio of the circular use of materials to the overall material use) • Private investments, jobs, and gross value added related to circular economy sectors: value added at factor cost (% of GDP) • Patents related to recycling and secondary raw materials (number) • Recycling rate of all waste excluding major mineral waste (% of recycled waste divided on total waste treated excluding major mineral wastes) • Generation of municipal waste per capita (Kg)
14	(Manea et al., 2021) CEI	NA
13	(Mazur-Wierzbicka, 2021) CEI	• Generation of municipal waste per capita • Generation of waste excluding major mineral wastes per GDP unit (Kg) • Generation of waste excluding major mineral wastes per

		domestic material consumption (Kg) • Recycling rate of municipal waste (%) • Recycling rate of all waste excluding major mineral waste (%) • Recycling rate of packaging waste by type of packaging (%) • Recycling rate of e-waste (%) • Recycling of biowaste (%) • Recovery rate of construction and demolition waste (%) • Circular material use rate (%) • Trade in recyclable raw materials (% of GDP) • Private investments, jobs and gross value added related to circular economy sectors (% of GDP) • Patents related to recycling and secondary raw materials (number)
11	(Silvestri et al., 2020) CESI	• Life expectancy (year) • Diseases of the circulatory system (rate over diseases) • Malignant neoplasms (rate over neoplasms) • Transport accidents (rate over accidents) • GDP at current market prices (euro per inhabitant)

		• Total intramural R&D expenditure (euro per inhabitant) • Total amount of fractional patents inv. per year (number/year) • Waste generated (tonnes per inhabitant) • Waste recycling - composting and digestion (tonnes per inhabitant) • Artificial land (%) • Estimated soil erosion by water (tonnes per hectare)
11	(Silvestri et al., 2020) CEDI	• Growth rate life expectancy (%) • Growth rate of diseases of the circulatory system (%) • Growth rate of malignant neoplasms (%) • Growth rate of transport accidents (%) • Growth rate of GDP at current market prices (%) • Growth rate of otal intramural R&D expenditure (%) • Growth rate of total amount of fractional patents inv. per year (%) • Growth rate of waste generated (%) • Growth rate of waste recycling - composting and digestion (%) • Growth rate of artificial land (%)

		• Growth rate of estimated soil erosion by water (%)
4	(de Souza et al., 2024) MCU	• Waste recovered locally (Kt/year) • Waste exports (Kt/year) • Imports of waste (Kt/year) • Domestic Material Consumption (Kt/year)
22	(Martínez Moreno et al., 2023) CECI	• EU self-sufficiency for raw materials • Green public procurement (mln €) • Generation of municipal waste per capita (Kg) • Generation of waste excluding major mineral waste (Kg) • Food waste (Kg) • Recycling rate of municipal waste (%) • Recycling rate of all waste excluding (%) • Recycling rate of overall packaging (%) • Recycling rate of plastic packaging (%) • Recycling rate of wooden packaging (%) • Recycling rate of e-waste (%) • Recycling rate of biowaste(%) • Recovery rate of construction and demolition waste (%) • End-of-life recycling input rates (EOLRIR), aluminium (%) • Circular material use rate (%)

		• Trade in recyclable raw materials: Imports from non-EU countries (mln €) • Trade in recyclable raw materials: Exports to non-EU countries (mln €) • Trade in recyclable raw materials: Intra EU trade (mln €) • Gross investment in tangible goods (mln €) • Employees (number) • Value added at factor cost (%) • Number of patents related to recycling and secondary raw materials (number)
11	(Stanković et al., 2021) CEI	• Generation of municipal waste pro capita (Kg) • Recycling rate of all waste excluding mineral waste (%) • Recycling rate of municipal waste (%) • Recycling rate of packaging waste by type of packaging (%) • Recycling of bio-waste (%) • Recovery rate of construction and demolition waste (%) • Recycling rate of e-waste (%) • Trade in recyclable raw materials (mln €) • Circular material use rate (%) • Private investments, jobs and gross value added related to CE sectors (% of GDP)

		• Patents related to recycling and secondary raw materials (number)
30	(Karman & Pawłowski, 2022) CECI	• Food waste (Kg) • Municipal waste pro capita (Kg) • WEEE waste collected from households (Kg) • Volume of sewage households (Kg) • Energy consumption per household (KGOE) • DMC per capita (Tones) • Water consumption per household (mln m^3) • Energy consumption per industrial sector (KGOE) • Direct material input (DMC per capita) • GHG emission from industrial sector (mln tones) • Waste from industrial sector (Ind2010) • Recycling rate of municipal waste (%) • Recycling rate of all waste excluding major mineral waste (%) • Recycling rate of packaging waste by type of packaging (%) • Recycling rate of e-waste (%) • Recycling rate of plastic (%) • Recycling rate of bio-waste (Kg per capita)

		• Recovery rate of construction waste and demolition waste (%) • Energy recovery per capita (Kg) • Circular material use rate (%) • Resource productivity (PPS) • Amount of treated sewage per capita (tones) • Share of ren. Energy in gross final energy consumption (%) • Eco-innovation index (EU100) • Patents related to recycling and secondary raw materials (number) • Private investments, cost factor related to CE sectors (% of GDP) • Private investments, jobs related to CE sectors (% of GDP) • Waste protection investments in mln EUR (% of GDP) • Labor productivity (Ind) • Trade in recyclable raw materials (Ind2010)
25	(Avdiushchenko & Zajaç, 2019) CEI	• GDP • Average life expectancy at birth for men (years) • Registered unemployment rate (%) • At-risk-of-poverty rate (%) • Municipal waste collected selectively in relation to the

		total amount of municipal waste collected (%) • Municipal waste collected per one inhabitant (tones) • Industrial and municipal wastewater purified in wastewater requiring treatment (%) • Outlays on fixed assets serving environmental protection and water management related to recycling and utilization of waste (mln) • Expenditures on research and development activities (mln) • Average share of innovative enterprises in the total number of enterprises (%) • Adults participating in education and training (%) • Patent applications for 1 million inhabitants (number) • Share of renewable energy sources in total production of electricity (5) • Outlays on fixed assets serving environmental protection and water management related to electricity saving (mln) • Electricity consumption (kWh/person) • Carbon dioxide emission from plants especially noxious to air purity (tons/person)

		• Emission of particulates (tons/1 km2) • Passenger cars (Cars/1000 population) • Pollutants retained or neutralized in pollutant reduction systems in total pollutants generated from plants especially noxious to air purity (%) • Outlays on fixed assets serving environmental protection and water management related to protection of air and climate (mln) • Households with personal computer with broadband connection to Internet (%) • Enterprises with access to the Internet via a broadband connection (%) • Forest cover indicator (%) • Street greenery and share of parks, lawns and green areas of the housing estate areas in the total area (%) • Urbanization rate (%)
3	(Gatto, 2023) EWIRII	• % of domestic waste based power production • Waste-based power production (Kg) divided by the amount of waste treated (Kg)

		• Total amount of waste treated divided by the number of plants (Kg/plant)
3	(Tong et al., 2021) EWRI	• Quantity of a specific component in a City (Kg) • Regional recycling capacity (Density of enterprises) (number/Km^2) • Road density of a City (Km/Km^2)
11	(Pitkänen et al., 2023) CEJ	• Number of workplaces and their personnel in the CE industries (number) • Pay level in the CE industries (€) • Educational background of persons employed in the CE industries (number from diff. backgrounds) • Subsidized employment of vulnerable groups in recycling (%) • CE education offerings of universities of applied sciences (number of credits) • Accessibility of waste infrastructure (plastic) (average distance) • Accessibility of waste infrastructure (reusable textiles bring sites) (average distance) • Accessibility of waste infrastructure (biomethane

		vehicle fuel stations) (average distance) • Accessibility of waste infrastructure (WEEE bring site) (average distance) • Bicycles shared per capita (number per capita) • Library loans (number of loans per capita)
12	(Kakwani & Kalbar, 2022) WCI	• Volume of water wasted in recycling (L) • Volume of water wasted in reclamation (L) • Volume of water wasted in restoration (L) • Usage efficiency in recycling (output/input) • Usage efficiency in reclamation (output/input) • Usage efficiency in restoration (output/input) • Volume of virgin water consumed (L) • Fraction of water reused (rate) • Fraction of water recycled from wastewater treatment facilities (rate) • Fraction of water reclaimed from wastewater treatment facilities (rate) • Volume of freshwater supplied from the centralized and decentralized, surface as well as groundwater sources (rate)

		• Fraction of water consumption reduced (rate)
13	(Haas et al., 2015) CEI	• PM (Gt) • Net addition to stocks as share of PM (%) • Recycling within the economy as share of PM (%) • Biomass as share of PM (%) • Domestic processed output as share of PM (%) • Flows either biodegradable or recycled in economy as share of PM (%) • Fossil energy carriers as share of PM (%) • Material for energetic use as share of PM (%) • Material for material use as share of PM (%) • Waste rock as share of PM (%) • Short-lived products as share of PM (%) • EOL waste as share of PM (%) • Recycling as share of EOL waste (%)
10	(Smol, 2023) FRENCH NATIONAL INDICATORS	• Domestic material consumption per capita (Mg/capita) • Resource productivity (EUR/kg) • Ecolabel holders (piece) • Industrial and territorial ecology projects (piece) • Car-sharing frequency rates (%)

		• Waste quantities (kg/capita/year) • Household spending on maintenance and repair (%) • Waste sent to landfill over time (%) • Use of secondary raw materials (%) • Employment in the circular economy (%)
11	(Smol, 2023) POLISH NATIONAL INDICATORS	• Resource productivity (GDP/DMC) • Share of renewable energy in the gross final energy consumption of enterprises (%) • Expenditure on R&D in relation to GDP (%) • Productivity of water resources (%) • Amount of industrial waste generated in relation to GDP (%) • Share of produced secondary raw materials in total production (%) • Greenhouse gas emissions from industrial activities in CO2 equivalent (CO2/year) • Number of e-state services for entrepreneurs (number) • Number of environmental certificates (number) • Share of expenditure on fixed assets for environmental

		protection in investment expenditure of the economy (%) • Share of full-time jobs in entities related to the activity of the CE in relation to total employment (%) • Value of public circular procurement in public procurement in total (%)
17	(Wang et al., 2018) UCDI	• Resource productivity (yuan/ton) • Energy productivity (yuan/ton) • Water resources productivity (yuan/ton) • Audit rate of cleaner production (%) • Utilization coefficient of agricultural irrigation water (%) • Utilization rate of crop straw (%) • Fecal resource utilization of livestock and poultry farms (%) • Comprehensive utilization rate of industrial solid waste (%) • Industrial water recycling rate (%) • Residential circularity Recovery rate of major renewable resources (%) • Construction waste recovery rate (%) • Harmless treatment rate of urban municipal garbage (%)

		• Urban green building standards implementation rate (%) • City restaurant waste recycling rate (%) • Urban reclaimed water utilization rate (%) • Mechanism and culture green products purchasing rate of government (%) • Creative culture of CE (Yes or no)
38	(Heshmati & Rashidghalam, 2021) MULTIPLE CEI	• Household waste collected for recycling, incl. biological treatment (%) • Organization of waste management • Accessibility of the largest recycling center in the evening/ weekend (hours/week) • Total accessibility to all recycling centers (minutes/inhabitant) • The recycling center's office lasts beyond 08–17 on weekdays (hours/week) • Collected packaging and recycled paper (kg/inhabitant) • Household waste collected for material recycling, incl. biological treatment, percentage (%) • Collected food waste that goes to biological recycling incl.

		home composting, percentage (%) • Collected coarse waste (kg/inhabitant) • Total household waste collected (kg/ inhabitant) • Collected hazardous waste (incl. Electrical waste and batteries) (kg/inhabitant) • Collected food and residual waste (kg/ inhabitant) • Emissions to air of greenhouse gases total, tons CO2 (equiv/ inhabitant) • Emissions to air of PM2.5 particles (kg/inhabitant) • Emissions to air of nitrogen oxides (NOx), total (kg/inhabitant) • Municipality water waste(L) • Need Citizens Index of Environmental work • Need for waste management Suitability, percentage (%) • Need to visit at the recycling center, percentage (%) • Need accessibility to the recycling center, percentage (%) • Larger individual water utilities with some form of protection (%)

		• Organic food in the municipality's operations, percentage (%) • Most common waste tax total incl. VAT for housing in apartment buildings, SEK • Charge for waste collection incl. VAT for type property according to the Nils Holgersson model (SEK/m2) • Fee for water and sewage incl. VAT for type property according to the Nils Holgersson model (SEK/m2) • Investment expenditure waste management (SEK/ inhabitant) • Investment expenditure in energy, water and waste by municipality (SEK/ inhabitant) • Investment expenditure water supply and wastewater treatment (SEK/ inhabitant) • Cost of waste management (SEK/ inhabitant) • Cost of water supply and waste management (SEK/ inhabitant) • Average mileage with passenger car (mile/ passenger car) • Environmental cars in the municipal organization, percentage (%)

		• Environmental cars, percentage of total cars in the geographical area (%) • Renewable fuels for food and residual waste collection, percentage (%) • Electricity generation of renewable energy sources in the geographical area, percentage (%) • Electricity generation of hydropower in the geographical area (MWh) • Electricity generation of wind power in the geographical area (MWh) • District heating production of renewable energy sources at geothermal plants in the geographical area, percentage (%)
7	(Musyarofah et al., 2023)	• Percentage of value added in price level (%) • Percentage of the number of unemployed to the total labor force (%) • Human development index • Energy consumption per capita (MWh) • Volume of municipal waste generated per capita to the land (Kg per capita) • Water consumption per capita (L)

		• Emission per capita (Kg/person)
27	(de Ferreira & Fuso-Nerini, 2019) CEI	• Wind potential (m/s) • Solar potential (W/m2) • Green roofs (%) • Imports/exports (€/€) • Renewable penetration (%) • Access to electricity (%) • Energy intensity (GWh/M€) • Public transport usage (%) • Electrical energy consumed in the transport sector (%) • Retrofitting (%) • Retrofitting (%) • Food waste treated (%) • Food waste treated in small and medium enterprises (SMEs) (%) • Safe water accessibility (%) • Water efficiency (%) • Landfilled waste (%) • Separated waste (Kg/capita*year) • CE innovation budget (%) • Recycling rate (%) • Synergies (%) • Basic education quitting (%) • Superior course (%) • Accessibility to smartphones (%) • Balance between men & women (%) • Heaviest age group (years) • Active population (%)

		• Man–woman balance in politics (%)
19	(Nurdiana et al., 2021) CEI	• Energy consumption (standard coal) per industrial value-added • Per capita energy consumption (standard coal) (tons/year) • Energy consumption/unit GDP • Energy consumption/industrial value-added • Per unit product energy consumption in key industrial sectors • The share of renewables % • Energy productivity • Energy dependence • Output of main mineral resource • Output of energy • Direct water use • Water consumption per industrial value-added • Water consumption per capita • Total industrial wastewater discharges The rate of municipal wastewater treatment/ reclaimed municipal wastewater/industrial water reuse ratio • Water used per unit GDP • Water used/ industrial value added

		• Per unit product water consumption in key industrial sectors • Irrigation coefficient of water utilization Water exploitation index • Water productivity
26	(Yang et al., 2011) CEI	• Gross Domestic Product (yuan) • Per Capita GDP (yuan) • Value-added of Secondary Industry (yuan) • Value-added of Tertiary Industry (yuan) • Output Value of Tertiary Industry account for GDP (%) • Unemployment Rate in Urban Area (%) • Engel's Coefficient (%) • Spending on Education Total as of GDP (%) • Energy Consumption per 10 000-yuan GDP by Region (MWh/10 000-yuan GDP) • Electricity Consumption per 10 000-yuan GDP by Region (MWH/10 000-yuan GDP) • Elasticity Ratio of Energy Production (%) • Ratio of Industrial Solid Wastes Utilized (%) • Water Reuse Rate of Industrial Enterprises (%) • Output Value of Products Made from Waste Gas, Waste Water

		&Solid Wastes account for GDP (%) • Per Capita Green Areas (sq. meters) • Urban Domestic Garbage Treatment Rate (%) • Urban Sewage Treatment Rate (%) • Volume of Industrial Wastewater Discharged (tons) • Percentage of Industrial Wastewater Meeting Discharged Standards (%) • Volume of Industrial Sulphur Dioxide Emission per 10 000-yuan GDP by Region (RMB per KG) • Volume of Industrial Soot Removed (tons) • Volume of Industrial Dust Removed (tons) • Volume of Industrial Solid Wastes Discharged (tons) • Investment in Pollution Treatment account for GDP (%) • Volume of Industrial Soot Discharged tons (tons) • Percentage of Industrial Soot Meeting Discharged Standards (%)
11	(Gao et al., 2021) CEI	• GDP (mln yuan) • DMI (Kg) • MR (Kg)

		• Waste disposal amount of the urban system (agriculture) (Kg) • Waste disposal amount of the urban system (mining) (Kg) • Waste disposal amount of the urban system (energy conversion) (Kg) • Waste disposal amount of the urban system (manufacturing) (Kg) • Waste disposal amount of the urban system (recycling) (Kg) • Waste disposal amount of the urban system (Household) (Kg) • Waste disposal amount of the urban system (construction) (Kg) • Waste disposal amount of the urban system (transportation) (Kg)
22	(Geng et al., 2012) CHINESE NATIONAL INDICATORS	• Output of main mineral resource • Output of energy • Energy consumption per unit GDP • Energy consumption per added industrial value • Energy consumption of per unit product in key industrial sectors • Water withdrawal per unit of GDP • Water withdrawal per added industrial value

		• Water consumption of per unit product in key industrial sectors • Coefficient of irrigation water utilization • Recycling rate of industrial solid waste • Industrial water reuse ratio • Recycling rate of reclaimed municipal wastewater • Safe treatment rate of domestic solid wastes • Recycling rate of iron scrap • Recycling rate of non-ferrous metal • Recycling rate of wastepaper • Recycling rate of plastic • Recycling rate of rubber • Total amount of industrial solid waste for final disposal • Total amount of industrial wastewater discharge • Total amount of SO2 emission • Total amount of COD discharge
AVERAGE = 15,16		

Table 6 Number of sub-indicators per assessment method

In terms of general scope of the investigation, significant effort has been made in the literature to understand and design assessment system suited with the national dimension although the regional and municipal focus is not left aside.

This assertion finds support in the percentages depicted in Table 7 that emphasize a not negligible occurrence of circularity evaluation approaches for cities and for regions (both with 28 % of the evidence).

It's important to outline the presence of methods that can perfectly be applied to different scopes of investigation since the parameters considered are not specific and so they can be shared between multiple dimensions.

Readers surely notice that making a circular assessment on a country can be sometimes very imprecise if using parameters such as, for example, circular jobs employment.

This information in not invariable all over a Country and surely, a Country is characterized by higher and lower density areas.

Making a Country-based circularity assessment exploiting this parameter would imply to considers country average values, a very rough estimation especially when the discrepancy is very pronounced.

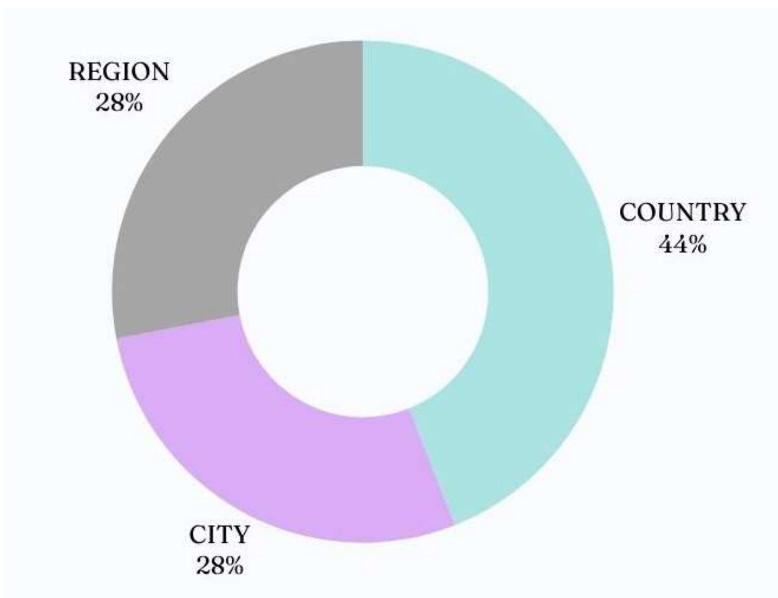

Table 7 Scope of circularity assessment methods

Shifting to the application side, findings depicted by Table 8 highlight that the highest portion of analyzed papers (92%) includes a real case study.

Sometimes the objective of the authors is not to rank alternatives based on a well-defined system of circularity evaluation but instead explaining to the readers the definition process that has been followed.

Within these theoretical papers the assumption that have been made and the mathematical computation that have been observed play a pivotal role.

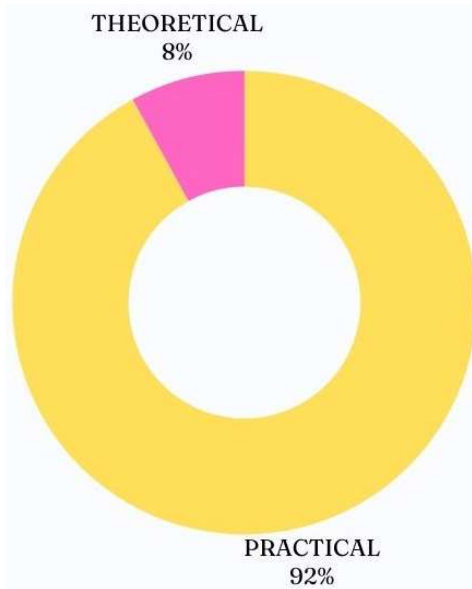

Table 8 Application of the assessment methods

Data fed for case studies are usually derived from secondary sources, most notably public databases.
Primary data collection is time consuming and was adopted solely in 8.7% of the case studies.
Table 9 confirms this trend.
Hybrid sector contains the studies that have employed at the same time both primary and secondary data depending on availability of data.

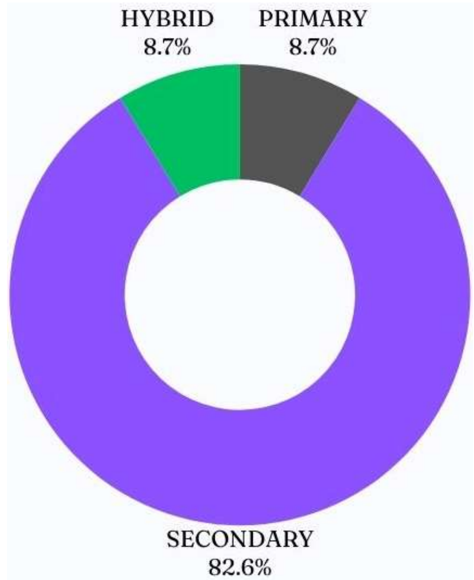

Table 9 Types of data used

Table 10 helps readers in summarizing and visualizing the concepts presented thus far.

AUTHOR	INDICATOR	Source	Circular strategy	Number of sub- indicators	Type of sub-idicators	Type of assessment instrument	Geographical scope	Application	Type of data	Database
AVDIUSHCHENKO	CEI	Economic and Business Aspects of Sustainability	Recover	25	Quantitative	Derived indicator	Region	Practical	Secondary	Malopolska Regional Statistical Office
DE SOUZA	MCU	Waste and Biomass Valorization	Recycle	4	Quantitative	Derived indicator	Region	Practical	Secondary	Eurostat
FERREIRA	CEI	Circular Economy, Ethical Funds, and Engineering Projects	Refurbish Recycle	27	Quantitative	Derived indicator	City	Practical	Secondary	Data sets for Porto, INE or PORDATA
GAO	CEI	Resources, Conservation & Recycling	Recycle	11	Quantitative	Derived indicator	City	Practical	Secondary	China City Statistical Yearbook, the Shandong Statistic Yearbook
GATTO	EWIRII	Journal of Cleaner Production	Recover	3	Quantitative	Derived indicator	Region	Practical	Secondary	National databases
GENG	CHINESE	Journal of Cleaner Production	Reuse Recycle	22	Quantitative	Multiple simple indicators	Country	Theoretical		
HAAS	CEI	journal of industrial ecology	Recycle Recover	13	Quantitative	Multiple simple indicators	Country	Practical	Secondary	
HESMATI	MULTIPLE CEI	Journal of Cleaner Production	Recycle	38	Quantitative	Multiple simple indicators	City	Practical	Secondary	Kolada
KAKWANI	WCI	Sustainable Production and Consumption	Reuse	12	Quantitative	Derived indicator	City	Practical	Secondary	
KARMAN	CECI	Journal of Environmental Management	Recycle	30	Quantitative	Derived indicator	Country	Practical	Secondary	Eurostat
MANEA	CEI	Journal of Business Economics and Management	Recycle	14	Quantitative	Derived indicator	Country	Practical	Secondary	Eurostat
MARTINEZ MORENO	CECI	Journal of Cleaner Production	Recycle Recover	22	Quantitative	Derived indicator	Country	Practical	Secondary	Eurostat
MAZUR-WIERZBIKA	CEI	Environmental Sciences Europe	Recycle	13	Quantitative	Multiple simple indicators	Country	Practical	Secondary	Eurostat
MUSYAROFAH	CEI	Management Systems in Production Engineering	Recycle Reuse	7	Quantitative	Derived indicator	City	Practical	Secondary	Government of Indonesia secondary data
NURDIANA	CEI	Sustainability	Reuse Recycle	19	Quantitative	Multiple simple indicators	City	Theoretical		
PITKANEN	CEJ	Journal of Cleaner Production	Reduce Recycle	11	Quantitative	Multiple simple indicators	Country	Practical	Hybrid	Statistics Finland's data and financial statement statistics
SILVESTRI	CESI	Journal of Cleaner Production	Recycle	11	Quantitative	Derived indicator	Region	Practical	Secondary	Eurostat
SILVESTRI	CEDI	Journal of Cleaner Production	Recycle	11	Quantitative	Derived indicator	Region	Practical	Secondary	Eurostat
SMOL	FRENCH	Circular Economy and Sustainability	Rethink Reduce Repair Recycle	10	Quantitative	Multiple simple indicators	Country	Practical	Primary	National databases
SMOL	POLISH	Circular Economy and Sustainability	Rethink Recycle	12	Quantitative	Multiple simple indicators	Country	Practical	Primary	National databases
STANKOVIC	CEI	Waste Management	Recycle	11	Quantitative	Derived indicator	Country	Practical	Secondary	Eurostat
TONG	EWRI	Journal of Cleaner Production	Recycle	3	Quantitative	Derived indicator	Region	Practical	Hybrid	Chinese bureau of statistics
VRANJANAC	CEI	Environmental Science and Pollution Research	Reuse Recycle	7	Quantitative	Derived indicator	Country	Practical	Secondary	Eurostat
WANG	UCDI	Journal of Cleaner Production	Reuse Recycle Recover	17	Quantitative and Qualitative	Multiple simple indicators	City	Practical	Secondary	City's implementation plan
YANG	CEI	Resources, Conservation and Recycling	Reuse Recycle Recover	26	Quantitative	Derived indicator	Region	Practical	Secondary	China Economic Net, China Energy Statistical Yearbook, Shaanxi Statistical Yearbook, Environmental status bulletin of Shaanxi Province

Table 10 Axial coding findings summary

3.4. Summary of open coding

To enhance the analytical depth of the indicator's discussion presented throughout Chapter 3.2, a personal (open) analysis is conducted in Table 11.

The aim of this chapter is to present an additive instrument of investigation of circularity assessment method, useful to make comparisons between different approaches and to draw important considerations. Nevertheless, Table 11 serves as a valuable tool for the audience, facilitating a more tangible comprehension of the extensive discussions up to this point.

Comparing the enumerated findings, a salient observation emerges, capturing immediate attention: Over 50% of the indicators intricately orbit around the realms of waste management and Circular Economy investments. Waste, undeniably, stands out as a focal point within the Circular Economy paradigm. Consequently, it emerges as an optimal candidate to underscore the degree to which a state/ country has not only recognized the essence of the environmental predicament but has also undertaken proactive measures to mitigate this hazardous obstacle. The centrality of waste management in the discourse on Circular Economy becomes emblematic of a nation's conscientious strides toward sustainable environmental control, emphasizing the imperative need for preventive actions in the face of pressing ecological challenges.

AUTHOR	**INDICATOR**	Recycling rate	Recovery rate	Waste management	Waste generation	Resources consumption	Circular materials usage rate	Recyclable material trade	Innovation in CE	Investments in CE	Jobs	Education	Health/ Life expectancy	Gender equality	GDP/GDP From CE	CE related patent
AVDIUSHCHENKO	CEI			x		x	x		x	x	x	x	x		x	x
DE SOUZA	MCU			x			x									
FERREIRA	CEI			x		x			x	x		x		x		
GAO	CEI	x		x		x									x	
GATTO	EWIRII		x	x												
GENG	CHINESE NATIONAL INDICATORS	x		x		x									x	
HAAS	CEI	x				x										
HESMATI	MULTIPLE CEI	x		x												
KAKWANI	WCI					x										
KARMAN	CECI		x	x	x	x	x	x		x	x					x
MANEA	CEI	x		x					x							
MARTINEZ MORENO	CECI	x	x	x	x		x	x		x	x				x	x
MAZUR-WIERZBIKA	CEI	x	x	x	x		x	x		x	x				x	
MUSYAROFAH	CEI	x			x						x	x	x			
NURDIANA	CEI	x		x		x	x			x	x	x	x	x		
PITKÄNEN	CEJ			x							x	x				
SILVESTRI	CESI			x	x					x			x			x
SILVESTRI	CEDI			x	x					x			x			x
SMOL	FRENCH NATIONAL INDICATORS															
SMOL	POLISH NATIONAL INDICATORS			x	x	x			x	x	x					
STANKOVIC	CEI			x	x			x		x	x				x	x
TONG	EWRI	x		x	x											
VRANJANAC	CEI	x		x	x		x			x	x				x	x
WANG	UCDI	x	x	x		x			x	x						
YANG	CEI	x				x					x	x			x	
TOTAL COUNT		13	5	20	10	11	7	4	5	12	11	6	5	2	8	7

Table 11 Open coding findings

Investments stand as a driving force in accelerating the shift to circularity, acting as a pillar for sustainable practices and championing a regenerative approach to resource utilization. Financial backing becomes instrumental in supporting research and development initiatives focused on creating eco-friendly products, advancing recycling technologies, and establishing closed-loop systems. These investments not only catalyze technological progress but also provide economic incentives for businesses to embrace circular practices, rendering them financially feasible. Furthermore, channeling funds into circular initiatives contributes to the creation of jobs and fosters economic growth, aligning environmental sustainability with overall economic prosperity. In essence, investments serve as a dynamic propeller allowing the Circular Economy to make a step forward, facilitating innovative changes across industries.

4. Research Gaps and Future Research Directions

Assumed that impact on the social dimension is unquestionable, the neglection of the social dimension in the argument surrounding Circular Economy is a conspicuous gap that hinders the holistic sustainability goals of this paradigm.

The presence of social factors assessed in the papers analysis, especially in (Pitkänen et al., 2023) and (Yang et al., 2011) work, is not sufficient to assign a significant weight to this dimension of circularity.

As a matter of facts, Table 11 shows that only 16% of the analyzed studies relies on the concept of 'health/life expectancy'. This trend gets even worse if we consider 'gender equality', where the percentage of inclusion falls under 10 %, surely not enough importance for a cardinal aspect of the CE paradigm like social impact.

While the emphasis has predominantly been on the environmental and economic aspects, the social dimension, encompassing aspects like equity on accessibility to circularity sites, healthcare, and community gender engagement, often deserve a backseat. Instinctively, someone can assume that this oversight may derive from the historical focus on resource efficiency and waste reduction, which tend by nature to be more quantifiable and directly measurable. Findings show that lot of metrics can be enrolled as valid instrument to analyze the social dimension.

However, the social component is integral to guarantee the achievement of any sustainable initiative. Ignoring the social dimension can perpetuate disparities, as vulnerable communities may be disproportionately affected by changes in consumption and waste recovery patterns. To capture the idea of CE as truly transformative and inclusive transformation, it must be addressed the social implications of its strategies, considering in which measure it ensures benefits equitably distributed and it doesn't affect adversely marginalized groups. Integrating social considerations into the CE assessment framework is crucial to build a more robust instrument. It requires a paradigm change that recognizes the interconnectedness of environmental, economic, and social factors in shaping a truly circular and equitable society.

Another notable omission in the current discourse on Circular Economy (CE) pertains to the inadequate consideration of cultural factors. The cultural dimension remains a missing spot in the existing literature and frameworks for assessing circularity. Culture plays a significant role in shaping consumption patterns, attitudes towards waste, and the adoption of sustainable practices. Yet, the previous discussions often overlook the cultural hint that influence people's behaviors and choices. Incorporating cultural considerations during the assessment of circular initiatives would provide valuable insights into the social acceptance and feasibility of circular practices within diverse communities. Recognizing and respecting diversity is essential for the successful computation of advancement status. The higher is the cultural distance between communities, the higher is the necessity to raise an adaptive tool able to adopt certain lens depending on people's individual perception.

Under this perspective allowances can be granted for the works of (Nurdiana et al., 2021), where the selection of metrics is mainly driven by the necessity to engage individuals with diverse backgrounds.

Everyone brings to the research a unique perspective that significantly differs from one another.

In this case, the viewpoint of everyone plays a pivotal role in determining the indicators of circularity.

By addressing this missing spot, the CE framework can be more inclusive and attuned to the different socio-cultural contexts in which it is applied.

The work of (Nurdiana et al., 2021) can be assumed as an example of how to properly include different people condition in the circular assessment context. Metrics should be defined in collaboration with people to have the broader possible measurement spectrum.

An alternative solution can be the establishment of an adaptive instrument able to refine and modify the metrics based on the community that is under inspection. In doing so, research would be able to have an extensive overview of the real status of CE implementation.

Although circularity is nowadays globally assumed one of the most effective development frontiers from a sustainability perspective and will surely gain importance years go by, a lot has still to be done to convince a significant portion of the population. This perceivable lack of confidence can be attributed to many different causes from the scarce knowledge of the topics and the benefit reachable to the mistrust of the utility contribution that used product can supply for the purposes for which they are employed.

Even if this document is not the right forum to address this psychological discussion behind population acceptance, assessment on population awareness has not been properly taken into account and it figure as a critical missing spot in the current discourse on Circular Economy (CE). Too limited consideration has been given of the cognitive dimension. The psychological aspects related to consumer behavior, perception, and motivation are usually avoided in discussions surrounding circularity. Understanding how individuals perceive and respond to circular initiatives, such as recycling programs or product design, is vital for their successful adoption. Integrating psychological indicators into the evaluation of CE adoption would provide valuable intuition into the effectiveness of strategies aimed at changing consumer behavior. By focusing on this psychological gap, the model can better matched with the intricacies of human behavior, inducing, as a response to this feedback, a more targeted and impactful interventions to promote a circular mindset among individuals and communities.

A possible solution can be the implementation of a personal feedback survey capable to outline the subjective response of population to this sustainable improvement.

The collection of these qualitative data would then be combined to generate an average assessment of the level of acceptance of CE.

Pairing this analysis with a quantitative circular assessment tool, Firms and Policy makers can get insight both on status of CE adaptation and on people opinion.

Knowing this additional information allows Governments and Firms to act accordingly to convince about the potentials of Circular Economy transition.

The concept of a circular economy is envisioned as a paradigm where the value of products and services is preserved within the economy for as long as possible, despite a gradual decline in economic value. Building on this principle, there should be a significant focus in literature on assessing the durability of products across countries and regions throughout their lifespan. While this aspect has been extensively discussed in the literature on circularity of products, MCI proposed by Macarthur Foundation (Ellen MacArthur Foundation, s.d.), this aspect has been overlooked in the circularity assessment literature at the macro level.

A potential remedy for this gap in literature could involve the creation of an index capable of calculating the average longevity of products within various industries. This metric would evaluate the extent to which different geographical areas consider the possibility of reintegrating products into the utilization cycle through various circular strategies, ranging from more conservative value saving approaches to more aggressive ones.

Throughout the thesis, the comprehensive consideration of the 9 Rs has been infrequent (nearly absent).

Table 4 proves this tendency since not even a paper was able to give importance simultaneously to all circular strategies.

Recognized this, evaluation approaches become partial, unable to capture the complete trajectory that goods undergo within the system. Consequently, these assessments cannot accurately determine whether countries have genuinely embraced the change.

Different areas of the world adopt varying strategies to boost their circular practices. Some prioritize recycling, establishing infrastructures to manage disposed materials, while others opt to promote the reuse of public goods through sharing services, such as car sharing.

Reasons for divergent choices derives from different economic condition and cultural background.

The implementation of Circular Economy practices is undeniably costly, making such substantial transformations unfeasible for many regions across the world to afford, especially when scarce cultural awareness about obtainable benefit represents a barrier for the transition.

When assessments are conducted with partiality, results can appear misleading, adding further confusion to an already intricated issue.

5. Conclusion

As we conclude this study, it becomes evident that circular economy holds immense promises for addressing the pressing environmental and economic issues facing our global society.

The journey through this Thesis has deep dived into the intricate landscape of the macro-level approaches for circularity assessment, exploring potential solutions and highlighting limits of the current literature.

This research started underscoring the significance of embracing a proper circular economy assessment benchmark to estimate the macro level implementation of the circular paradigm. The transition from a linear to a circular economy requires an important shift in how society approaches production, consumption, and waste management. By emphasizing the principles of reduce, reuse, recycle and many others, it's possible not only to mitigate the negative environmental impacts but also unlock new economic opportunities and social challenges.

This work systematically reviewed 25 circular assessment tools composed by 379 indicators at the macro level. Reviewed indicators were utilized in various contexts from the city scope to the country one and touched upon several areas such as material flow analysis and waste management.

The SLR kicked-off by defining the primary inquiries that forms the core of this work. The subsequent phase of this study involved the delineation of criteria essential to properly create the sample of research works, forming the bedrock for the subsequent analysis of the literature.

Following the establishment of these criteria, the study proceeded specifying the database, and the formulation of research string employed to systematically identify and retrieve articles pertaining to the subject matter. This methodological approach aimed to ensure a comprehensive and rigorous selection of literature for subsequent examination, thereby laying the groundwork for an exploration of the circular economy indicators at the macro level.

The work progressed with an examination of the obtained sample, approached from the lens of a common coding scheme (Bibliometric analysis), widely employed in systematic literature reviews (SLR), and the lens of an open and axial coding scheme designed to analyze articles. The latter was tailored for a more nuanced understanding and precise evaluation.

The study concluded with the presentation of results, accentuating not only the mathematical developments behind the assessment methods but also motivating their robustness with real-world evidence, bridging theoretical findings with tangible empirical support.

It is important to stress that this study exclusively relies on published literature on Scopus database, which might be biased towards studies with positive or statistically significant results. Negative findings may be underrepresented. In addition, the methodological quality that lays behind the sieved studies in not known and for that reason may be impactful for the study.

Diversity of methodologies reflects the natural complexity of capturing circularity within a unique macroeconomic framework. The value added by these indicators lies in their capacity to go over traditional economic metrics, compounding environmental and social dimensions crucial for a holistic understanding.
The diverse range of methodologies presented so far has contributed to address the fundamental questions posed at the beginning of this study. Despite the lack of a comprehensive evaluation of the different circular strategies, as highlighted in chapter 4, the tools examined have successfully captured a multitude of factors directly and indirectly influencing the applicability and development of Circular Economy (CE).
The absence of a complete evaluation on the circular strategies framework poses challenges for effective comparisons between regions, countries and cities, hindering the establishment of benchmarks able to track progresses. As observed in numerous articles, the social influence in Circular Economy assessments is evident but remains somewhat underdeveloped, resulting in imbalanced outcomes.
Addressing this gap emerges as a critical task for researchers to foster an adequate language in advancing circular economy objectives.
While the literature review has provided a comprehensive overview of existing circular economy indicators, it also points to avenues for further research. The identification of research gaps in the current body of knowledge, such as the integration of psychological aspects into circular economy indicators opens new frontiers for future findings.
Moreover, the review highlighted the dynamic nature for circular economy indicators, emphasizing the need for continuous refinement and adaptation. Future research should focus on developing flexible and responsive frameworks that can accommodate changes in consumption patterns, and technological advancements, ensuring the relevance and effectiveness over time.
The suggestions put forth in this study are not exhaustive in exploring the subject area; instead, they aim to promote continued discussions and advancements in the examined topic.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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"Nella speranza che questo elaborato possa costituire un modesto contributo per promuovere una maggiore consapevolezza e rispetto verso la natura, l'ambiente e le persone che ci circondano per il futuro del nostro Pianeta e delle generazioni future."