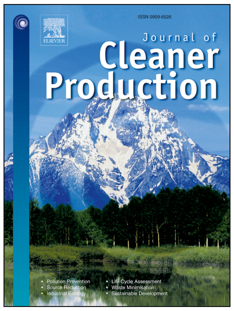

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Techno-Sustainable Analysis of Circular Economy-Indicators for Corporate Supply Chains

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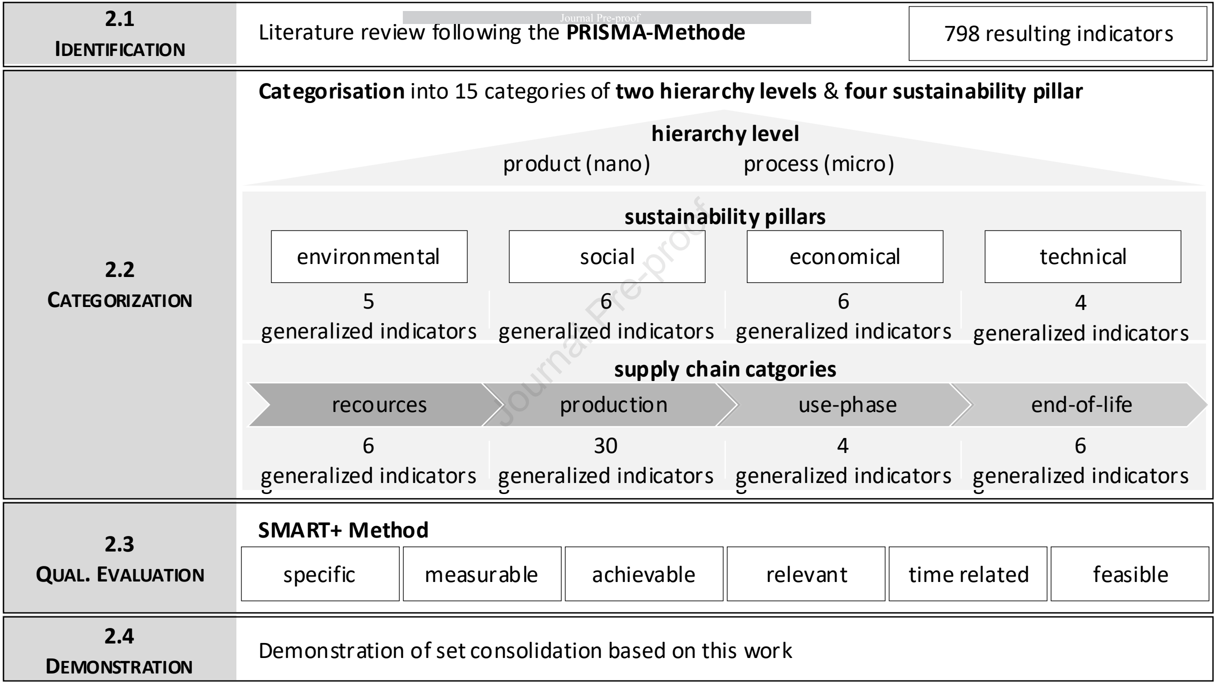
Abstract

Circular economy indicators can help companies track their production and develop products that meet the requirements of a circular economy. Those indicators not only cover sustainability aspects but also technical aspects of circular economy measurement. This work considers both the classic pillars of sustainability—environmental, economic, and social—and the technical aspects of a circular economy within a techno-sustainable analysis. Although existing frameworks and metrics exist on the micro (company) and nano (product) levels, a standard for creating sets of circular economy indicators still needs to be developed. To help practitioners monitor their CE progress using indicators suitable for their requirements, a comprehensive framework for existing circular economy indicators at the product and company level is conducted, and a Database with all identified indicators is provided. The indicators are categorized following the techno-sustainable pillars and addressed supply chain stages to enable selection according to the applicant's specific requirements. To simplify the selection process and to identify research hotspots, indicators that measure similar or identical aspects are grouped and generalized. Moreover, a SMART+ method is introduced to evaluate the feasibility of possible CE indicators.

798 individual indicators are extracted from the literature and categorized according to the Techno-Sustainable Analysis. Furthermore, they are classified into nine supply chain-oriented categories. The Environmental and Technical pillars are the most frequently represented, which confirms the relevance of the technical aspects of circular economy indicators. The shares of the indicators assigned to the individual pillars and hierarchy levels differ significantly depending on the life cycle stage under consideration. 67 generalized indicators are derived from indicators measuring similar or identical circular economy aspects, and calculation formulas are presented. A demonstration case of a ceramic matrix composites producer demonstrates creating an indicator set based on the provided 4-step action recommendation. This approach combines the provided indicator pool with the generalized indicators and the SMART+ method to create individually adjusted sets. In conclusion, this paper provides a detailed analysis of existing CE indicators and demonstrates how users can create application-specific indicator sets based on this research.


2.1
IDENTIFICATION
Literature review following the PRISMA-Methode
798 resulting indicators
2.2
CATEGORIZATION
Categorisation into 15 categories of two hierarchy levels & four sustainability pillar
hierarchy level
product (nano)
process (micro)
sustainability pillars
environmental
social
economical
technical
5 generalized indicators
6 generalized indicators
6 generalized indicators
4 generalized indicators
supply chain catgories
recources
production
use-phase
end-of-life
6 generalized indicators
30 generalized indicators
4 generalized indicators
6 generalized indicators
2.3
QUAL. EVALUATION
SMART+ Method
specific
measurable
achievable
relevant
time related
feasible
2.4
DEMONSTRATION
Demonstration of set consolidation based on this work

1. Introduction

Modern society is based on massive energy, mineral, and biogenic raw materials demands, which has led to extensive changes in natural material flows. Concepts such as *Planetary Boundaries* exemplify the transgression of *safe operating spaces* for different planetary systems, which will most likely destabilize life on Earth (Rockström et al., 2009). Unless society establishes nearly closed material cycles similar to natural systems, the anthropogenic system will not be sustainable (O'Rourke, 1996).

Companies play a crucial role in providing goods and services to society. Progress towards a circular economy (CE) must be monitored steadily, and decisions must be aligned with CE targets. However, the 'circularity' of products or processes is not directly measurable. Therefore, so-called 'circular economy' indicators are used for measuring, monitoring, and steering the circular economy's current state and future development (Kristensen and Mosgaard, 2020). Indicators can support understanding complex systems by processing and synthesizing large amounts of data, classifying the current status compared to the target status, monitoring progress toward targets and objectives, and communicating (Mitchell et al., 1995).

Circular economy indicators available on the corporate level often resemble the different dimensions of sustainability. However, while CE primarily benefits the organizations that adopt it, sustainability focuses on broader environmental, economic, and social advantages (Geissdoerfer et al., 2017). Existing frameworks, like Kristensen and Mosegaard, highlight this by showing that CE indicators frequently emphasize sustainability dimensions (Kristensen and Mosgaard, 2020). However, when analyzing CE indicator frameworks, it becomes evident that specific indicators can not be aligned with the sustainability pillars as they primarily assess the technical aspects of production or products.

In this paper, we conduct a techno-sustainable analysis that categorizes indicators along the traditional three pillars of sustainability—economic, environmental, and social—and introduces an additional technical pillar. This approach allows a more nuanced understanding of how CE indicators align with or diverge from sustainability goals. Based on this analysis, company-specific indicator sets can be derived to support companies transitioning to a circular economy.

While the European Union provides circular economy indicators on a macro level (European Commission, 2018), the literature rarely addresses indicators on the company (micro) and product (nano) level. Two frameworks by Alamerew and colleagues address the product level and present a multi-criteria evaluation method to support CE-oriented decision-making by providing a systematic analysis of relevant criteria and possible indicators (Alamerew et al., 2020; Alamerew and Brissaud, 2019). On the company level, Baratsas et al. (2022) provide a tool for companies to track their transition towards the circular economy and to compare it with their industrial standard. For this purpose, 50 indicators of the categories organization, waste, water, procurement, energy, GHG emissions, spillages & discharges, and durability are presented. The approach is demonstrated through 3 case studies from the energy utilities, manufacturing, and automotive sectors. Additionally, De Oliveira et al. (2021) published a comprehensive literature review covering both the product and company level. Fifty-eight indicators are categorized according to the three sustainability pillars and assigned to four life cycle stages: *take, make, use, and recover*. Rossi et al. (2020) link Circular Economy principles, the Circular Business Model, and sustainability pillars with their indicator set. Most frameworks and literature reviews only address specific aspects of the circular economy, such as remanufacturing (Fatimah and Aman, 2018) or resource efficiency (Ardente and Mathieux, 2014), or address specific industrial sectors like building (Khadim et al., 2022) or agriculture (Poponi et al., 2022)

The British Standards Institution provided the first Circular Economy standard for companies (BS 8001:2017) in 2017. This standard offers organizations practical guidance and a structured framework, enabling them to capitalize on the opportunities presented by the circular economy (British Standards Institution, 2017). Pauliuk (2018) takes a critical stand on this standard as it is vague in monitoring CE strategies and does not connect the measurement of CE with existing quantitative and scientifically backed methods like Material Flow Analysis (MFA) or Life Cycle Assessments (LCA). Another technical standard, UNI/TS 11820:2022, was published in 2022 in Italy and contains 71 indicators for companies to track their CE state (Enrico M. Mosconi et al., 2023). Amicarelli and Bux (2023) tested the awareness and perception of CE indicators provided by the Italian UNI/TS 11820:2022 standard among 105 managers. They highlighted the need for enhanced education in companies, precise definitions of boundaries and technical terms, and emphasizing the economic and environmental benefits of improved circularity practices.

The need for simplification and standardization of CE metrics to increase user acceptance is highlighted by several frameworks (Kristensen & Mosgaart, 2019; De Oliviera,2021; Alamerew, 2020). Therefore, analyzing and evaluating existing indicators to derive potential simplifications may be helpful. Alamerew (2020) additionally suggests a more in-depth consideration of the life cycle stages before end-of-life, while both Kristensen & Mosgaart (2019) and De Oliviera (2021) remark that indicator sets must address the feasibility of CE indicators. To address these research gaps, this paper aims to review existing CE indicators on the micro and nano level, categorize them according to a techno-sustainable analysis, harmonize them using generalized indicators with mathematical formulas, and help to evaluate the quality of indicators using the adjusted SMART+ method.

Respectively, this work addresses the following research questions:

1) Which Circular Economy Indicators on micro and nano level exist in the scientific literature?
2) What is the ratio of the identified indicators between the different techno-sustainable dimensions regarding the addressed life cycle stages?
3) What are the main CE aspects addressed by current literature, and is it possible to derive a set of generalized indicators by harmonizing the indicator computation?
4) How can the quality of indicators be systematically evaluated, and a suitable indicator set be derived for a specific use case?

This work begins with a literature review to identify circular economy indicators on micro and nano level, compiling an indicator pool. The indicators are categorized by reference level and life cycle stage before being generalized with similar CE indicators. The techno-sustainable analysis assesses their distribution across sustainability and technical aspects of the CE. Finally, the indicators are evaluated qualitatively using the SMART+ method, demonstrating the creation of a *use-case-specific indicator set* from the derived indicator pool.

2. Method

Figure 1 illustrates a four-step approach utilized in this study to address the research questions. The initial step reviews the literature on Circular Economy indicators. Secondly, the indicators are categorized by hierarchy level and application area combined with an aggregation of similar indicators. The third step applies an adapted SMART+ method (Doran, G. T., 1981) to prioritize indicators based on quality and feasibility. The final step demonstrates this approach for tailoring indicator sets to specific applications.

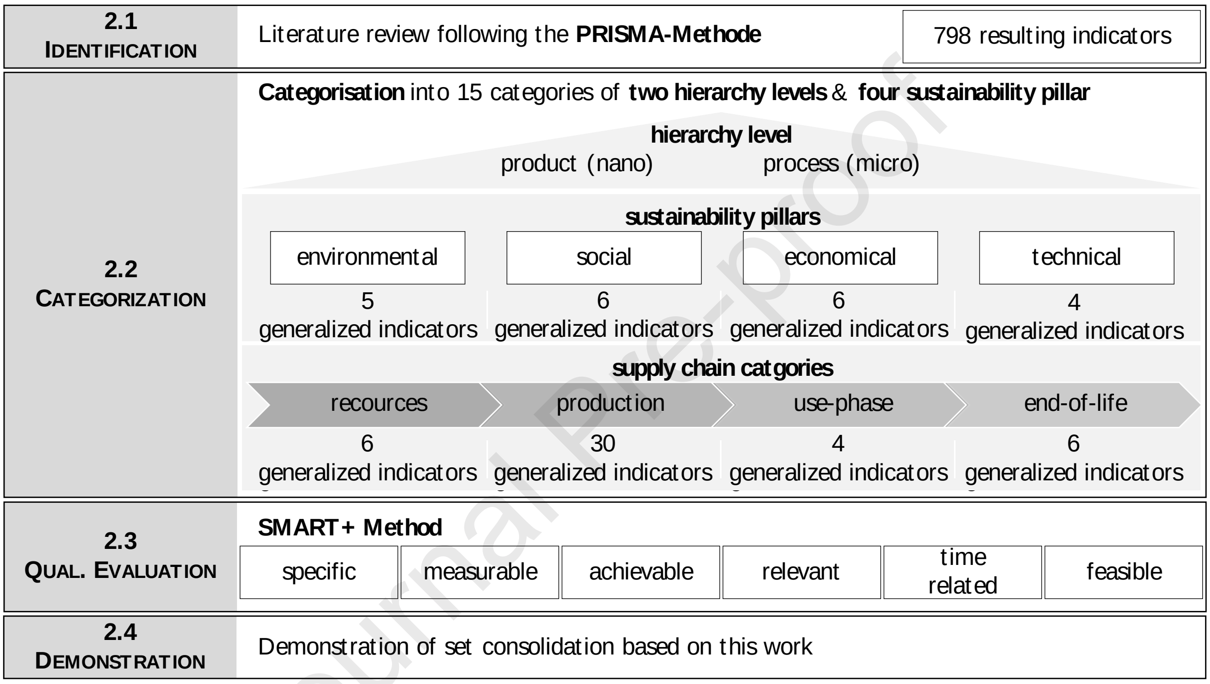


Figure 1 Framework to assess Circular Economy indicators using the techno-sustainable analysis

2.1 Identification of Existing Circular Economy Indicators

A literature review following the PRISMA Method was conducted on Web of Science platform in November 2023. The search string includes four parts at the topic level. The first part addresses the topic of the *circular economy*: *("circular economy" OR " CE " OR circular* OR circulytic*)*. This is combined with the terms *(indicator OR measure* OR index OR indice* OR metric)* to identify literature on the measurement of CE. Since this work focuses on material and product level indicators, *(material* OR product*) and (micro* OR nano*)* are added. To exclude works on nano materials, the following keywords are excluded for all fields: *"nano material*" OR "nano tube*" OR "nano part*"OR "nano techn*" OR "nano research*" OR "nano chemistry" OR "nano physics".* Grey and non-reviewed literature, as well as proceedings, are excluded.

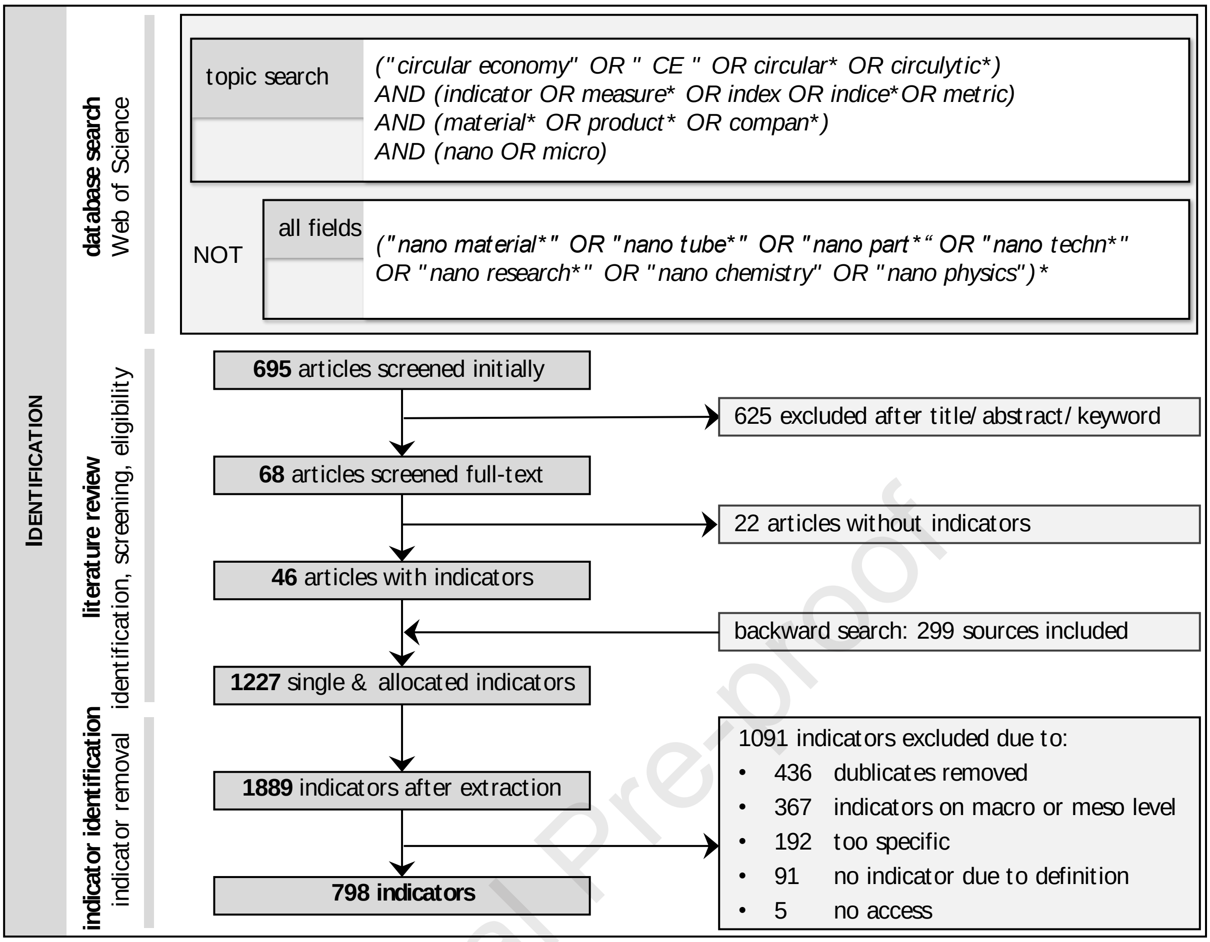


Figure 2 Literature review and indicator pool

The search identified 695 publications, with titles and abstracts screened for CE indicators on micro or nano level. Out of these, 627 are excluded due to a lack of clear CE relation, leaving 68 for full-text analysis. Most excluded papers focus on technical research on nano or micro materials. A full-text analysis is performed identifying primary sources of CE indicators and extracting them for further analysis. The allocated indicators were subsequently disaggregated into their respective subordinate indicators. In total, 1,889 indicators are collected, of which 436 duplicates are removed. 367 indicators are assigned to industrial complexes (meso) or country (macro) level without transferability to the micro or nano level and are therefore excluded. Indicators within the indicator pool should be relevant and applicable to several different industries and products. Therefore, 192 Indicators are excluded as they are too specific. Examples of this often refer to the construction or agricultural sector, such as the *laying rate* (Rukundo et al., 2021) of hens or the *cereal import independency ratio* (Al-Thani and Al-Ansari, 2021). Additionally, 91 items are not classified as indicators because they are compiled within questionnaires or methodologies such as Life Cycle Assessments. Eventually, 5 indicators could not be extracted as access rights were missing. In total, 798 indicators at nano and micro level are identified as eligible for further consideration. The source of each indicator can be found in the Excel file included in the Supplementary material.

2.2 Categorization following the Techno-Sustainable Analysis

We differentiate between two indicator levels: *aggregated indicators*, which consist of two or more subordinate indicators, and *indicators*, which are the smallest, indivisible measurement. In the supplementary material, we additionally differentiate between sub-indicators linked to an *aggregated indicator* and *single indicators*, which exist independently. The categorization excludes *aggregated indicators* to prevent double counting, as they inherit all properties of their subordinated indicators.

General Categorization

Table 1 shows all categories applied in this work for categorizing CE indicators. The most common categorization is based on the hierarchy level, which defines the scope of an indicator (De Oliveira et al., 2021; Kristensen and Mosgaard, 2020). While we focus on micro and nano level indicators (company and product-based), all four levels (micro, nano, meso, and macro) are considered since indicators of the literature review refer to all levels. P*roduct level indicators* are often included at the micro level, but this work differentiates in *micro* (company or process) and nano (product) level to harmonize literature and categorizes the identified indicators, regardless of how the underlying literature ascribes the hierarchy level.

Our techno-sustainable analysis categorizes the indicators based on the sustainability pillars commonly done in CE reviews (De Oliveira et al., 2021). Since several CE indicators refer to technical aspects of production processes or products, like the *Number of parts* (Zwolinski et al., 2006) or the *Total duration of the production cycle* (Rukundo et al., 2021), without a direct link to one specific sustainability pillar, our analysis adds the category of *technical indicators*. This highlights two main parameters of the circular economy - sustainability and technology. We further categorize them by life cycle stage: *resource extraction*, *production*, *use phase,* and *end-of-life* to comprehensively map the diverse intervention points and facilitate a detailed depiction of the circularity state. The categorization encompasses 15 distinct categories; each indicator can be classified under multiple categories.

Table 1 Categorisation

	Category	Description
Hierarchy level	Nano	Product based indicators
	Micro	Company based indicators (process and company)
	(Meso)	The industrial symbiosis between companies
	(Macro)	One or more countries or regions
Sust. Pillars	Environmental	
	Economical	
	Social	
	Technical	
Extraction	Resources	Indicators for input materials
Production	Water	Water inputs/outputs, water quality
	Energy	Energy input/output, renewable energy
	Emissions	Gaseous emissions emitted
	Waste production	Amount and type of waste streams
	Hazardous substances	Hazardous waste, exposure during production processes
	Transport / Packaging	Transport and packaging indicators
Use phase	Use phase	Indicators addressing the product in use
EoL	EoL	End-of-Life indicators

Indicator generalization

Many indicators measure the same or similar CE aspects. For instance, the indicators of *cumulated energy demand* (Huijbregts et al., 2006) and *energy intensity* (Lokesh et al., 2020) measure the *energy input into* a production system or product. To harmonize indicators with the same intention but different terminology, this approach merges similar indicators into 67 generalized indicators, offering a generic formula when applicable. The mathematical formulas represent the commonality of most indicators within each generalized indicator, though some particular calculation schemes may not be fully covered. This step aims to harmonize a large number of identified indicators to unveil the main aspects covered by existing CE indicators. On average, each indicator category (cf. Table 1) consists of 4 to 5 generalized indicators per category. A generalized indicator is also formed if no generalized mathematical formula can be abstracted. Indicators that cannot be assigned to a specific life cycle stage are categorized under their respective techno-sustainable pillar: *environmental*, *social*, *economic,* or *technical*.

2.3 Qualitative Evaluation using the SMART+ Method

To tailor indicator sets and select the most appropriate indicators, they can be evaluated regarding different quality features. However, the qualitative evaluation of indicators is partly subjective and depends on the use case and the final applicant. A standard method for evaluating the quality of indicators is the SMART method, initially developed for management goals by Doran (1981). Indicators are defined as good if they are ***S**pecific*, ***M**easurable*, ***A**chievable*, ***R**elevant,* and ***T**ime-related*. While the attributes *time-related* and *measurable* are objective, *specific*, *achievable,* and *relevant* are subjective and depend on the given context. For instance, a raw material supplier defines other indicators as *achievable* and *relevant* compared to a producer of end-products.

In addition to the SMART attributes, it is particularly relevant for companies whether the indicators are feasible for their use case and the given circumstances. Therefore, this work further specifies the **SMART+** method by adding the factor *feasibility and* a *local reference*. The feasibility is estimated by the *necessary data volume*, the *effort* to calculate the indicator, and the applicant's *comprehensibility*. This results in eight attributes to evaluate an indicator's quality: *Specific*: The Indicator is specific in what it measures; *Measurable*: The indicator can quantitatively be calculated; *Achievable*: Relevant data is available, and the goal set can be achieved; *Relevant*: The indicator measures a relevant aspect for the applicant; *Location-based*: The result depends on the location it is calculated for; *Time-related*: The results depend on the time of calculation or a time period. *Necessary data volume*: Amount and quality of required data. *Effort*: effort for calculating the indicator. *Comprehensibility*: The applicant understands what and how the indicator measures CE aspects.

The three attributes *necessary data volume*, *effort*, and *comprehensibility* are scalable. Therefore, the respective categories are ordinally scaled and, in this work, rated as high, medium, and low. All other attributes are evaluated binary by "yes" or "no".

2.4 Final indicator set compilation

Several approaches exist for tailoring an indicator set to a specific application case. Boulkedid et al. (2011) apply the Delphi Method with an iterative process of consecutive expert interviews. Another option to rank indicators is the Analytic Hierarchy Process (AHP), which was done by Osmani and Kochov (2018), for instance, in which experts rank indicators one-on-one. The final selection method depends on the applicant's availability and the willingness of experts to participate in interviews. This paper provides generalized indicators for each life cycle stage and the SMART+ method for systematic quality assessment, aiming to enable companies create application-specific indicator sets efficiently while maintaining flexibility in decision-making. The approach is comparable with established decision-making methodologies, such as the AHP or the Delphi method, while being applicable for implementation by individuals or within group settings. The generalized indicators offer insights into certain CE areas, while the SMART+ method helps identify appropriate indicators for specific applications. To ensure transparency and user flexibility, all CE indicators from the literature are provided within the indicator pool, allowing for the compilation of different indicator sets with diverging focus, goals, and complexity.

To compile a final indicator set for a specific use case, we recommend the following steps:

Step 1: Definition of the set´s goal and scope. The applicant should define the purpose of the indicator set and where it is applied. A committee comprising individuals from management, research and development, and operations could be established for this purpose.

Step 2: Definition of relevant categories. The compiled set should include only those categories relevant to the use case.

Step 3: Evaluation of generalized indicators' suitability in the relevant categories. If the generalized indicators cover the targeted CE aspects to an appropriate extent and depth, they can be integrated directly into the set. In this case, only the appropriate calculation set, e.g., calculation per product or process step, needs to be selected.

Step 4: Detailed analysis. If the general indicators do not adequately measure the CE aspect under consideration, the subjective attributes of the SMART+ method can be applied to each indicator in this category from the user's perspective. In particular, the relevance and feasibility characteristics must be assessed subjectively, while the objective characteristics can be adopted from the SMART+ evaluation provided by this work. If more indicators are rated as potentially good than needed for the set, the final decision can be made using the same or another decision-making method. If an industry-specific indicator is needed, it may be beneficial to search for previously excluded industry-specific indicators in the database (supplementary material) and include them in the user´s indicator pool.

The approach is demonstrated for an exemplary use case in Chapter 3.5.

3. Results

3.1 Frequently used CE indicators

We identified 1,889 indicators, of which 1091 are excluded, as described in Chapter 2.1. The largest group are duplicates, i.e., indicators used in several works but based on a single primary source. It is noticeable that a few indicators are mentioned more frequently in literature reviews and indicator sets, reflecting a high level of acceptance. Therefore, we first examine those frequent indicators to determine which indicators already exhibit a high level of acceptance. Foremost, the *Material Circularity Indicator*, developed by the Ellen MacArthur Foundation, was found in 30 sources. This indicator considers the minimization of linear flows in products based on weight. To determine this, the linearity of flows is determined using the *Linear Flow Index* and then related to the functionality of the product (Goddin and Marshall, 2015). The *Circular Economy Index* by Di Maio and Rem is also frequently mentioned and identified 17 times. This index assesses the performance of recycling companies based on economic indicators. Therefore, the material value of the recycled end-of-life (EoL) products is put into relation with the material value of the EoL products required for (re)production (Di Maio and Rem, 2015). The *Longevity Indicator* by Franklin-Johnson et al. was identified 14 times. This indicator determines the length of time a material is retained in a product system. The original lifespan of the product is added to the lifespan after refurbishment, as well as a proportional extension of the lifespan through products produced from the recyclate of the original product (Franklin-Johnson et al., 2016). The indicators *Product-Level Circularity Metric* by Linder et al. (2017) and *Reuse Potential Indicator* by Park and Chertow (2014) were identified thirteen and eleven times. The *Product-Level Circularity Metric* quantifies the proportion of a product derived from reused components based on their economic value relative to the total economic value of all constituent parts (Linder et al., 2017). Conversely, the *Reuse Potential Indicator* assesses the feasibility of reusing a material or product by evaluating the potential for reuse of its individual components (Park and Chertow, 2014).

3.2 Techno-Sustainable Analysis

After exclusion, 798 individual indicators remain, with 274 having no direct interference with others. In the supplementary, 60 additional aggregate indicators are listed, which combine several subordinated indicators. For further evaluations, these aggregated indicators are pulled apart into their single constituent, adding 524 indicators to the final pool of 798 indicators for the following techno-sustainable analysis. An Excel file in the supplementary material contains all identified indicators and their relation to associated indicators.

Figure 3 shows the distribution of indicators across various categories, as outlined in Table 1, highlighting the research focus in the literature. This enables the identification of well-investigated fields and potential research gaps. 507 indicators focus on the process/company level, 222 on products, and 69 can be applied to both. Regarding sustainability, 329 indicators are assigned to the *environmental* pillar, followed by *technical* aspects with 279 indicators, covering aspects as the *Separability of materials* (Alamerew et al., 2020) or the *Durability or lifetime compared with an industry average for a similar product* (EEA, 2016). 211 indicators relate to the *economic* dimension of sustainability, and only 84 relate to the *social* dimension.

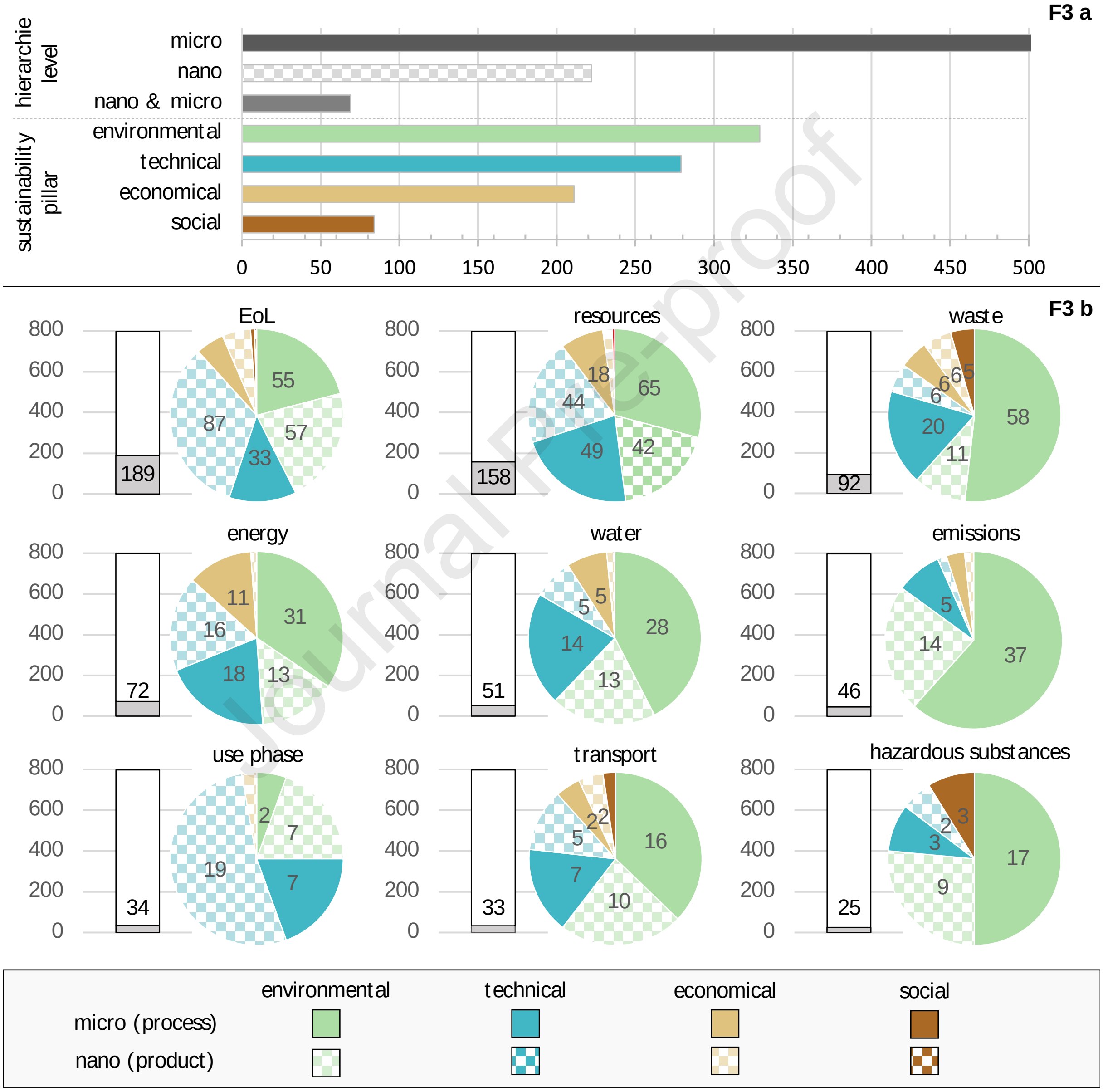


Figure 3 Distribution of indicators
Figure 3 a. shows the distribution of the indicators in respect of their hierarchy level and their Techno-Sustainable Pillar. Figure 3 b. further disaggregates the indicators and displays the number of indicators per life cycle stage categorized by their techno-sustainable pillar and hierarchy level.

Almost a quarter of the identified indicators relate to the *end-of-life of the product* or *by-products*, indicating that most research centers on closing material loops at the end of the product life. This is followed by indicators related to *resource use*, *waste*, and *energy*. Indicators referring to the *use phase*, or *transportation & packaging*, are infrequent, with *hazardous substances* being least, likely because authors often conflate this category with categories like emissions or waste.

More indicators are identified at the micro level across most life cycle stages. In the waste stage, over 80% of indicators are micro level, largely due to the focus on production waste monitored by process steps rather than individual products. A similar trend is seen for input and output streams like water and energy, making it difficult to trace these streams to specific products. The end-of-life (EoL) and use phases are dominated by nano level indicators, with EoL focusing on re-options for products or materials, and the use phase tailored to individual products.

The *environmental* sustainability pillar is prominent in most categories, comprising over half of the indicators related to *waste*, *water*, *emissions*, transport, and *hazardous substances*. Notably, *environmental*, *economic*, and *social* sustainability is least frequently represented in the *use phase*, which mainly features *technical indicators*. This is due to many indicators referring to the time of use or the product utility, not directly addressing one of the three sustainability pillars.

Technical indicators are also strongly represented in the *EoL* and *resources* categories, while less common in the *emissions* and *hazardous substances* categories, which are primarily the focus of *environmental* considerations.

Economic indicators occur in small numbers along all life cycle stages, besides *hazardous substances* with no *economic* indicator. Many of the 84 *social* indicators cannot be assigned to a life cycle stage, meaning they are rarely represented in all categories. They often refer to CE aspects like *Human rights* or *community interactions*, as shown in chapter 3.3. Consequently, there are no *social* indicators in *energy*, *water*, *emissions*, and *use phase*. The *hazardous substances* category has the highest share of *social* indicators (3), primarily linked to health aspects. Further information on distributions can be found in the Supplementary material.

3.3 Detailed examination and generalization

This section examines each category in detail and harmonizes the assigned indicators into a few generalized indicators. Table 2 provides an overview of generalized indicators, the number of indicators, the generalized calculation was retrieved from an in-depth analysis of existing calculation schemes, and an overview of sets for which it is usually calculated. Individual indicators may diverge or delve deeper into specific aspects. First, we conduct a detailed examination of categories with generalized indicators, beginning with the category containing the highest number of indicators and progressing to the category with the fewest.

Resources: The most addressed indicator of this category is *circular resource use*, referring to the share of materials or resources that can be reused or recycled compared to the total resource use assessed during both production or the end of the product's use phase. Conversely, *recycled content* indicators measure the share of secondary input materials in total inputs. Indicators of *resource efficiency* focus on the input required for specific outputs, while *resource environmental impact* indicators address the environmental damage from resource use. *Resources supply* indicators address the import and availability of resources. The indicators of *resource environmental impacts* and *resources saved* are parallel to their pendants of other categories and refer to the environmental impact of resource use and the quantity of raw materials employed.

Waste: Most indicators are related to *waste generation* measuring the relative or absolute waste output per product or process. The second most important indicators measure *waste reutilization* and address the share of waste that could be reused, recycled, or recovered. The indicator *waste collection* addresses the waste separation during collection and distribution to appropriate EoL- processes. Additional indicators address the *waste reduction* or the *environmental impact* of waste. While only four indicators can be attributed to the *waste input*, this generalized indicator is included due to the importance of waste as feedstock within a production process to reduce primary feedstock.

Energy: Energy indicators primarily relate to the absolute or relative *energy input* in the production or a process step. The second most important generalized indicator is *efficient energy use*, which measures improvements in energy consumption, frequently employing processes or products as reference points. Indicators on *renewable energy use* measure the absolute amount of energy generated by renewable sources or compare the share of renewable energy to fossil energy in a product or production process. A further indicator focuses on the amount of *energy produced* within a plant or company's boundaries through production processes or installed renewable energy sources. *Energy general* covers all energy-related indicators not covered by one of the previously described generalized indicators.

Water: Similar to energy, many indicators focus on the absolute or relative *water input* followed by *water recirculation,* measuring the share of water reused or recycled. Complementary, some indicators focus on the amount of *wastewater discharged* relative to the applied process or produced product. Also common are indicators addressing the *environmental impacts* of water use, which are partly based on Life Cycle Assessments (LCA). Indicators addressing the amount of *water saved* are less common and measure the reduction of water input per process or product.

Emissions: This group's indicators predominantly focus on greenhouse gas emissions in general or CO_2 emissions. *Climate change* indicators often refer to a process or product and can be accumulated via LCA or carbon footprint analysis. Equally prevalent are indicators addressing the *environmental impact* of emissions followed by the group of *emissions avoided* to measure the contribution of CE actions. All indicators in this category not linked to previously described generalized indicators are covered by *emissions general*.

Use phase: Use phase indicators emphasize the *duration of usage,* divided based on their relation to *products* or *materials* utilized within several production circles. Another generalized indicator centers around *design for circularity*, addressing the topics of designing products that allow reuse, a design for enhanced repair possibilities, extending the use phase, or intensifying the use by renting or sharing options. Some indicators also assess the *environmental impacts* of a product during its use phase.

Transport and packaging: This category can be divided into packaging and transport indicators. Packaging indicators either address *renewable packaging* materials or the *packaging utility* covering the appropriate packaging size or reusability. Transport indicators focus on *transport optimization* in terms of reducing transport distances or their *environmental impact*.

Hazardous substances: Indicators in this category focus on hazardous substances from production processes, divided into the generalized indicators of *special waste* for toxic solid or liquid substances and *hazardous emissions* for gaseous substances. Other address *hazardous inputs* in the production process. Some indicators are based on the *environmental impacts* computed by LCA, and two address workers' *exposure* to hazardous materials.

Generalized indicators could not be established for the following categories as the individual indicators within are too different and specific. Nevertheless, they are divided into thematic groups.

End of Life: The End-of-Life category is subdivided according to the 9R mentioned, for instance, by Potting et al. (2017). These are extensions of the 3Rs and support the differentiation of the EoL category. *R0 Refuse, R1 Rethink,* and *R2 Reduce* are not directly assigned to the end of life and, therefore, do not serve as a subcategory. However, those Rs are relatively rare, with *R0 Refuse* being the least with only three indicators like the *Avoided environmental burden* indicator from Nelen et al. (Nelen et al., 2014). 23 Indicators are linked to *R1 Rethink as* the generalized indicator *Types of CE innovations* by Demirel and Danisman (Demirel and Danisman, 2019), which addresses the redesign of products and services, as well as energy, water, and waste management. 57 entries represent the category *R2 Reduce*. It should be noted that only indicators that directly address the reduction are included like *reduction of raw material* and *reduction of toxic substances* (Rossi et al., 2020).

Of the Rs directly addressing EoL, the most represented is *R8 Recycling*, with 124 entities. The indicators comprehensively span across all pillars of sustainability and hierarchical levels. Prominent examples within this category are the *Recycling Input Rate* and the *End of Life Recycling Rate,* as proposed by Graedl et al. (2011).

When exclusive EoL scenarios are contemplated, we categorize them based on the product condition. Consequently, the *R3 Reuse* and *R7 Repurpose* categories are dedicated to products requiring no condition improvement before reuse, including 77 indicators. Moreover, the 49 indicators within the *R4 Repair + R5 Refurbish* category assess the elongation of a product's use phase through preparation measures. Conversely, the *remanufacture* group (*R6*) focuses on partially reusing the product, often by reusing functional components with 46 indicators. Among these, 43 indicators from the *R9 Recovering* group relate to the partial recuperation of materials through energy recovery. To complete the feasible EoL options, the 9Rs are complemented by the category *landfilling*, which does not align with the goals of a circular economy. Since it is a viable option for EoL materials and products, we identified 20 indicators in the literature that specifically relate to landfilling.

In addition, some indicators cannot be assigned to the different life cycle stages. Therefore, they are directly grouped under their respective techno-sustainability pillars.

Environmental: Thirty-six indicators cannot be categorized and often refer to a corporation's *environmental commitment* (10) within the company or its community. These are followed by indicators addressing environmental *regulations* by governments (6), especially by complying with ISO standards. Additionally, some indicators cover the implementation of *environmental management* structures (5) or *environmental investments* (4).

Economical: 138 economic indicators are not directly linked to the supply chain. Most of them refer to *corporate performance (47),* followed by indicators for *investments (28)*. In addition, some indicators address *CE cost* (19), or *CE innovation* (16). Furthermore, some indicators relate to a company's *market situation* (17).

Social: Social indicators often do not fit the supply chain categorization (74), as seen in Figure 3. Most indicators address aspects of *employment (22),* like job creation or treatment of employees. Followed by *interactions* with (local) *communities (18),* while additional indicators treat *labor & human rights (4)* as well as *health & safety* aspects (9). Further indicators refer to the transition towards a *circular/environmental society* (11).

Technical: There are 44 technical indicators without links to supply chain categories, many focusing on the product *development* phase (18). Additional indicators refer to *efficiency* (11) factors without referring to *resource input*, while some refer to *repurposing* product parts (3).

Table 2 shows all generalized indicators of the individual life cycle stages.

Table 2 Generalized indicators

cat.	Generalized indicator	#	Formula *	possible sets
Resource	Circular resource use	67	$\frac{\sum_{set}(reusable\ material + recyclable\ material)\ [t]}{\sum_{set} material\ used\ [t]}$	products; machines; process steps
	Resource efficiency	33	$\frac{\sum_{set} input\ under\ consideration\ [t]}{\sum_{set} output\ [t]}$	products; machines; process steps
	Recycled content	19	$\frac{\sum_{set}(recycled\ input + reused\ input)\ [t]}{\sum_{set} input\ [t]}$	products; machines; process steps
	Resource supply	19	No generalized formula	
	Resource env. impact	18	LCA	
	Resources saved	8	$\frac{\sum_{set} resource\ reduction\ [t]}{product\ or\ process\ [u]}$	machines; process steps
Waste	Waste generation	30	$\frac{\sum_{set} waste\ output\ [t]}{product\ or\ process\ [u]}$	machines; process steps
	Waste reutilization	24	$\frac{\sum_{set}(waste\ reused + recycled + recovered)[t]}{\sum_{set} waste\ [t]}$	machines; process steps
	Waste collection	14	$\frac{\sum_{set} waste\ collected\ for\ EoL\ treatment\ [t]}{\sum_{set} waste\ [t]}$	collecting units
	Waste reduction	7	$\frac{\sum_{set} waste\ reduction\ [t]}{product\ or\ process\ [u]}$	machines; process steps
	Waste env. impact	6	LCA	
	Waste input	4	$\frac{\sum_{set} cost\ reduction\ due\ to\ saved\ raw\ materials\ [€]}{product\ or\ process\ [u]}$	process steps
Energy	Energy input	32	$\frac{\sum_{set} energy\ used\ [kWh\ or\ €]}{product\ or\ process\ [u]}$	energy source; machines; process steps
	Renewable energy	15	$\frac{\sum_{set} renewable\ energy\ consumed\ [kWh\ or\ €]}{\sum_{set} energy\ consumption\ [kWh\ or\ €]}$	energy source; machines; process steps
	Efficient energy utilization	14	$\frac{\sum_{set} energy\ reduction[kWh\ or\ €]}{product\ or\ process\ [u]}$	energy source; machines; process steps
	Energy produced	7	$\frac{\sum_{set} energy\ generated\ [kWh\ or\ €]}{product\ or\ process\ [u]}$	energy source; machines; process steps
	Energy general	4	No generalized formula	
Water	Water input	17	$\frac{\sum_{set} water\ used\ [m^3]}{product\ or\ process\ [u]}$	water streams; machines; process steps
	Water recirculation	13	$\frac{\sum_{set} water\ reused\ or\ recycled\ [m^3]}{water\ used\ [m^3]}$	water streams; machines; process steps
	Wastewater discharge	9	$\frac{\sum_{set}(waste)water\ output\ [m^3]}{product\ or\ process\ [u]}$	water streams; machines; process steps
	Water env. impact	9	LCA	
	Water saved	3	$\frac{\sum_{set} water\ reduction\ [m^3]}{product\ or\ process\ [u]}$	water streams; machines; process steps

cat.	Generalized indicator	#	Formula *	possible sets
Emissions	Climate change	16	LCA	
	Emissions env. impact	16	LCA	
	Emissions avoided	9	$\frac{\sum_{set} emission\ reduction\ [m^3\ or\ t]}{product\ or\ process\ [u]}$	products; machines; process steps
	Emissions general	5	$\frac{\sum_{set} non\ specified\ emissions\ [m^3\ or\ t]}{product\ or\ process\ [u]}$	products; machines; process steps
Use phase	Design for circularity	12	No generalized formula	
	Duration of usage product	11	Use time of product $[a]$ + credit for additional use time through re-options $[a]$	
	Duration of usage material	9	Use time of material or resource in product $[a]$ + additional use time through re-options $[a]$	
	Use phase env. impact	2	LCA	
Transport & Packaging	Renewable packaging	12	$\frac{\sum_{set} renewable\ packaging\ [t]}{product\ or\ process [u]}$	products; machines; process steps
	Transport optimization	8	$\sum_{set} transport\ distance\ [km] * product\ weight\ [t]$	product; material
	Transport env. impact	7	LCA	
	Packaging utility	3	No generalized formula	
Hazardous substances	Special waste	7	$\frac{\sum_{set} special\ waste\ [t]}{product\ or\ process\ [u]}$	machines; process steps
	Toxic emissions	7	$\frac{\sum_{set} emissions\ [t] * toxicity\ of\ emission\ [tox.\ eq.]}{product\ or\ process\ [u]}$	machines; process steps
	Hazardous input	5	$\frac{\sum_{set} hazardous\ input\ [t]}{product\ or\ process\ [u]}$	machines; process steps
	Haz. substances env. impact	4	LCA	
	Worker exposure	2	No generalized formula	

* Physical units: t = tonnes; u = units; € = euro; kWh = kilowatt hours; m^3 = cubic metres; a = year; tox. eq. = toxic equivalents

3.4 Qualitative Evaluation using SMART+

The SMART+ method evaluates the quality of identified indicators, which is provided in the Excel file included in the supplementary material. In the first step of SMART+, the aspect *specific* and *measurable* are assessed, and only indicators for which both aspects are fulfilled are considered in the further evaluation. Out of 798 indicators, 109 are not considered to be specific, such as *effect of regulatory pressure* (Alamerew et al., 2020), *utility during use phase* (Azevedo et al., 2017), and many others. 154 indicators are not quantitatively measurable, such as *Product destination* (Zwolinski et al., 2006) and *Brand image recognition* (Fatimah and Aman, 2018), and are therefore not applicable in most indicator-based assessments. As some indicators exhibit neither of the two properties, 609 of the 798 are both specific and measurable.

The criteria *time-based* as well as the in SMART+ included *local* criteria are not necessary for every applicant, wherefore, indicators lacking these characteristics are not excluded. Nevertheless, these two characteristics can be evaluated objectively. 401 indicators relate to a local reference, and 501 relate to time. This results in 381 indicators that meet all four characteristics and pass the objective step of the SMART+ evaluation.

The characteristics *relevant*, *specific*, and the additional *feasibility* factors are context specific and will vary between industrial sectors and different applicants. As detailed in section 3.5, these have been evaluated as an illustration for a producer in the CMC sector and are only intended as guidance during individual evaluations. All evaluated characteristics can be found in the supplementary material.

3.5 Demonstration of set compilation for action recommendations

This work illustrates the creation of a customized indicator set in the case of a producer of generic CMC (Ceramic Matrix Composites) products. For a better understanding, the demonstration starts with a short introduction to the material CMC. CMCs belong to the class of composite materials that combines favorable material properties to achieve lightweight components with superior material properties compared to the ones of their single constituents (Hsissou et al., 2021). This allows load-oriented and lightweight engineering solutions that have the potential to considerably reduce the overall material requirement (Watari et al., 2021). In recent years, composites have significantly gained importance as an emerging material class (Sauer and Schüppel, 2023; Witten and Mathes, 2023). However, current literature has not yet addressed circular economy in connection with CMC, although CE could contribute to reducing environmental impacts and increasing the economic viability of CMC (Wietschel et al., 2023). For this reason, the case of a Ceramic Matrix Composites producer of a single generic CMC product is used to demonstrate the 4-step action recommendations for creating a set of CE indicators.

Step 1: Definition of the set´s goal and scope: For this demonstration, the resulting set should provide insight into the present situation of a CMC-producing company and the 4-step approach is conducted by a single expert. The focus is on the most important parts of the CMC supply chain, while Indicators must be adaptable to composite materials and their areas of application. Relevant features for the indicator selection are the long potential use phase through high mechanical and thermal properties as well as their resistance to corrosion. CMC products usually represent a component of the final product and are manufactured in small quantities using time and energy-intensive processes. To start with a lean set that can be expanded at critical points later, a maximum of one indicator per category is selected initially.

Step 2: Definition of relevant categories: Not all categories are relevant for a CMC-producing company. So far, treating end-of-life composites presents new challenges for recirculating such materials due to the limited separability of the different materials (Naqvi et al., 2018). To the authors' knowledge, there is still no commercially viable recycling technology for CMCs, meaning they are mostly sent to landfills. Therefore, considering *EoL* indicators is not relevant at the present time. Similarly, no solid or liquid hazardous waste streams are generated during production, and water use is insignificant. For these reasons, no indicators are sought for the *EoL*, *water*, and *hazardous waste* categories.

Step 3: Generalized indicators are discussed and checked for suitability. The generalized indicators for the *use phase, transport/packaging*, and *social* category do not fit the requirements of the CMC producer and must, therefore, be defined in Step 4. Generalized indicators are selected for all other categories and calculation sets are defined. The calculations are defined at the *process step* level as the CMC producer only produces a single product. The only exception is the share of renewable energy, which should be calculated separately for gas and electricity.

Step 4: The SMART+ Method is used to carry out a detailed analysis of the indicators in the indicator pool for the remaining categories. For demonstration, the SMART+ Method was performed on every indicator of the indicator pool. In practice, this step is only necessary for categories not covered by generalized indicators. Afterwards, a final decision can be made based on the decision-makers' AHP or comparable processes.

The initial use phase is an essential advantage over competing material classes for the application of CMC. In a more detailed analysis of the use phase indicators, the indicators are evaluated along the SMART+ criteria. The indicator should be *specific*, *measurable*, *time-bound*, and *relevant*, with high *comprehensibility* and low or medium *required data volume* and *calculation effort*. The three indicators, *Actual average lifetime of selected products* (EEA, 2016), *First wear-out life* (Zwolinski et al., 2006), and *Durability or lifetime compared with an industry average for a similar product* (EEA, 2016), meet these requirements. In this case, the indicator *Durability or lifetime compared with an industry average for a similar product* (EEA, 2016) is selected to enable comparison with reference products.

For the transport and packaging category, only one indicator focusing on packaging material is picked for the CMC producer, as an external service provider provides transportation and logistics and cannot be optimized currently. We assume that most input materials are delivered in mesh boxes and other reusable transport containers, which means that the generalized indicator is not optimally applied here. Therefore, the SMART+ method is used for all packaging-related indicators. Assuming the same requirements as for the use phase category, 5 possible indicators remain. The three indicators *Recycled packaging material used (volume or weight)*; *Reusable, compostable or recyclable packaging material (share)*; and *Packaging Material to be reclaimed/recovered (number of products or share)* of Baratsas et al. (2022) as well as *Renewable or recycled resources used for packaging* and *Renewable of recycled res. For packaging / total packaging used* of the UNI/TS 11820:2022 (Enrico M. Mosconi et al., 2023). As only the indicator *Reusable, compostable, or recyclable packaging material* (share) (Baratsas et al., 2022) directly considers the use of the mesh boxes, this indicator is selected for the set.

Since the company in the demonstration case wants to focus on itself and its immediate environment at the start of its circular economy efforts, one indicator is included for each of the social groups *health & safety*, *community interaction*, and *employment*. One indicator fulfills the requirements described above for both *employment*, with the *Number of persons employed* (Azevedo et al., 2017), and *community interaction*, with *Total social investment for environmental sustainability and circular economy* (Baratsas et al., 2022). There are three possible indicators for *health and safety*: *Number of accidents per year by company* (Azevedo et al., 2017), *Work injury rate* (Fatimah and Aman, 2018), and *Output Accidents* (Baumer-Cardoso et al., 2023), of which *Number of accidents per year by company* (Azevedo et al., 2017) is selected.

To summarise, the SMART+ method only had to be used for the transport & packaging, use phase, and social categories, which significantly reduces the effort required by the company compared to conventional methods. The resulting set consists of 12 indicators: 7 derived from generalized indicators and 5 determined using the SMART+ method. The complete set of this demonstration can be found in Table 3. This demonstration shows an example set for a company producing CMCs. The sets of other companies may vary considerably, even within the same industry.

Table 3 Resulting indicator set for CMC

Step 1	Definition of the set´s goal and scope		
	first insights to identify hotspots	focus on the most important parts of the CMC supply chain	
	indicators must be adaptable to composites		
Step 2	Exclusion of irrelevant categories		
	end-of-life	no commercial End-of-Life Treatment so far	
	water	not significant	
	hazardous waste	no liquid or solid hazardous waste streams	
Step 3	Generalized indicators used		
resource	recycled content	$\frac{\sum_{\text{process steps}}(recycled\ input + reused\ input)\ [t]}{total\ input\ [t]}$	
	resource efficiency	$\frac{\sum_{\text{process steps}}(recycled\ input + reused\ input)\ [t]}{total\ input\ [t]}$	
	circular resource use	$\frac{\sum_{\text{process steps}}(reusable\ material + recyclable\ material)\ [t]}{total\ material\ used\ [t]}$	
waste	waste generation	$\frac{\sum_{\text{process steps}} waste\ output\ [t]}{product\ or\ process}$	
energy	energy input	$\frac{\sum_{\text{process steps}} energy\ used\ [kWh\ or\ €]}{product\ or\ process}$	
	renewable energy	$\frac{\sum_{\text{electricity, gas}} renewable\ energy\ consumed\ [kWh\ or\ €]}{total\ energy\ consumption}$	
emissions	climate change	LCA	
Step 4	Indicators identified using SMART+ Method		
use phase	durability or lifetime compared with an industry average for a similar product	/	(EEA, 2016)
transport & packaging	reusable packaging material	/	(Baratsas et al., 2022)
social	number of persons employed	/	(Azevedo et al., 2017)
	total social investments	/	(Baratsas et al., 2022)
	number of accidents per year	/	(Azevedo et al., 2017)

* Physical units: t = tonnes; u = units; € = euro; kWh = kilowatt hours; m^3 = cubic metres; a = year; tox. eq. = toxic equivalents

4 Discussion

In the following part, we discuss the results of our techno-sustainable analysis according to the research questions.

1) Which Circular Economy Indicators on micro and nano level exist in the Literature?

Through our literature analysis, we identified 798 different circular economy indicators on micro and/or nano level. The pool of indicators is comprehensive and heterogeneous with some indicators being mentioned frequently in several frameworks and metrics, as presented in Chapter 3.1. This implies that a few indicators are already well-established and repeatedly used, while new and slightly different indicators are constantly introduced for specific aspects of the circular economy. One reason for that expansion could be that the most widely used indicators are relatively difficult to calculate and comprehend. Although these indicators theoretically provide a suitable basis for quantifying the state of Circular Economy, it might be challenging for individual companies to apply them due to a general lack of data or appropriate assumptions to disaggregate material and energy flows to single processes or products. The need for standardization and simplification to increase the acceptance of CE is also highlighted by other frameworks in the field of CE metrics (Kristensen & Mosgaart, 2019; De Oliviera,2021; Alamerew, 2020).

The identified publications originate from different research fields, such as sustainability, economic evaluation, agriculture, and supply chain management, which demonstrates the high relevance of progress towards a CE in various research fields.

Like De Oliviera et al. (2021), we conclude that the distinction between micro and nano indicators is useful for building a deeper understanding and more advanced indicator sets. Our results show that more indicators are provided on the corporate than on the product level, indicating that companies prioritize closing internal process loops, while the end of the product life cycle is still considered to lie beyond the company`s responsibilities. New concepts are needed to advance the circular economy, especially to enhance the use of secondary materials and reduce primary material demands. Although policymakers repeatedly attempt to make manufacturers accountable for EoL products, for example with the EU directive on end-of-life vehicles, enforcement is often inadequate (D'Adamo et al., 2020). The indicators at product level identified in this work can contribute to tailoring policy regulations to specific products.

2) What is the ratio of the identified indicators between the different techno-sustainable dimensions regarding the addressed life cycle stages?

Circular economy indicators can be categorized according to their hierarchical level, their techno-sustainability dimension, and the addressed life cycle stage.

As some indicators address resource efficiency or technical possibilities without linkage to traditional sustainability aspects, we introduce an additional technical pillar. An example of this indicator type is the *Anthropogenic lifetime of material in product* (Pauliuk, 2018), which does neither address the environmental, economic nor social dimension, but reflects technical specificities. Our analysis revealed that indicators relating to the technical aspects of CE are the second most frequently used after indicators relating to environmental aspects. Technical aspects are represented throughout all life cycle stages and occur most frequently in percentage terms in the categories of *use phase*, *resources*, and *EoL*. The results reveal that social indicators are rarely addressed in the life cycle stages of products or processes besides in the *waste* and *hazardous substances* category. This may be due to the fact that CE measures have little social impact, although this is unlikely due to the potentially far-reaching consequences on material flows. De Oliviera (2021), Kristensen & Mosgaart (2019), and Baratsas (2022) also share the realization that social indicators are too rarely represented. In our analysis most indicators can be allocated to one of the four techno-sustainability pillars, with only some exceptions being appropriate in more than one sustainability pillar. While De Oliviera, like this work, considers the share of environmental indicators to be the most significant, Kristensen & Mosgaart assign most indicators to the economic pillar. This difference may be favored by the absence of the technical pillar, as De Oliviera assigns, for example, resource efficiency to the environmental pillar, although this could also be assigned to the economic pillar if no technical pillar is defined.

We additionally elaborated the life cycle stages as proposed by Alamerew (2020) to ensure acceptance by potential applicants and used intuitive and familiar categories for companies. This is especially important for product and company level indicators, as one of our aims is to streamline companies' access to the circular economy.

We identified indicators for all implied life cycle stages from resource extraction to the end of life of products. The number of indicators varies between 189 and 25, giving all stages a wide range of potential indicators. As there are 189 indicators for the end-of-life stage, a research focus on this life cycle stage can be ascertained. However, indicators should be included along the holistic life cycle to support companies in developing circular production processes and products to help them track their current transformation towards a circular economy. As shown in Chapter 3, the proportion of indicators per techno-sustainable pillar differs significantly between the life cycle stages. This could be due to different life cycle stages being focussed on by different research disciplines.

3) What are the main CE aspects addressed by current literature, and is it possible to derive a set of generalized indicators by harmonizing the indicator computation?

According to Kristensen and Mosgaart (2020), standardization can help improve the acceptance of CE and CE indicators. Chapter 3.3 generalizes indicators measuring similar or identical aspects of CE into

67 generalized indicators, with an average of 4 to 5 per life cycle category. For most, a generalized mathematical formula can be derived, which implies that many indicators, although not considered duplicates, vary only slightly and can, therefore, be generalized. The generalization thus provides a simplification for the compilation of indicator sets since the large number of similar indicators complicates the selection process. Even though the general formulas can be used for most sets, the more specific indicators can also be relevant for some sets by giving more in-depth insight into specific CE aspects.

Regarding the importance of individual CE aspects, similar indicators may also lead to distortion, as the high number of indicators may not necessarily reflect a high research focus or corporate acceptance. Instead, an aspect may be determined multiple times with a slightly different reference point or calculation methods, especially in frequently addressed categories such as energy and water usage, distorting the research focus.

4) How can the quality of indicators be systematically evaluated, and a suitable indicator set be derived for a specific use case?

De Oliviera (2021) and Kristensen & Mosgart (2020) found that integrating feasibility characteristics for CE indicators can be beneficial for acceptance. Our SMART+ Method adapts this idea, and one possibility for creating indicator sets based on our categorized indicator pool is demonstrated. The indicator pool simplifies the creation of sets by removing the time-consuming step of compiling CE indicators.

For many companies, the generalized indicators provide a straightforward starting point from which indicator sets covering large parts of the circular economy can be created with reasonable effort. When companies seek to evaluate specific aspects of CE, the generalized indicators can be adapted, and the indicator pool given in the supporting information provides the opportunity to dive deep into alternative indicators. The SMART+ method is an effective tool for refining the selection of indicators based on quality and feasibility for their use case. The method is adaptable and can be combined with various decision-making methods, like the Delphi method or the Analytic Hierarchy Process (AHP), allowing companies with diverse needs to select the most suited indicators.

5 Conclusion and Outlook

This work provides a techno-sustainable analysis of circular economy indicators at company and product level based on scientific literature. The indicators were compiled from all identified sources of micro and nano level indicators and categorized according to the techno-sustainability pillar, hierarchy level, and life cycle stage to simplify the selection of suitable indicators. In addition, all indicators were qualitatively assessed using a refined SMART+ method. Indicators measuring similar or identical aspects of CE are grouped, revealing 67 generalized indicators. For most of these, a generalized mathematical formula is presented.

Nevertheless, this study is constrained by certain limitations. Whether this framework covers all current CE indicators depends on the definition of the circular economy. In this work, we only integrate reviewed sources and consider all indicators as CE indicators stated to be CE-relevant by at least one author. In individual cases, this can lead to indicators not being considered when using a different definition of CE, as the number of indicators can vary significantly with a wider or tighter definition. This is also relevant to the definition of an indicator. We excluded questionnaires and methods which can also be useful tools for certain users. Future work can start here and expand the pool of indicators, especially by integrating more qualitative indicators. Furthermore, some assignments to life cycle stages, and especially parts of the SMART+ method, are subjective and may be assigned differently by various researchers. Future research could assist in assigning the indicators to clearly defined CE stages in a standardized and comprehensive format.

Future work could put a stronger focus on social implications of CE measures. Additionally, the techno-sustainable analysis could be conducted for the macro and meso level to determine the impact of technical aspects at these hierarchical levels. Additional categories along the life cycle stages can be added to provide a more in-depth clustering. Furthermore, additional case studies can test the SMART+ method with various decision-making methods.

Overall, this work provides a baseline to establish individual CE indicator sets for different industries, companies, or products. The indicator pool and the underlying database with over 2000 entries from over 300 sources categorize the identified indicators according to various characteristics and offer numerous links to be adapted and expanded by future work.

4. Literature

Alamerew, Y.A., Brissaud, D., 2019. Circular economy assessment tool for end of life product recovery strategies. Jnl Remanufactur 9, 169–185. https://doi.org/10.1007/s13243-018-0064-8

Alamerew, Y.A., Kambanou, M.L., Sakao, T., Brissaud, D., 2020. A Multi-Criteria Evaluation Method of Product-Level Circularity Strategies. Sustainability 12, 5129. https://doi.org/10.3390/su12125129

Al-Thani, N.A., Al-Ansari, T., 2021. Comparing the convergence and divergence within industrial ecology, circular economy, and the energy-water-food nexus based on resource management objectives. Sustain. Prod. Consum. 27, 1743–1761. https://doi.org/10.1016/j.spc.2021.04.008

Amicarelli, V., Bux, C., 2023. Users' Perception of the Circular Economy Monitoring Indicators as Proposed by the UNI/TS 11820:2022: Evidence from an Exploratory Survey. Environments 10, 65. https://doi.org/10.3390/environments10040065

Ardente, F., Mathieux, F., 2014. Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product. Journal of Cleaner Production 83, 126–141. https://doi.org/10.1016/j.jclepro.2014.07.058

Azevedo, S., Godina, R., Matias, J., 2017. Proposal of a Sustainable Circular Index for Manufacturing Companies. Resources 6, 63. https://doi.org/10.3390/resources6040063

Baratsas, S.G., Pistikopoulos, E.N., Avraamidou, S., 2022. A quantitative and holistic circular economy assessment framework at the micro level. Computers & Chemical Engineering 160, 107697. https://doi.org/10.1016/j.compchemeng.2022.107697

Baumer-Cardoso, M.I., de Souza Campos, L.M., Pigosso, D.C.A., Ashton, W., 2023. Measuring the adoption of circular economy at the company level: usefulness and applicability of the OCE index. Journal of Industrial and Production Engineering 40, 572–588. https://doi.org/10.1080/21681015.2023.2244496

British Standards Institution (Ed.), 2017. BSI Standards publication: Framework for implementing the principles of the circular economy in organizations – Guide. BSI, Frankfurt am Main.

D'Adamo, I., Gastaldi, M., Rosa, P., 2020. Recycling of end-of-life vehicles: Assessing trends and performances in Europe. Technological Forecasting and Social Change 152, 119887. https://doi.org/10.1016/j.techfore.2019.119887

De Oliveira, C.T., Dantas, T.E.T., Soares, S.R., 2021. Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. Sustainable Production and Consumption 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024

Demirel, P., Danisman, G.O., 2019. Eco-innovation and firm growth in the circular economy: Evidence from European small- and medium-sized enterprises. Bus Strat Env 28, 1608–1618. https://doi.org/10.1002/bse.2336

Di Maio, F., Rem, P.C., 2015. A Robust Indicator for Promoting Circular Economy through Recycling. J. Environ. Prot. 6, 1095–1104. https://doi.org/10.4236/jep.2015.610096

Doran, G. T., 1981. There´s a S.M.A.R.T way to write management´s goals and objectives Management Review, 35, 36.

EEA, 2016. Circular economy in Europe - Developing the knowledge base (EEA report No. 2). European Environment Agency, Luxembourg.

Enrico M. Mosconi, Sergio Bini, Andrea Colantoni, 2023. Economia circolare. Dinamica e gestione delle organizzazioni. Commento alla norma UNI/TS 11820:2022. EPC.

European Commission, 2018. Measuring progress towards circular economy in the European Union – Key indicators for a monitoring framework (Staff Working Document No. 17). European Commission, Strasbourg.

Fatimah, Y.A., Aman, M., 2018. Remanufacturing sustainability indicators: An Indonesian small and medium enterprise case study. IOP Conf. Ser.: Mater. Sci. Eng. 403, 012055. https://doi.org/10.1088/1757-899X/403/1/012055

Franklin-Johnson, E., Figge, F., Canning, L., 2016. Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Goddin, J., Marshall, K., 2015. Circularity Indicators: An Approach to Measuring Circularity (Methodology). Ellen MacArthur Foundation.

Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What Do We Know About Metal Recycling Rates? J. Ind. Ecol. 15, 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Hsissou, R., Seghiri, R., Benzekri, Z., Hilali, M., Rafik, M., Elharfi, A., 2021. Polymer composite materials: A comprehensive review. Composite Structures 262, 113640. https://doi.org/10.1016/j.compstruct.2021.113640

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, A.J., van de Meent, D., Ragas, A.M.J., Reijnders, L., Struijs, J., 2006. Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? Environ. Sci. Technol. 40, 641–648. https://doi.org/10.1021/es051689g

Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. Journal of Cleaner Production 357, 131859. https://doi.org/10.1016/j.jclepro.2022.131859

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? Journal of Cleaner Production 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531

Linder, M., Sarasini, S., van Loon, P., 2017. A Metric for Quantifying Product-Level Circularity. J. Ind. Ecol. 21, 545–558. https://doi.org/10.1111/jiec.12552

Lokesh, K., Matharu, A.S., Kookos, I.K., Ladakis, D., Koutinas, A., Morone, P., Clark, J., 2020. Hybridised sustainability metrics for use in life cycle assessment of bio-based products: resource efficiency and circularity. Green Chem. 22, 803–813. https://doi.org/10.1039/C9GC02992C

Mitchell, G., May, A., McDonald, A., 1995. PICABUE: a methodological framework for the development of indicators of sustainable development. International Journal of Sustainable Development & World Ecology 2, 104–123. https://doi.org/10.1080/13504509509469893

Naqvi, S.R., Prabhakara, H.M., Bramer, E.A., Dierkes, W., Akkerman, R., Brem, G., 2018. A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy. Resources, Conservation and Recycling 136, 118–129. https://doi.org/10.1016/j.resconrec.2018.04.013

Nelen, D., Manshoven, S., Peeters, J.R., Vanegas, P., D'Haese, N., Vrancken, K., 2014. A multidimensional indicator set to assess the benefits of WEEE material recycling. Journal of Cleaner Production 83, 305–316. https://doi.org/10.1016/j.jclepro.2014.06.094

O'Rourke, D., 1996. Industrial ecology: a critical review. Industrial ecology.

Osmani, F., Kochov, A., 2018. Definition of indicators for decision-making to contribute to sustainable development through Cleaner Production and Resource Efficiency by using the AHP method. energetika 64. https://doi.org/10.6001/energetika.v64i3.3808

Park, J.Y., Chertow, M.R., 2014. Establishing and testing the "reuse potential" indicator for managing wastes as resources. J. Environ. Manage. 137, 45–53. https://doi.org/10.1016/j.jenvman.2013.11.053

Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour Conserv Recycl 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Poponi, S., Arcese, G., Pacchera, F., Martucci, O., 2022. Evaluating the transition to the circular economy in the agri-food sector: Selection of indicators. Resources, Conservation and Recycling 176, 105916. https://doi.org/10.1016/j.resconrec.2021.105916

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation In The Product Chain (Policy Report No. 2544). PBL Netherlands Environmental Assessment Agency, The Hague.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity Johan. Nature 461, 472–475. https://doi.org/10.1038/461472a

Rossi, E., Bertassini, A.C., dos Santos Ferreira, C., Weber Antonio Neves, do A., Ometto, A.R., 2020. Circular Economy indicators for organizations considering Sustainability and Business Models: plastic, textile and electro-electronic cases. J. Clean. Prod. 247, 119137. https://doi.org/10.1016/j.jclepro.2019.119137

Rukundo, R., Bergeron, S., Bocoum, I., Pelletier, N., Doyon, M., 2021. A Methodological Approach to Designing Circular Economy Indicators for Agriculture: An Application to the Egg Sector. Sustainability 13, 8656. https://doi.org/10.3390/su13158656

Sauer, M., Schüppel, D., 2023. CU-Marktbericht_2022_GER_Kurzfassung.pdf.

Watari, T., Nansai, K., Nakajima, K., 2021. Major metals demand, supply, and environmental impacts to 2100: A critical review. Resources, Conservation and Recycling 164, 105107. https://doi.org/10.1016/j.resconrec.2020.105107

Wietschel, L., Halter, F., Thorenz, A., Schüppel, D., Koch, D., 2023. Literature review on the state of the art of the circular economy of Ceramic Matrix Composites. Open Ceramics 14, 100357. https://doi.org/10.1016/j.oceram.2023.100357

Witten, D.E., Mathes, V., 2023. Der europäische Markt für Faserverstärkte Kunststoffe / Composites 2022.

Zwolinski, P., Lopez-Ontiveros, M.-A., Brissaud, D., 2006. Integrated design of remanufacturable products based on product profiles. Journal of Cleaner Production 14, 1333–1345. https://doi.org/10.1016/j.jclepro.2005.11.028

Appendix

Table A1

#	Indicator	Source
1	Global Resource Indicator	(Adibi et al., 2017)
	Product Recovery Multi-Criteria Decision Tool Environmental (I1)	(Alamerew and Brissaud, 2019)
2	EoL impact indicator	
3	CO2 emissions	
4	SO2 emissions	
5	Energy consumption	
6	Net recoverable value	
7	Logistic cost (Collection and transport cost)	
8	Disassembly cost	
9	Product cost (What is paid for: incineration recycle, landfill etc.)	
10	Number of employees to perform the scenario	
11	Exposure to hazarous materials (Exposure of employees to hazardous	
	Multi-Criteria Evaluation Method of Product-Level Circularity Strategies	(Alamerew et al., 2020)
12	Resources	
13	EoL treatment cost	
14	Job creation opportunity	
15	Exposure of employees to hazardous materials	
16	Level of customer satisfaction	
17	Effect of legislative pressure	
18	Compliance with new and existing legislation	
19	Technical state	
20	Availability of recovery facilities,	
21	Separability of materials	
22	Advancement in technology	
23	Presence/removability of hazardous content	
24	Market demand	
25	Competitive pressure	
26	Return core volume	
	Resource Efficiency Assessment of Products	(Ardente and Mathieux, 2014)
27	Reusability rates (in mass)	
28	Recyclability rates (in mass)	
29	Recoverability rates (in mass)	
30	Reusability rates (in terms of environmental impacts/benefits)	
31	Recyclability rates (in terms of environmental impacts/benefits)	
32	Recoverability rates (in terms of environmental impacts/benefits)	
33	Recycled content rate (in mass)	
34	Recycled content rate (in terms of environmental impacts/ benefits	
35	Use of hazardous substances	
	Sustainable Circular Index	(Azevedo et al., 2017)
36	Number of accidents per year by company	
37	Loss of productivity by company	
38	Percentage of contracted women employed by company	
39	Percentage of temporary workers employed by company	
40	Absenteeism rate by company	
41	Rotation of workers by company	
42	Percentage of people with special needs employed by company	
43	Direct economic value generated and distributed	
44	Research and development expenditures	
45	Number of persons employed	
46	Rate of non-hazardous waste	
47	Rate of hazardous waste	
48	Amount of water consumed per year in industrial processes	
49	Amount of energy used per year	
50	Input in the production process	
51	Utility during use phase	
52	Efficiency of recycling	
53	Material Efficiency in Supply Chains Spreadsheets	(Braun et al., 2018)
54	Circularity Index	(Cullen, 2017)
55	Circular Economy Index	(Di Maio and Rem, 2015)
56	Material Circularity Indicator	(Goddin and Marshall, 2015)
	EoL indices	(Favi et al., 2017)
57	Reuse index	
58	Remanufacture index	
59	Recycling index	
60	Incineration index (with energy recovery)	
	Longevity and Circularity	(Figge et al., 2018)
61	Circularity	

62	Longevity	
63	Circular Economic Value	(Fogarassy et al., 2017)
64	Resource Duration Indicator	(Franklin-Johnson et al., 2016)
	Set of Indicators to Assess Sustainability	(Golinska et al., 2015)
65	Overall equipment effectiveness	
66	Remanufacturing process flow	
67	Adequacy of remanufacturing process planning	
68	Availability of machines and tools	
69	Level of executed orders	
70	Availability of materials (overall out of stock)	
71	Waste generation level	
72	Material recovery rate	
73	Generated emissions level	
74	Employment	
75	Staff training	
76	Harmfulness of the remanufacturing process	
77	Average level of comfort at work	
78	Innovation level	
79	Circular Economy Performance Indicator	(Huysman et al., 2017)
	Circular Economy Benefit Indicators	(Huysveld et al., 2019)
80	Recyclability Benefit Rate	
81	Recycled Content Benefit Rate	
	End of Life Best Practice Indicators	(Jiménez-Rivero and García-Navarro, 2016)
82	Effectiveness of the audit	
83	Effectiveness of the deconstruction process	
84	Effectiveness of the traceability	
85	GW sent to landfill	
86	Transport of GW emissions comparison	
87	Labour time comparison between techniques	
88	Productivity	
89	Training of the deconstruction team	
90	Follow-up of the waste management	
91	Audit cost	
92	Cost comparison between routes	
93	Waste acceptance criteria	
94	GW rejected	
95	Warehouse space	
96	Output materials of the recycling process	
97	GHG emissions processing and transport	
98	Stakeholders' satisfaction	
99	End-of-Life Index	(Lee et al., 2014)
100	Product-Level Circularity Metric	(Linder et al., 2017)
	Sustainability Performance Indicators	(Mesa et al., 2018)
101	Linear Flow Index for Product Families	
102	Potential Reuse Index	
103	Potential Recycle Index	
104	Reconfiguration Index	
105	Functional Range Index	
106	Functional Variety Index	
	Product Recycling Desirability Index	(Mohamed Sultan et al., 2017)
107	Material security index	
108	Recycling technology readiness level	
109	Simplicity of separating materials	
	Multidimensional Indicator Set	(Nelen et al., 2014)
110	Weight recovery of target material(s)	
111	Recovery of scarce materials	
112	Closure of material cycles	
113	Avoided environmental burdens	
	Assessment of Circular Economy Strategies at the Product Level	(Niero and Kalbar, 2019)
114	Climate Change	
115	Abiotic Resource Depletion	
116	Acidification	
117	Particulate Matter	
118	Water Consumption	
119	Reuse Potential Indicator	(Park and Chertow, 2014)
	Environmental Sustainability of Food Packaging	(Pauer et al., 2019)
121	Appropriateness of packaging size	
122	Resealability	
123	Circ(T)	(Pauliuk et al., 2017)
	Systems Indicators for Circular Economy Dashboard	(Pauliuk, 2018)
124	Total restored products	
125	Total restored	
126	Total recycled	
127	Recovery rates	
128	Lifetime of material in the anthroposphere	
129	Supply chain footprint of regenerative flows	

130	Quantity of material restored and its quality:	
131	Contamination	
132	Tramp element content	
133	Ratio of recirculated economic value from EoL components over total product	
134	Anthropogenic lifetime of material in product	
135	Material stock per service	
136	Service generated by material consumption,	
137	Material input per service	
138	Value-based resource efficiency	(Di Maio et al., 2017)
139	Waste reduction	(Pauliuk, 2018)
140	Reduce, reuse, recycle	
141	Increase recycled	
142	Natural resource conservation (What and how much primary resource does	
143	Life cycle greenhouse gas emissions and changes thereof	
144	Cumulative exergy demand	
145	Water footprint	
146	Land footprint	
147	Material footprint	
148	Combination of water, land, material footprint	
149	Vulnerability to supply restriction and supply risk	
150	Work safety	
151	Transparency	
152	Supplier relations	
153	Costs of reducing environmental damage over product price	
154	Primary production	
155	Ratio of stock growth over primary production	
	Circular Business Model Set of Indicators based on	(Rossi et al., 2020)
156	Reduction of raw material - Manufacturing	
157	Reduction of raw materials - Product	
158	Renewable energy	
159	Renewable raw materials	
160	Recycled materials	
161	Recyclability potential	
162	Reduction of toxic substances	
163	Reuse - Manufacturing process	
164	Reuse - Product	
165	Remanufacturing	
166	Refurbishment	
167	Product longevity	
168	Stakeholder structure and diversity	
169	Cost reduction	
170	Revenue generation	
171	Profitability	
172	Taxation or regulatory milestones	
173	Circular investment	
174	Job creation	
175	Income generated by jobs	
176	Employee participation in the circular mode	
177	Client mindset - Client	
178	Client mindset - Value	
179	Client mindset - Communication	
180	Involvement of stakeholders in decision-making processes	
181	Mindset/cultural change	
182	Improved Water Circularity Index	(Sartal et al., 2020)
183	Circularity of Material Quality	(Steinmann et al.,
184	Ease of Disassembly Metric	(Vanegas et al., 2018)
	Expended Zero Waste Practice Model	(Veleva et al., 2017)
185	GHG emissions avoided	
186	Energy saved	
187	Water saved	
188	Jobs created	
189	Other social impacts	
190	Dollar savings	
191	% and number of customers attracted as result of strategy	
192	Fair market value	
193	RoI from employee zero waste training	
194	Improved company resilience or competitiveness	
195	Long term ROI of upgraded equipment/systems	
196	% of employees aware of company's waste reduction goals	
197	% of employees who participated in training on zero waste/circular economy	
198	% of employees reporting "significant" contribution to waste reduction goals	
199	% and # of employees recognized for their innovative waste	
200	% increase in employee engagement as result of involvement in zero waste	
201	Waste generation intensity	
202	% reduction in key materials in relation to sales	
203	% of materials from renewable stock	
204	Tons and % of sustainaly sourced materials and products	
205	% of suppliers selected using sustainability criteria	
206	% of renewable energy used in manufacturing & operations	
207	Tons of waste diverted through reuse	
208	% non-hazardous waste reused	
209	% of products or equipment reused	
210	Fair market value (FMV) of reused equipment/materials	

211	% and tons of waste recycled	
212	% and tons of waste composted	
213	% and tons of non-hazardous waste converted to energy	
214	% and tons of waste incinerated	
215	% and tons of waste sent to landfill	
216	Material and Energy Circularity Indicators	(Zore et al., 2018)
	Category-based Circularity Index	(Baratsas et al., 2022)
	Overall Circularity Index	
217	Revenues (million $)	
218	Total social investment for environmental sustainability and circular economy	
219	Products sold (weight or volume)	
220	Number of products sold (# of products)	
221	Full time employees (# of people)	
222	Operational building/facilities space	
223	Waste generated - Hazardous (weight)	
224	Waste generated - Non Hazardous (weight)	
225	Diverted waste from disposal (reused, recycled, recovered) (weight)	
226	Water withdrawal (volume)	
227	Fresh water discharge (<= 1,000 mg/L TDS) (volume)	
228	Other water discharge (>= 1,000 mg/L TDS) (volume)	
229	Water recycled or reused (volume)	
230	Non-renewable material used (volume or weight)	
231	Non-renewable packaging material used (volume or weight)	
232	Renewable material used (volume or weight)	
233	Renewable packaging material used (volume or weight)	
234	Recycled input material used (volume or weight)	
235	Recycled packaging material used (volume or weight)	
236	Reusable, compostable or recyclablematerial (%)	
237	Reusable, compostable or recyclable packaging material (%)	
238	Paper consumption (weight)	
239	Single-use plastis consumption (weight)	
240	Total energy generated (joules or multiples)	
241	Total non fossil fuel energy generated (joules or multiples)	
242	Total energy consumed (joules or multiples)	
243	Renewable energy consumed (joules or multiples)	
244	Certified buildings and facilities i.e LEED (%)	
245	Direct GHG emissions (Scope 1) (tCO2e)	
246	Energy indirect GHG emissions (Scope 2) (tCO2e)	
247	Total use of products (Scope 3) (metric tons CO2) equivalent (tCO2e))	
248	Average specific CO2 emissions (gCO2/km)	
249	Emissions neutralized by carbon offset projects (tCO2e)	
250	Emissions of ozone-depleting substances (ODS) (metric tons of CFC-11	
251	Nitrogen oxides (NOx), sulfur oxides (SOx) & other significant air emissions	
252	Environmental fines ($)	
253	Volume or flared hydrocarbon (tCO2e)	
254	Volume or vented hydrocarbon (tCO2e)	
255	Packaging Material to be reclaimed/recovered (# of products or %)	
256	Material to be reclaimed/recovered (%)	
257	Average lifespan of product or Warranty provided (years)	
258	Ecological Rucksack	(Elia et al., 2017)
259	Cumulative Energy Demand	(Huijbregts et al., 2006)
260	Embodied Energy	(Brown and Herendeen, 1996)
261	EMergy Analysis	(Angelakoglou and Gaidajis, 2015)
262	EXergy Analysis	(Rosen and Dincer, 2001)
263	Sustainable Process Index	(Narodoslawsky and Krotscheck, 1995)
264	Dissipation area index	(Herva et al., 2011)
265	Carbon footprint	(Elia et al., 2017)
266	Ecosystem Damage Potential	(Koellner and Scholz, 2008)
	Sustainable Environmental Performance Indicator	(De Benedetto and Jirí, 2009)
267	Energy footprint	
268	Emission footprint	
269	Work environment footprint	
270	Cost	
271	Total Restored Products	(Pauliuk, 2018)
272	Eco-cost value ratio	(Scheepens et al., 2016)
273	Old Scrap Collection Rate	(Graedel et al., 2011)
274	Recycling Input Rate	
275	Recycling process efficiency Rate	
276	Old Scrap Ratio	
277	End of Life Recycling Rate	
278	Number of Times of Use of a Material	(Matsuno et al., 2007)
279	Lifetime of Materials on Anthroposphere	(Pauliuk, 2018)
280	Displacement	(Zink et al., 2016)

281	Recycling rate of all waste	(European Commission, 2018a)
282	End-of-life recycling input rates	
283	Circular material use rate	
284	Imports from non-EU countries	
285	Exports to non-EU countries	
286	Imports from EU countries	
287	Exports to EU countries	
288	Gross investment in tangible goods	
289	Number of persons employed	
290	Value added at factor cost	
291	Intensity use (in terms of cost) of material and other disposables	(Rukundo et al., 2021)
292	Share of packaging material used that are made of biodegradable matter	
293	Renewable rate of light production equipment (cages, feeder and waterers,	
294	Variability (in days) of down time between production cycles	
295	Total direct energy used	
296	Share (in %) of the total energy used which is from renewable sources	
297	Total annual distance (in km) done for inputs supply	
298	Total annual distance (in km) done for products and by-products delivery	
299	Total duration of the production cycle	
300	Percentage of CE procurement	(Rincón-Moreno et al., 2021)
301	Generation of waste per €	
302	Percentage of generation of waste per material consumption	
303	Energy productivity	
304	Percentage of green energy consumption	
305	Water consumption productivity	
306	Percentage of recycling rate of all waste	
307	Percentage of recycling rate of plastic waste	
308	Percentage of recycling rate of paper and paperboard	
309	Percentage of circular material use (CMU) rate	
310	Percentage of CE investment	
311	Percentage of CE jobs	
312	Percentage of CE patents	
313	Eco-efficient Value Ratio	(Scheepens et al.,
314	Material Reutilisation Part	(C2C, 2014)
315	Material Reutilisation Score	
316	End-of-live recycling input rates (EOL-RIR), aluminium	(European Commission, 2017)
317	Private Investments	
318	Persons employed	
319	Consumption footprint	
320	GHG emissions from production activities	
321	Material import dependency	
	Circular Economy Toolbox US	(U.S. Chamber of
322	Amount Recovered	
323	Estimated Cost Savings per Rental	
324	Estimated Impact Offset (Resources, GHGs, Water)	
325	kWh Produced	
326	Payback Time	
327	Percent Materials Composition	
328	Percent Recovered	
329	Percent Recyclable	
330	Progress Toward Goal	
331	Return on investment	
	Circular Impacts Project EU	(European Commission, 2018b)
332	Changes in factor productivity	
333	Changes in trade flows	
334	Amount of investment needed	
335	Changes in employment quantity	
336	Composition of labour demand compared with scarcities on the labour	
337	Externalities in production that may be reduced by the circular opportunity	
338	Welfare effects of the externalities that may be reduced	
339	Does the circular opportunity create skills that provide competitive advantage	
	Evaluation of CE Development in Cities	(Li et al., 2010)
340	Cleaner energy ratio	
341	Repeated use rate of industrial water	
342	New increase industrial solid waste emission for value of industrial output	
	Evaluation Indicator System of Circular Economy	(Zhou et al., 2013)
343	Ratio of resource comprehensive yield	
344	Main resource consumption of unit product (iron ore)	
345	Energy consumption of unit value output	
346	Comprehensive cost of unit product	
347	Added value of unit value output	
348	Ratio of industrial waste recycling	
349	Ratio of interior energy utilization (coal gas, waste heat, etc)	
350	Comprehensive cost loss of unit value output	
351	Comprehensive ratio of rolled steel into production	
352	“three-wastes” discharge of unit product	
353	Disposal cost of unite waste	
354	External environmental damage cost of unite value output	

355	Certification of environmental management system	
	Five Category Index Method	(Li and Su, 2012)
356	Rate of return on common stockholders' equity	
357	Annual growth rate of industrial added value	
358	Water consumption per unit of industrial output	
359	Energy consumption per unit of industrial output	
360	Comprehensive utilization of industrial solid waste	
361	Recycling rate of industrial water	
362	Emission reduction rate of industrial wastewater COD	
363	Emission reduction rate of SO2	
364	Rate cut of industrial solid waste generation	
365	Wastewater emissions per unit industrial output	
366	SO2 emissions per unit of industrial output	
367	Solid waste emissions per unit of industrial output	
368	Net profit / environmental investment	
369	The proportion of technology investment to total industrial output	
370	Capital accumulation rate	
371	Rate of sales growth	
	Indicators for material input	(EEA, 2016)
372	Proportion of material losses in key material cycles	
373	Share of secondary raw materials in material consumption	
374	Share of sustainability-certified materials in material use	
	Indicators for consumption	
375	Environmental footprint of consumption (including materials)	
376	Material footprint per euro spent (EEA indicator SCP013)	
377	Actual average lifetime of selected products	
378	Market share of preparing for reuse and repair services related to sales of	
379	Waste generation (consumption activitie) CSI041/WST004)	
	Indicators for Eco-design for CE in Europe	
380	Durability or lifetime compared with an industry average for a similar product	
381	Time and number of necessary tools for disassembly	
382	Proportion of recycled material in new products	
383	Share of materials where safe recycling options exist	
	Indicators for Economic Circularity in France	(Magnier, 2017)
384	Resource Productivity	
385	Ecolabel Holders	
386	Use of recycled raw materials in production processes	
387	Employment in the Circular Economy	
	Integrative Evaluation on the Development of CE	(Qing et al., 2011)
388	Ratio of Industrial Solid Wastes Utilized	
389	Water Reuse Rate of Industrial Enterprises	
390	Output Value of Products Made from Waste Gas, Waste Water &Solid	
391	Volume of Industrial Wastewater Discharged	
392	Volume of Industrial Solid Wastes Discharged	
393	Volume of Industrial Soot Discharged	
	Indicators for Production for CE in Europe	(EEA, 2016)
394	Input of substances that are classified as hazardous	
395	Waste generation (production activities) CSI041/WST004)	
396	Generation of hazardous waste in production processes	
397	Involvement of companies in circular company networks	
398	Recycling Rates	(Haupt et al., 2017)
399	Disassembly Effort Index	(Das et al., 2010)
	Remanufacturing Product Profiles	(Zwolinski et al., 2006)
400	Percentage of product to remanufacture	
401	Recycled materials revenue	
402	Reuse cycle (years)	
403	First wear-out lfe	
404	Second wear-out life	
405	Global wear-out life	
406	Typology of technology	
407	Technology cycle	
408	Redesign cycle	
409	Reason for redesign	
410	Level of redesign	
411	Product destination	
412	Total number of competition	
413	Image	
414	Percentage of parts to remanufacture of the product	
415	Number of parts	
416	Number of modules	
417	Dimension of the product	
418	Number of active function	
419	Number types of fastener	
420	Total number of fastener	
421	Product architecture	
422	Material´s separability	
423	Number of replaced parts	
424	Percentage of parts reused after cleaning	
425	Percentage of parts reused after repairing	
426	Number of parts reused after reconditioning	
427	Number types of test	
428	Total number of test	
429	Price of the remanufactured product/price of the new product	

430	Price of the buying back/price of the new product	
431	The cost of refurbishment/price of the new product	
432	Energy saved by using remanufactured product/energy for new product	
433	Industry life cycle	
434	Resarch and development	
435	Mass rate of reconditioned parts used in the product	
	End-of-life Indices (Design Methodology)	(Favi et al., 2017)
436	Effective Disassembly Time	(Marconi et al., 2018)
	Set of indicators for raw material, use, and end of life stages	(ETSI, 2018)
437	Proportion, by mass, of recycled material in a product or packaging.	
438	Ratio of cumulated mass of recycled material per part and mass of good	
439	Mass of good Plastics recycling traceability and assessment of conformity	
440	Mass of the good and its re-use percentages.	
441	Average recycled content for metals of secondary metal in the total metal	
442	The average recycled content of steel as annual tonnage of steel scrap	
443	Percentage in mass of the part/good that is potentially reusable	
444	Percentage of the component/product potentially be recycled, reused or both	
445	Sum of recyclable mass of each part, divided by the mass of the good.	
446	Percentage in mass of the part/good that is potentially recyclable.	
447	The share of materials that are expected to enter the recycling stream.	
448	Percentage of the component/product potentially able to be recovered.	
449	Sum of recoverable mass of each part, divided by the mass of the good	
450	Percentage of the part/good that is energy-recoverable by incineration	
451	Service Output per material input	
452	Circularity product indicator	(Angioletti et al., 2017)
453	Environmental break-even point	(Barletta et al., 2018)
454	Circularity Indicator	(Cobo et al., 2018)
	Remanufacturing Sustainability Indicators	(Fatimah and Aman, 2018)
455	Job creation	
456	Employment remuneration	
457	Salary improvement	
458	Tax revenue	
459	Production cost	
460	Net profit	
461	Material efficiency cost	
462	Energy efficiency cost	
463	Productivity	
464	Technology investment	
465	Market development	
466	Brand image recognition	
467	Enterprise competiveness	
468	Waste treatment cost	
469	Water treatment cost	
470	Pollution treatment cost	
471	Health & safety	
472	Work injury rate	
473	Labor productivity	
474	Remanufacturing training	
475	Education level	
476	Skill level	
477	Gender equity	
478	Customer satisfaction	
479	Community complaints	
480	Public acceptability	
481	Used material acquisition	
482	Material efficiency	
483	Solid waste intensity	
484	Water waste intensity	
485	Residual intensity	
486	GHG emission intensity	
487	Hazardous gas intensity	
488	Dusk	
489	Hazardous chemical	
490	Acidification substance	
491	Water intensity	
492	Landfilling	
493	Biodiversity impacts	
494	Water treatment	
495	Waste treatment	
496	Pollution treatment	
497	Product Waste Footprint	(Laurenti et al., 2018)
498	E-factor	(Sheldon, 2018)
499	Process mass intensity	
500	Reaction mass efficiency	
501	Circular-process energy intensity	(Lokesh et al., 2020)
502	Circular-process feedstock intensity	
503	Circular-process waste factor	
504	Collection rate	(Haupt et al., 2017)
505	Energy intensity	(Lokesh et al., 2020)
506	Feedstock intensity	
507	Landfill to recycle ratio	(Marvuglia et al., 2018)
508	Process material circularity	(Lokesh et al., 2020)

Product Circularity Indicator	(Bracquené et al.,
Product renewability	(Lokesh et al., 2020)
Recycle benefit ratio	(Marvuglia et al., 2018)
Recycle yield ratio	
Relative net loss	(Ljunggren Söderman and André, 2019)
Waste factor	(Lokesh et al., 2020)
Interim outputs	(Jacobi et al., 2018)
Design Solutions to Maximise Future Circularity	(Abadi et al., 2022)
Use of Low-impact Innovative Materials	
Embed Recycled Materials in Design	
Reduced Material Inputs	
Durability of Building, Asset or Project	
Reduced Environmental Impact of Operation	
New Business Models and Strategies	
Planning, Collaboration and CE Data Management	
Education, Training and Stakeholder CE Awareness	
Water scarcity index	(Del Borghi et al., 2018)
Use of primary energy	(Abejón et al., 2020)
Use of primary renewable energy	
Use of primary non-renewable energy	
Waste sent to landfill	(Pagotto and Halog, 2016)
Production costs	
Total revenue	
Child labour	(Benoît Norris et al., 2020)
Forced or compulsory labour	
Technological efficiency	(Dewulf and Van Langenhove, 2005)
Renewability of resources	
Toxicity of emissions	
Input of used materials	
Recoverability of products at the end of their use	
Granting of funds to finance the projects of eco-innovation investment self-powered by the sum of financial and economic benefits of the system	(Albertario, 2016)
Emergy based performance measurement	(Alkhuzaim et al., 2021)
Environmental loading ratio	
Environmental yield ratio	
Emergy sustainability index	
Emergy investment ratio	
Percent renewable	
Total energy costs	(Almagtome et al., 2020)
Production energy costs	
Saving in total energy costs	
Saving in production energy costs	
Energy investments	
Renewable energy investments	
Environmental taxes	(Anishchenko et al., 2019)
Economic impact	(Aranda-Usón et al., 2019)
Financial resources	
Return on assets	(Bartolacci et al., 2018)
Resource efficiency: logistics and handling costs	(Bockholt et al., 2020)
Resource effectiveness: recovered value	
Economic performance	(Cong et al., 2017)
Value recovery	Cong et al. (2017)
Firm growth variable	(Demirel and Danisman, 2019)
Types of CE innovations	
Replanning of water	
Renewable energy	
Replanning energy	
Minimizing waste	
Redesigning products and services	
Total investments into CE	
External finance	
Bank loans	
Green loans	
EU funds	
Government grants	
Crowdfunding	
Venture Capital	
Green banks	
Peer-to-peer investments	
Business angels	
Capital market	
Research and development expenditures	

Firm size	
Firm age	
Circular economy investments and finance	(Dewick et al., 2020)
Fixed capital investment	(Dheskali et al., 2020)
Net present value	(Dobrota et al., 2020)
Internal rate of financial return	
Economic performance indicator	(Fraccascia et al.,
Environmental performance indicator	
Economic Rate of Return	(Gigli et al., 2019)
Benefit/Cost ratio	
Payback	(Gimeno et al., 2020)
Access to financing	
Installation costs	
Individual expected monetary value	(Hald et al., 2020)
Return on sales	(Ionascu and Ionascu, 2018)
q de Tobin	
Market value	
Market to book	
Costs in the production flow, considering the costs of external environmental damage	(Li et al., 2019)
Financial performance	(Li et al., 2020)
Ratio of recirculated economic value from EoL	(Pauliuk, 2018)
Profitability Index	(Portillo-Tarragona et al., 2018)
Internal rate of return of the investment project	
Level of investment	
% investment in research and development	
Return on equity	(Scarpellini et al., 2018)
Information related to eco-innovation level	
% of components replaced by innovative ones to comply with regulations.	
% of the total amount of the company's R&D investments is invested in environmental R&D, eco-design or similar.	
Financial resource quality	
% of the company's total revenues invested in environmental R&D	
% of the company's total revenues invested in innovative	
% of the investments in environmental R&D, eco-design or similar that are financed with the company's own funds.	
Public financial resources	
% of environmental R&D investments, eco-design or similar that are financed through public funds	
Financial Resources Availability	
Level to which the availability of the company's financial resources	
Technological and sectorial capabilities	
Range of possibilities for eco- innovation offered by the company's products	
Level to which eco-innovations' reduction of environmental impact, even if	
Environmental management capabilities	
Level of the managers' personal linkage with the eco-innovation activities' implementation.	
Environmental and certification standards (ISO 14001, EMAS, ISO 50001, ISO 14006)	
Firm size	
Total Assets	
Total turnover	
Total employees	
Total cost of waste	(Titova and Terentyeva, 2020)
Differentiation of waste in accordance with its potential value	
Profit from waste use	
Cost of primary resource replacement	
Price ratio between primary and secondary resources	
Minimization of production costs	
Volume of non-renewable resource consumption	
Savings from the use of renewable resources	
Product replacement cost	
Level and nature of investments	(Zamfir et al., 2017)
Whether the companies have undertaken circular economy-related activities in the last three year	
Evolution of the company's turnover since the beginning of the 2015	
Waste Recovery	(Aranda-Usón et al., 2019)
% of recycling waste within the company itself (treated to be recycled)	
% of waste recovery and reuse within the company	
Dematerialization and Recycled Materials	
% of resources replaced by other fully recycled materials to manufacture products or provide services	
% of products' design or services modified to reduce resource intensity	
Circular Eco-Design	
% of products' design or services modified to extend life	

632	% of products' design or services modified to increase recyclability	
	Resource Saving and Efficiency	
633	% of equipment or facilities replaced and/or improved to reduce energy	
634	% of processes replaced or improved to reduce energy consumption	
635	Level to which the company implements the ISO 14001 standards	(Scarpellini et al., 2020)
636	Level to which the company implements theEMAS standards	
637	Level to which the company implements the ISO 50000 standards	
638	Level to which the company implements the ISO 14006 standards	
639	Level to which the company posts entries related to environmental activities	
640	Number of employees in the environmental management department	
641	Level to which the company applies and disseminates its good corporate governance rules	
642	Level to which the company adheres to the CSR model compared to other companies in the sector	
643	Level to which the company voluntarily reports on its activity related to sustainability in open access platforms (web, reports and press)	
644	Level to which the company provide specific sustainability reports of environmental impacts addressed to stakeholders	
645	Level to which the company has a specific policy on reporting	
646	Degree to which the company must reduce its environmental impact to comply with regulations in the short term	
647	Level of social pressure on the company to reduce its environmental impact	
648	Material stock	(Cheng et al., 2019)
649	Material intensity	
650	Recycling content	(Thomas and Birat, 2013)
651	Impacts of production from material virgin	
652	Impacts of production from material secondary	
653	Impacts of virgin production from substituted material	
654	Impacts of secondary production from substituted material	
655	Impacts of the end of life treatment excluding recycling	
656	Material Durability Indicator	(Mesa et al., 2020)
657	Waste recycling	(European Environment Agency, 2022)
658	Trade in recyclable raw materials	(European Commission, 2020)
659	Circular Material Rate	(European Commission, 2018c)
660	Local Circularity Rate	(de Souza et al., 2023)
	Overall Circularity Effectiveness Index	(Baumer-Cardoso et al., 2023)
661	Input Material 1	
662	Input Water 1	
663	Input Energy 1	
664	Input Material 2	
665	Input Water 2	
666	Input Energy 2	
667	Output Emission	
668	Output Material	
669	Output Water	
670	Output Equipment	
671	Output Product	
672	Input Training	
673	Input DIE	
674	Output Accidents	
675	Output Turnover	
676	In-use occupation	(Moraga et al., 2020)
677	By-products and/ or secondary material resources	(Amicarelli and Bux, 2023)
678	Renewable or recycled resources used for packaging	
679	In bound virgin material resources, out bound residues	
680	Self-produced electricity from renewable sources and/or recovery processes	
681	Electricity consumed	
682	Water from recovery and/ or recycling	
683	Water needs	
684	Municipal and/ or special waste produced	
685	Municipal and/ or special waste sent to landfills	
686	Municipal and/ or special waste collected separately	
687	Waste treated at local valorization plants	
688	Waste treated at not local valorization plants	
689	Employees adhering to sustainable mobility initiatives	
690	Energy performance index of the buildings	
691	Circular economy strategies in the organization	
692	Acircularity	(Halada et al., 2022)
693	Resource Efficiency Accout	
694	Generated production and consumption waste by type of economic activity	(Elokhova et al., 2023)
695	Discharge of polluted wastewater into surface water bodies by type	
696	Emissions into the atmosphere of pollutants from stationary sources	
697	Electricity consumption by type of economic activity "Mining"	

698	Water intake from natural water bodies by type of economic activity "Mining"	
699	The ratio of generated production and consumption waste	
700	The ration of the discharge of polluted wastewater into surface water bodies	
701	The ration of air emissions of pollutants from stationary sources	
702	The ration of electricity consumption	
703	The ration of water intake from natural water bodies	
704	Electricity consumption costs	
705	The cost of collecting and transporting water	
706	Electricity consumption costs per unit of economic result	
707	Water collection and transportation costs per unit of economic result	
708	Inbound raw materials and secondary res. From local suppliers / total inbound raw material and secondary resources	(Amicarelli et al., 2023)
709	Inbound material res. Equipped with tracking systems / total inbound material res. Equipped with tracking systems	
710	Inbound by products and (or) secondary res. / total inbound material res.	
711	Renewable of recycled res. For packaging / total packaging used	
712	1 - Total restricted or authorised substances / total inbound material res.	
713	(Inbound resources - residues produced) / total residues produced	
714	Self produced electricity from ren. Res. Or recovery / total electricity	
715	Purchased electricity from ren. Res. / total electricity purchased	
716	Inbound water from reuse and recycling / total water need	
717	1 - Urban and (or) special waste sent to landfills / total urban and (or) special waste generated	
718	Municipal and (or) special waste collected separately / total urban and (or) special waste generated	
719	Has the organization carried out the assessment of its carbon footprint	
720	Waste treated at local valorization plants / total waste treated at valorisation plants (local or not)	
721	Actual load capacity used by vehicles (round trip) / total capacity of the vehicles	
722	Number of employees adhering to sustainable mobility / total employees	
723	Outbound resources with a tracking system / total outbound resources	
724	Products and services sold with supporting information for repair / total sold products	
725	Quantity of products generated / quantity of resources employed	
726	Value of products and services from local suppliers / total value of products and services	
727	Has the organization made investments in the circular design of ist products and/or services in years n and/or n-1 and/or n-2?	
728	Has the organization made investments in circular desing of its processes in years n and/or n-1 and/or n-2?	
729	Has the organization made investments in circular design of its assets in year n and /or n-1 and/or n-2?	
730	Investment in R&D linkes to the circular economy / total investment in R&D	
731	Has the organization already carried out staff training on the circular economy in the current year and in the two years before?	
732	Which is the average energy performance index of buildings for civil use of the organisation?	
733	Has the organization developed and implemented a circular economy strategy?	
734	Does the organization carry out external communication of ist sustainability and circularity performance	
735	Has the organization planned to carry out internal staff information and training activities on the circualr economy?	
736	Has the organization carried out external training and information plans on the circular economy aimed at stakeholders?	
737	Does the organization have an energy efficiency plan?	
738	Does the organization adopt an Enviornmental Management system?	
739	Green Water Footprint	(Poponi et al., 2022)
740	Blue Water Footprint	
741	Water use	
742	Nonrenewable energy demand	(Del Borghi et al., 2018)
743	Renewable energy share in the total final energy consumption	(UNSD, 2020)
744	Waste sent to landfill	(Pagotto and Halog, 2016)
745	PackagetoProduct	(Šerešová and Kočí, 2020)
746	Total capital investment	(Sgarbossa and Russo, 2017)
747	Cost of manufacture	(Ioannidou et al., 2020)
748	Minimum selling price	
749	Gross profit	
750	Social inclusion	(Benoît Norris et al.,
751	Forced or compulsory labor	
752	Adapted MCI for multi-layer plastic packaging	(Vadoudi et al., 2022)

Material Efficiency Metric	(Brändström and Eriksson, 2022)
Circularity performance	(Yang et al., 2023)
Material used in the production process	(Lanaras-Mamounis et al., 2022)
Energy used in the production process	
Renewable energy used in the production process	
Energy certification of production facilities	
Product's energy class	
Waste production	
Packaging materials used in the production process	
Energy consumption due to the transportation of products	
Work-related injuries	
Health and safety risks	
Product durability	
Product maintenance	
Dismantling of products	
Reused materials utilized in the production process	
Downcycled materials used in the production process	
Reused water utilized in the production process	
Recycled materials used in the production process	
Recyclable materials used in the production process	
Recycled packaging materials used in the production process	
Recyclable packaging materials used in the production process	
Product compatibility	
Product upgrade	
Product refurbish	
Circular Material Productivity	(“CTI Tool,” 2020)
On-Site Water Circulation	
Critical Inflow	
Water Circularity	
Circularity Index	
Circular Outflow	
Circular Inflow	
Energy recoverability benefit rate	(Vercalsteren et al., 2017)
Waste generation	
Product environmental footprint	
Amount of Product/Material collected	(U.S.Ch. of Commerce Foundation, 2017)
Product/material diverted from Landfill	
Amount of Money Saved by leasing or renting vs. buying a product	
Emissions that aren´t made	
Certified Content (%)	
Compostable (%)	
Containing Remanufactured Components (%)	
Percent Reused	
Percent Recycled/Reclaimed	
Percent Closed Loop/Upcycling/Downcyling	
Percent Recyclable	

1. References of the indicator pool

Abadi, M., Moore, D.R., Sammuneh, M.A., 2022. A framework of indicators to measure project circularity in construction circular economy. Proceedings of the Institution of Civil Engineers - Management, Procurement and Law 175, 54–66. https://doi.org/10.1680/jmapl.21.00020

Abejón, R., Bala, A., Vázquez-Rowe, I., Aldaco, R., Fullana-i-Palmer, P., 2020. When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. Resour Conserv Recycl 155. https://doi.org/10.1016/j.resconrec.2019.104666

Adibi, N., Lafhaj, Z., Yehya, M., Payet, J., 2017. Global Resource Indicator for life cycle impact assessment: Applied in wind turbine case study. Journal of Cleaner Production 165, 1517–1528. https://doi.org/10.1016/j.jclepro.2017.07.226

Alamerew, Y.A., Brissaud, D., 2019. Circular economy assessment tool for end of life product recovery strategies. Jnl Remanufactur 9, 169–185. https://doi.org/10.1007/s13243-018-0064-8

Alamerew, Y.A., Kambanou, M.L., Sakao, T., Brissaud, D., 2020. A Multi-Criteria Evaluation Method of Product-Level Circularity Strategies. Sustainability 12, 5129. https://doi.org/10.3390/su12125129

Albertario, P., 2016. System of self-financing strategy for the policies aimed at the eco-innovation in the productive sectors. Procedia Environmental Science, Engineering and Management 3, 1–6.

Alkhuzaim, L., Zhu, Q., Sarkis, J., 2021. Evaluating Emergy Analysis at the Nexus of Circular Economy and Sustainable Supply Chain Management. Sustain. Prod. Consum. 25, 413–424. https://doi.org/10.1016/j.spc.2020.11.022

Almagtome, A.H., Al-Yasiri, A.J., Ali, R.S., Kadhim, H.L., Bekheet, H.N., 2020. Circular Economy Initiatives through Energy Accounting and Sustainable Energy Performance under Integrated Reporting Framework. International Journal of Mathematical, Engineering and Management Sciences 5, 1032–1045. https://doi.org/10.33889/IJMEMS.2020.5.6.079

Amicarelli, V., Bux, C., 2023. Users' Perception of the Circular Economy Monitoring Indicators as Proposed by the UNI/TS 11820:2022: Evidence from an Exploratory Survey. Environments 10, 65. https://doi.org/10.3390/environments10040065

Amicarelli, V., Primiceri, M., Misino, E., Bux, C., 2023. An application of the UNI/TS 11820:2022 on the measurement of circularity in an electrical equipment manufacturing organization in Italy. J. Clean. Prod. 420, 138439. https://doi.org/10.1016/j.jclepro.2023.138439

Angelakoglou, K., Gaidajis, G., 2015. A review of methods contributing to the assessment of the environmental sustainability of industrial systems. J. Clean. Prod. 108, 725–747. https://doi.org/10.1016/j.jclepro.2015.06.094

Angioletti, C.M., Despeisse, M., Rocca, R., 2017. Product Circularity Assessment Methodology, in: Lödding, H., Riedel, R., Thoben, K.-D., Von Cieminski, G., Kiritsis, D. (Eds.), Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing, IFIP Advances in Information and Communication Technology. Springer International Publishing, Cham, pp. 411–418. https://doi.org/10.1007/978-3-319-66926-7_47

Anishchenko, V., Marhasova, V., Fedorenko, A., Puzyrov, M., Ivankov, O., 2019. ENSURING ENVIRONMENTAL SAFETY VIA WASTE MANAGEMENT. Journal of Security & Sustainability Issues 8.

Aranda-Usón, A., Portillo-Tarragona, P., Marín-Vinuesa, L.M., Scarpellini, S., 2019. Financial Resources for the Circular Economy: A Perspective from Businesses. Sustainability 11, 888. https://doi.org/10.3390/su11030888

Ardente, F., Mathieux, F., 2014. Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product. Journal of Cleaner Production 83, 126–141. https://doi.org/10.1016/j.jclepro.2014.07.058

Azevedo, S., Godina, R., Matias, J., 2017. Proposal of a Sustainable Circular Index for Manufacturing Companies. Resources 6, 63. https://doi.org/10.3390/resources6040063

Baratsas, S.G., Pistikopoulos, E.N., Avraamidou, S., 2022. A quantitative and holistic circular economy assessment framework at the micro level. Computers & Chemical Engineering 160, 107697. https://doi.org/10.1016/j.compchemeng.2022.107697

Barletta, I., Despeisse, M., Johansson, B., 2018. The Proposal of an Environmental Break-Even Point as Assessment Method of Product-Service Systems for Circular Economy. Procedia CIRP 72, 720–725. https://doi.org/10.1016/j.procir.2018.03.257

Bartolacci, F., Paolini, A., Quaranta, A.G., Soverchia, M., 2018. The relationship between good environmental practices and financial performance: Evidence from Italian waste management companies. Sustainable Production and Consumption 14, 129–135. https://doi.org/10.1016/j.spc.2018.02.002

Baumer-Cardoso, M.I., de Souza Campos, L.M., Pigosso, D.C.A., Ashton, W., 2023. Measuring the adoption of circular economy at the company level: usefulness and applicability of the OCE index. Journal of Industrial and Production Engineering 40, 572–588. https://doi.org/10.1080/21681015.2023.2244496

Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G., 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (Guidelines). United Nations Environment Programme (UNEP).

Bockholt, M.T., Kristensen, J.H., Colli, M., Meulengracht Jensen, P., Vejrum Waehrens, B., 2020. Exploring factors affecting the financial performance of end-of-life take-back program in a discrete manufacturing context. J. Clean. Prod. 258, 120916. https://doi.org/10.1016/j.jclepro.2020.120916

Bracquené, E., Dewulf, W., Duflou, J.R., 2020. Measuring the performance of more circular complex product supply chains. Resour Conserv Recycl 154, 104608. https://doi.org/10.1016/j.resconrec.2019.104608

Brändström, J., Eriksson, O., 2022. How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models. Journal of Cleaner Production 342, 130973. https://doi.org/10.1016/j.jclepro.2022.130973

Braun, A.T., Kleine-Moellhoff, P., Reichenberger, V., Seiter, S., 2018. Case Study Analysing Potentials to Improve Material Efficiency in Manufacturing Supply Chains, Considering Circular Economy Aspects. Sustainability 10, 880. https://doi.org/10.3390/su10030880

Brown, M.T., Herendeen, R.A., 1996. Embodied energy analysis and EMERGY analysis: a comparative view. Ecol Econ 19, 219–235.

C2C, 2014. Pilot study - Impacts of the cradle to cradle certified products program (Technical report). Cradle to Cradle products Innovation Institute.

Cheng, K.-L., Hsu, S.-C., Hung, C.C.W., Chen, P.-C., Ma, H., 2019. A hybrid material flow analysis for quantifying multilevel anthropogenic resources. J. Ind. Ecol. 23, 1456–1469. https://doi.org/10.1111/jiec.12940

Cobo, S., Dominguez-Ramos, A., Irabien, A., 2018. Trade-Offs between Nutrient Circularity and Environmental Impacts in the Management of Organic Waste. Environ. Sci. Technol. 52, 10923–10933. https://doi.org/10.1021/acs.est.8b01590

Cong, L., Zhao, F., Sutherland, J.W., 2017. Value recovery from end-of-use products facilitated by automated dismantling planning. Clean Technologies and Environmental Policy 19, 1867–1882.

CTI Tool [WWW Document], 2020. URL https://ctitool.com/ (accessed 12.12.24).

Cullen, J.M., 2017. Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? J. Ind. Ecol. 21. https://doi.org/10.1111/jiec.12599

Das, S.K., Yedlarajiah, P., Narendra, R., 2010. An approach for estimating the end-of-life product disassembly effort and cost. Int. J. Prod. Res. 38, 657–673. https://doi.org/10.1080/002075400189356

De Benedetto, L., Jirí, K., 2009. The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process. J. Clean. Prod. 17, 900–906. https://doi.org/10.1016/j.jclepro.2009.02.012

de Souza, V.M., Fröhling, M., Pigosso, D.C.A., 2023. A Multi-level Resource Circularity Index based in the European Union’s Circular Economy Monitoring Framework. Waste and Biomass Valorization. https://doi.org/10.1007/s12649-023-02193-6

Del Borghi, A., Strazza, C., Magrassi, F., Taramasso, A.C., Gallo, M., 2018. Life Cycle Assessment for eco-design of product–package systems in the food industry—The case of legumes. Sustain. Prod. Consum. 13, 24–36. https://doi.org/10.1016/j.spc.2017.11.001

Demirel, P., Danisman, G.O., 2019. Eco-innovation and firm growth in the circular economy: Evidence from European small- and medium-sized enterprises. Business Strategy and the Environment 28, 1608–1618. https://doi.org/10.1002/bse.2336

Dewick, P., Bengtsson, M., Cohen, M.J., Sarkis, J., Schröder, P., 2020. Circular economy finance: Clear winner or risky proposition? Journal of industrial Ecology 24, 1192–1200.

Dewulf, J., Van Langenhove, H., 2005. Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment. Resour Conserv Recycl 43, 419–432. https://doi.org/10.1016/j.resconrec.2004.09.006

Dheskali, E., Koutinas, A.A., Kookos, I.K., 2020. A simple and efficient model for calculating fixed capital investment and utilities consumption of large-scale biotransformation processes. Biochemical Engineering Journal 154, 107462.

Di Maio, F., Rem, P.C., 2015. A Robust Indicator for Promoting Circular Economy through Recycling. J. Environ. Prot. 6, 1095–1104. https://doi.org/10.4236/jep.2015.610096

Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: A market value approach. Resour Conserv Recycl 122, 163–171. https://doi.org/10.1016/j.resconrec.2017.02.009

Dobrota, D., Dobrota, G., Dobrescu, T., 2020. Improvement of waste tyre recycling technology based on a new tyre markings. J. Clean. Prod. 260, 121141. https://doi.org/10.1016/j.jclepro.2020.121141

EEA, 2016. Circular economy in Europe - Developing the knowledge base (EEA report No. 2). European Environment Agency, Luxembourg.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: A critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

Elokhova, I., Vyatkin, K., Ilyushin, P., Krutova, A., Pepelyaeva, A., Sliusar, N., 2023. Evaluating the Eco-Intensity Dynamics of the Mining Industry in Russia: Towards a Circular Economy. Recycling 8, 31. https://doi.org/10.3390/recycling8020031

ETSI, 2018. Environmental Engineering (EE); Circular Economy (CE) in Information and Communication Technology (ICT); Definition of approaches, concepts and metrics (Technical Report). ETSI.

European Commission, 2020. Trade in recyclable raw materials.

European Commission, 2018a. Measuring progress towards circular economy in the European Union – Key indicators for a monitoring framework (Staff Working Document No. 17). European Commission, Strasbourg.

European Commission, 2018b. Circular impacts - Methodologies for Measuring the Macroeconomic and Societal Impacts of the Circular Economy. European Commission.

European Commission, 2018c. Circular material use rate: Calculation method.

European Commission, 2017. Circular economy - Monitoring framework.

European Environment Agency, 2022. Waste recycling in Europe [WWW Document]. European Environment Agency. URL https://www.eea.europa.eu/ims/waste-recycling-in-europe (accessed 10.4.23).

Fatimah, Y.A., Aman, M., 2018. Remanufacturing sustainability indicators: An Indonesian small and medium enterprise case study, in: 1st International Conference on Engineering and Applied Technology (ICEAT), Materials Science and Engineering. Presented at the IOP Conference, ÎOP Publishing Ltd, Mataram, Indonesia.

Favi, C., Germani, M., Luzi, A., Mandolini, M., Marconi, M., 2017. A design for EoL approach and metrics to favour closed-loop scenarios for products. Int. J. Sustain. Eng. 10. https://doi.org/10.1080/19397038.2016.1270369

Figge, F., Thorpe, A.S., Givry, P., Canning, L., Franklin-Johnson, E., 2018. Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. Ecological Economics 150, 297–306. https://doi.org/10.1016/j.ecolecon.2018.04.030

Fogarassy, C., Horvath, B., Kovacs, A., Szoke, L., Takacs-Gyorgy, K., 2017. A Circular Evaluation Tool for Sustainable Event Management – An Olympic Case Study. Acta Polytechnica Hungarica 14, 161–177.

Fraccascia, L., Yazan, D.M., Albino, V., Zijm, H., 2020. The role of redundancy in industrial symbiotic business development: A theoretical framework explored by agent-based simulation. International Journal of Production Economics 221, 107471. https://doi.org/10.1016/j.ijpe.2019.08.006

Franklin-Johnson, E., Figge, F., Canning, L., 2016. Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023

Gigli, S., Landi, D., Germani, M., 2019. Cost-benefit analysis of a circular economy project: a study on a recycling system for end-of-life tyres. J. Clean. Prod. 299, 680–694. https://doi.org/10.1016/j.jclepro.2019.03.223

Gimeno, J.Á., Llera-Sastresa, E., Scarpellini, S., 2020. A Heuristic Approach to the Decision-Making Process of Energy Prosumers in a Circular Economy. Appl. Sci. 10, 6869. https://doi.org/10.3390/app10196869

Goddin, J., Marshall, K., 2015. Circularity Indicators: An Approach to Measuring Circularity (Methodology). Ellen MacArthur Foundation.

Golinska, P., Kosacka, M., Mierzwiak, R., Werner-Lewandowska, K., 2015. Grey Decision Making as a tool for the classification of the sustainability level of remanufacturing companies. J. Clean. Prod. 105, 28–40. https://doi.org/10.1016/j.jclepro.2014.11.040

Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What Do We Know About Metal Recycling Rates? J. Ind. Ecol. 15, 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Halada, K., Tahara, K., Matsumoto, M., 2022. New Indicators ‘Acircularity’ and ‘Resource Efficiency Account’ to Evaluate the Efforts of Eco-Design in Circular Economy. Int. J. Autom. Technol. 16, 684–695. https://doi.org/10.20965/ijat.2022.p0684

Hald, K.S., Wiik, S., Larssen, A., 2020. Sustainable procurement initiatives and their risk-related costs: a framework and a case study application. Meas. Bus. Excell. 25, 230–243. https://doi.org/10.1108/MBE-04-2020-0052

Haupt, M., Vadenbo, C., Hellweg, S., 2017. Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System. J. Ind. Ecol. 21, 615–627. https://doi.org/10.1111/jiec.12506

Herva, M., Franco, A., Carrasco, E.F., Roca, E., 2011. Review of corporate environmental indicators. J. Clean. Prod. 19, 1687–1699. https://doi.org/10.1016/j.jclepro.2011.05.019

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, A.J., van de Meent, D., Ragas, A.M.J., Reijnders, L., Struijs, J., 2006. Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? Environ. Sci. Technol. 40, 641–648. https://doi.org/10.1021/es051689g

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., De Meester, S., 2017. Performance indicators for a circular economy: A case study on post-industrial plastic waste. Resour Conserv Recycl 120, 46–54. https://doi.org/10.1016/j.resconrec.2017.01.013

Huysveld, S., Hubo, S., Ragaert, K., Dewulf, J., 2019. Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. J. Clean. Prod. 211, 1–13. https://doi.org/10.1016/j.jclepro.2018.11.110

Ioannidou, S.M., Pateraki, C., Ladakis, D., Papapostolou, H., Tsakona, M., Vlysidis, A., Kookos, I.K., Koutinas, A., 2020. Sustainable production of bio-based chemicals and polymers via integrated biomass refining and bioprocessing in a circular bioeconomy context. Bioresource Technology 307, 123093. https://doi.org/10.1016/j.biortech.2020.123093

Ionascu, I., Ionascu, M., 2018. Business Models for Circular Economy and Sustainable Development: The Case of Lease Transactions. Amfiteatru Economic 20, 336–372. https://doi.org/10.24818/EA/2018/48/356

Jacobi, N., Haas, W., Wiedenhofer, D., Mayer, A., 2018. Providing an economy-wide monitoring framework for the circular economy in Austria: Status quo and challenges. Resour Conserv Recycl 137, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022

Jiménez-Rivero, A., García-Navarro, J., 2016. Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum. Waste Biomass Valorization 7, 913–927. https://doi.org/10.1007/s12649-016-9561-x

Koellner, T., Scholz, R.W., 2008. Assessment of land use impacts on the natural environment. Int J Life Cycle Assess 13, 32–48. https://doi.org/10.1065/lca2006.12.292.2

Lanaras-Mamounis, G., Tsalis, T.A., Anagnostopoulou, K., Vatalis, K.I., Nikolaou, I.E., 2022. The development of an index for assessing the circularity level of eco-labels. Sustainable Production and Consumption 33, 586–596. https://doi.org/10.1016/j.spc.2022.07.019

Laurenti, R., Martin, M., Stenmarck, A., 2018. Developing Adequate Communication of Waste Footprints of Products for a Circular Economy—A Stakeholder Consultation. Resources 7, 78. https://doi.org/10.3390/resources7040078

Lee, H.M., Lu, W.F., Song, S., 2014. A framework for assessing product End-Of-Life performance: reviewing the state of the art and proposing an innovative approach using an End-of-Life Index. J. Clean. Prod. 66, 355–371. https://doi.org/10.1016/j.jclepro.2013.11.001

Li, H., Bao, W., Xiu, C., Zhang, Y., Xu, H., 2010. Energy conservation and circular economy in China's process industries. Energy 35, 4273–4281. https://doi.org/10.1016/j.energy.2009.04.021

Li, L., Msaad, H., Sun, H., Tan, M.X., Lu, Y., Lau, A.K.W., 2020. Green Innovation and Business Sustainability: New Evidence from Energy Intensive Industry in China. Int. J. Environ. Res. Public Health 17, 7826. https://doi.org/10.3390/ijerph17217826

Li, R.H., Su, C.H., 2012. Evaluation of the circular economy development level of Chinese chemical enterprises. Procedia Environ. Sci. 13, 1595–1601. https://doi.org/10.1016/j.proenv.2012.01.151

Li, Z., Zeng, H., Xiao, X., Cao, J., Yang, C., Zhang, K., 2019. Resource value flow analysis of paper-making enterprises: A Chinese case study. J. Clean. Prod. 213, 588–587. https://doi.org/10.1016/j.jclepro.2018.12.158

Linder, M., Sarasini, S., van Loon, P., 2017. A Metric for Quantifying Product-Level Circularity. J. Ind. Ecol. 21, 545–558. https://doi.org/10.1111/jiec.12552

Ljunggren Söderman, M., André, H., 2019. Effects of circular measures on scarce metals in complex products – Case studies of electrical and electronic equipment. Resour Conserv Recycl 151, 104464.

Lokesh, K., Matharu, A.S., Kookos, I.K., Ladakis, D., Koutinas, A., Morone, P., Clark, J., 2020. Hybridised sustainability metrics for use in life cycle assessment of bio-based products: resource efficiency and circularity. Green Chem. 22, 803–813. https://doi.org/10.1039/C9GC02992C

Magnier, C., 2017. 10 Key Indicators for Monitoring the Circular Economy.

Marconi, M., Germani, M., Mandolini, M., Favi, C., 2018. Applying data mining technique to disassembly sequence planning: a method to assess effective disassembly time of industrial products. Int. J. Prod. Res. 57, 599–623. https://doi.org/10.1080/00207543.2018.1472404

Marvuglia, A., Santagata, R., Rugani, B., Benetto, E., Ulgiati, S., 2018. Emergy-based indicators to measure circularity: promises and problems. Energy Policy Journal 21, 179–196. https://doi.org/10.24425/124510

Matsuno, Y., Daigo, I., Adachi, Y., 2007. Application of Markov Chain Model to Calculate the Average Number of Times of Use of a Material in Society. An Allocation Methodology for Open-Loop Recycling. Part 2: Case Study for Steel (6 pp). Int J Life Cycle Assess 12, 34–39.

Mesa, J., Esparragoza, I., Maury, H., 2018. Developing a set of sustainability indicators for product families based on the circular economy model. J. Clean. Prod. 196, 1429–1442. https://doi.org/10.1016/j.jclepro.2018.06.131

Mesa, J., González-Quiroga, A., Maury, H., 2020. Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective. Resour Conserv Recycl 160, 104887. https://doi.org/10.1016/j.resconrec.2020.104887

Mohamed Sultan, A.A., Lou, E., Tarisai Mativenga, P., 2017. What should be recycled: An integrated model for product recycling desirability. J. Clean. Prod. 154, 51–60. https://doi.org/10.1016/j.jclepro.2017.03.201

Moraga, G., Huysveld, S., de Meester, S., Dewulf, J., 2020. Towards a circularity indicator to assess products' materials and lifetime: In-use occupation. Procedia CIRP 90, 10–13. https://doi.org/10.1016/j.procir.2020.01.085

Narodoslawsky, M., Krotscheck, C., 1995. The sustainable process index (SPI): evaluating processes according to environmental compatibility. J. Hazard. Mater. 41, 383–397. https://doi.org/10.1016/0304-3894(94)00114-V

Nelen, D., Manshoven, S., Peters, J.R., Vanegas, P., D'Haese, N., Vrancken, K., 2014. A multidimensional indicator set to assess the benefits of WEEE material recycling. J. Clean. Prod. 83, 305–316. https://doi.org/10.1016/j.jclepro.2014.06.094

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

Pagotto, M., Halog, A., 2016. Towards a Circular Economy in Australian Agri-food Industry: An Application of Input-Output Oriented Approaches for Analyzing Resource Efficiency and Competitiveness Potential. J. Ind. Ecol. 20, 1003–1249. https://doi.org/10.1111/jiec.12373

Park, J.Y., Chertow, M.R., 2014. Establishing and testing the "reuse potential" indicator for managing wastes as resources. J. Environ. Manage. 137, 45–53. https://doi.org/10.1016/j.jenvman.2013.11.053

Pauer, E., Wohner, B., Heinrich, V., Tacker, M., 2019. Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment. Sustainability 11, 925. https://doi.org/10.3390/su11030925

Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour Conserv Recycl 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019

Pauliuk, S., Kondo, Y., Nakamura, S., Nakajima, Kenichi, 2017. Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. Resour Conserv Recycl 116, 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029

Poponi, S., Arcese, G., Pacchera, F., Martucci, O., 2022. Evaluating the transition to the circular economy in the agri-food sector: Selection of indicators. Resources, Conservation and Recycling 176, 105916. https://doi.org/10.1016/j.resconrec.2021.105916

Portillo-Tarragona, P., Scarpellini, S., Moneva, J.M., Valero-Gil, J., Aranda-Usón, A., 2018. Classification and Measurement of the Firms' Resources and Capabilities Applied to Eco-Innovation Projects from a Resource-Based View Perspective. Sustainability 10, 3161. https://doi.org/10.3390/su10093161

Qing, Y., Qiongqiong, G., Mingyue, C., 2011. Study and Integrative Evaluation on the development of Circular Economy of Shaanxi Province. Energy Procedia 5, 1568–1578. https://doi.org/10.1016/j.egypro.2011.03.268

Rincón-Moreno, J., Ormazábal, M., Álvarez, M.J., Jaca, C., 2021. Advancing circular economy performance indicators and their application in Spanish companies. J. Clean. Prod. 279, 123605. https://doi.org/10.1016/j.jclepro.2020.123605

Rosen, M.A., Dincer, I., 2001. Exergy as the confluence of energy, environment and sustainable development. Exergy 1, 3–13. https://doi.org/10.1016/S1164-0235(01)00004-8

Rossi, E., Bertassini, A.C., dos Santos Ferreira, C., Weber Antonio Neves, do A., Ometto, A.R., 2020. Circular Economy indicators for organizations considering Sustainability and Business Models: plastic, textile and electro-electronic cases. J. Clean. Prod. 247, 119137. https://doi.org/10.1016/j.jclepro.2019.119137

Rukundo, R., Bergeron, S., Bocoum, I., Pelletier, N., Doyon, M., 2021. A Methodological Approach to Designing Circular Economy Indicators for Agriculture: An Application to the Egg Sector. Sustainability 13, 8656. https://doi.org/10.3390/su13158656

Sartal, A., Ozcelik, N., Rodríguez, M., 2020. Bringing the circular economy closer to small and medium enterprises: Improving water circularity without damaging plant productivity. J. Clean. Prod. 256, 120363. https://doi.org/10.1016/j.jclepro.2020.120363

Scarpellini, S., Marín-Vinuesa, L.M., Aranda-Usón, A., Portillo-Tarragona, P., 2020. Dynamic capabilities and environmental accounting for the circular economy in businesses. Sustain. Account. Manag. Policy J. 11, 1129–1158. https://doi.org/10.1108/SAMPJ-04-2019-0150

Scarpellini, S., Marín-Vinuesa, L.M., Portillo-Tarragona, P., Moneva, J.M., 2018. Defining and measuring different dimensions of financial resources for business eco-innovation and the influence of the firms' capabilities. J. Clean. Prod. 204, 258–269. https://doi.org/10.1016/j.jclepro.2018.08.320

Scheepens, A.E., Vogtländer, J.G., Brezet, J.C., 2016. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. J. Clean. Prod. 114, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075

Šerešová, M., Kočí, V., 2020. Proposal of Package-to-Product Indicator for Carbon Footprint Assessment with Focus on the Czech Republic. Sustainability 12, 3034. https://doi.org/10.3390/su12073034

Sgarbossa, F., Russo, I., 2017. A proactive model in sustainable food supply chain: Insight from a case study. International Journal of Production Economics 183, 596–606. https://doi.org/10.1016/j.ijpe.2016.07.022

Sheldon, R.A., 2018. Metrics of Green Chemistry and Sustainability: Past, Present, and Future. ACS Sustainable Chem. Eng. 6, 32–48. https://doi.org/10.1021/acssuschemeng.7b03505

Steinmann, Z.J.N., Huijbregts, M.A.J., Reijnders, L., 2019. How to define the quality of materials in a circular economy? Resour Conserv Recycl 141, 362–363. https://doi.org/10.1016/j.resconrec.2018.10.040

Thomas, J.-S., Birat, J.-P., 2013. Methodologies to measure the sustainability of materials – focus on recycling aspects. Rev. Metall. 110, 3–16. https://doi.org/10.1051/metal/2013054

Titova, N.Y., Terentyeva, T., 2020. Principles of circular economy introduction in russian industry. Revista Universidad y Sociedad 12, 203–208.

UNSD, 2020. Global indicator framework for the sustainable development goals and targets of the 2030 agenda for sustainable development, Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development. UNSD New York, NY, USA.

U.S. Chamber of Commerce Foundation, 2017. Measuring Circular Economy.

Vadoudi, K., Deckers, P., Demuytere, C., Askanian, H., Verney, V., 2022. Comparing a material circularity indicator to life cycle assessment: The case of a three-layer plastic packaging. Sustainable Production and Consumption 33, 820–830. https://doi.org/10.1016/j.spc.2022.08.004

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., Duflou, J.R., 2018. Ease of disassembly of products to support circular economy strategies. Resour Conserv Recycl 135, 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022

Veleva, V., Bodkin, G., Todorova, S., 2017. The need for better measurement and employee engagement to advance a circular economy: Lessons from Biogen's "Zero Waste" journey. J. Clean. Prod. 154, 517–529. https://doi.org/10.1016/j.jclepro.2017.03.177

Vercalsteren, A., Christis, M., Van Hoof, V., 2017. Indicators for a Circular Economy.

Yang, C.-K., Ma, H.-W., Liu, K.-H., Yuan, M.-H., 2023. Measuring circular economy transition potential for industrial wastes. Sustainable Production and Consumption 40, 376–388. https://doi.org/10.1016/j.spc.2023.06.013

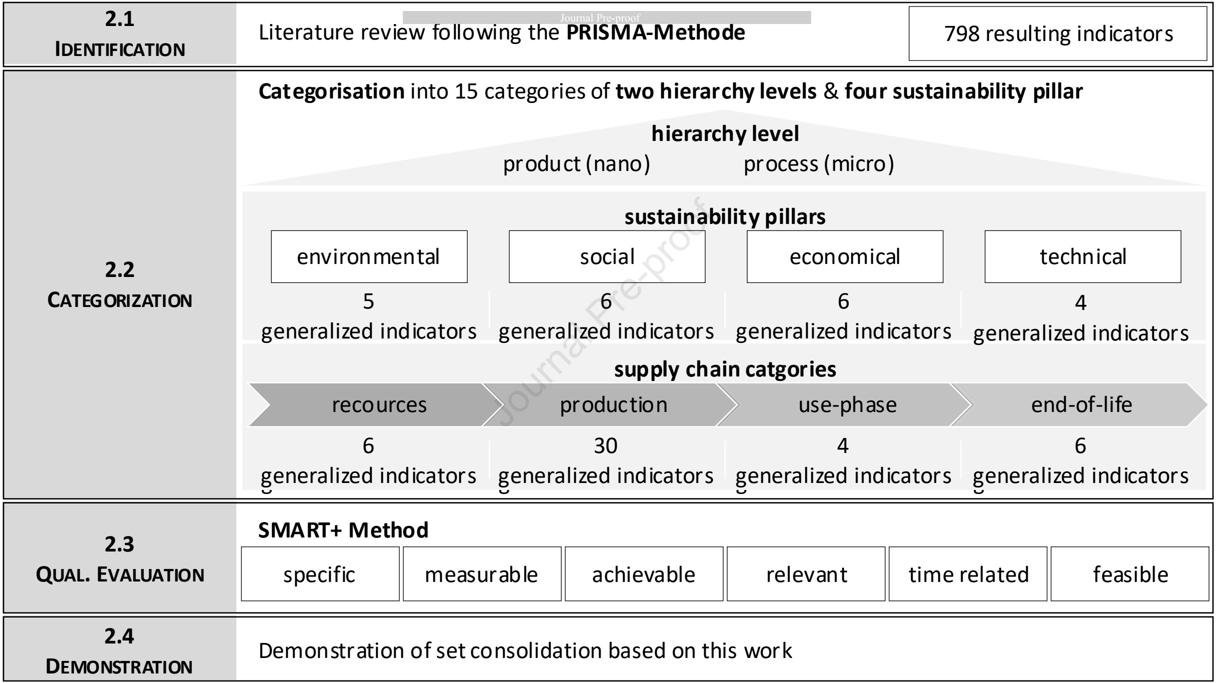
Zamfir, A.-M., Mocanu, C., Grigorescu, A., 2017. Circular Economy and Decision Models among European SMEs. Sustainability 9, 1507. https://doi.org/10.3390/su9091507

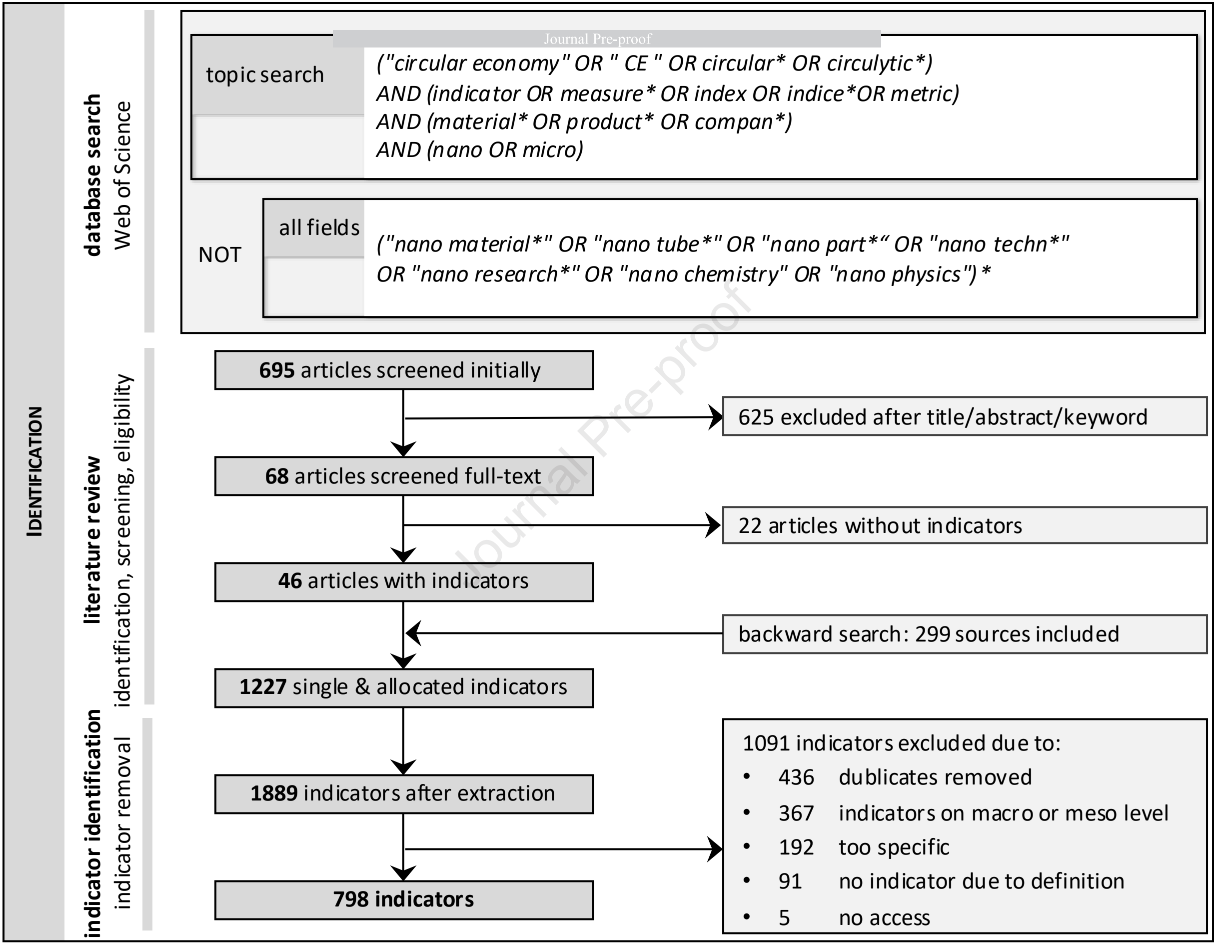
Zhou, Z., Chen, X., Xiao, C., 2013. On Evaluation Model of Circular Economy for Iron and Steel Enterprise Based on Support Vector Machines with Heuristic Algorithm for Tuning Hyper-parameters. Appl. Math. Inf. Sci. 7, 2215–2223. https://doi.org/10.12785/amis/070611

Zink, T., Geyer, R., Startz, R., 2016. A Market-Based Framework for Quantifying Displaced Production from Recycling or Reuse. J. Ind. Ecol. 20, 719–729. https://doi.org/10.1111/jiec.12317

Zore, Ž., Čuček, L., Kravanja, Z., 2018. Synthesis of sustainable production systems using an upgraded concept of sustainability profit and circularity. J. Clean. Prod. 201, 1138–1154. https://doi.org/10.1016/j.jclepro.2018.07.150

Zwolinski, P., Lopez-Ontiveros, M.-A., Brissaud, D., 2006. Integrated design of remanufacturable products based on product profiles. J. Clean. Prod. 14, 1333–1345. https://doi.org/10.1016/j.jclepro.2005.11.028


2.1
IDENTIFICATION
Literature review following the PRISMA-Methode
798 resulting indicators
2.2
CATEGORIZATION
Categorisation into 15 categories of two hierarchy levels & four sustainability pillar
hierarchy level
product (nano)
process (micro)
sustainability pillars
environmental
social
economical
technical
5 generalized indicators
6 generalized indicators
6 generalized indicators
4 generalized indicators
supply chain catgories
recources
production
use-phase
end-of-life
6 generalized indicators
30 generalized indicators
4 generalized indicators
6 generalized indicators
2.3
QUAL. EVALUATION
SMART+ Method
specific
measurable
achievable
relevant
time related
feasible
2.4
DEMONSTRATION
Demonstration of set consolidation based on this work


IDENTIFICATION
database search
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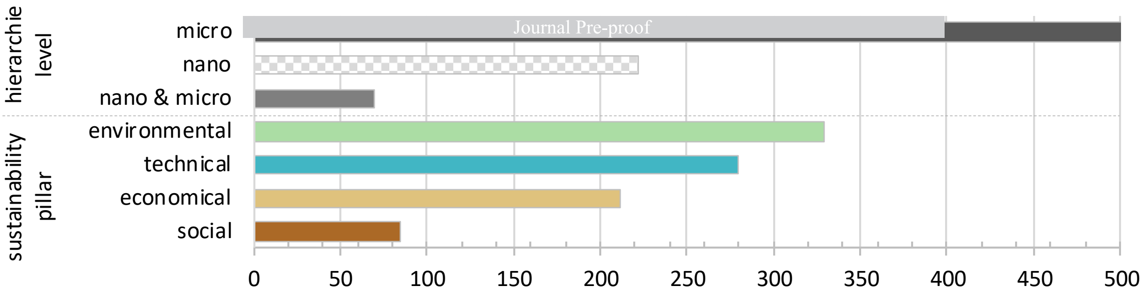
("circular economy" OR " CE " OR circular* OR circulytic*)
AND (indicator OR measure* OR index OR indice*OR metric)
AND (material* OR product* OR compan*)
AND (nano OR micro)
NOT
all fields
("nano material*" OR "nano tube*" OR "nano part*“ OR "nano techn*"
OR "nano research*" OR "nano chemistry" OR "nano physics") *
literature review
identification, screening, eligibility
695 articles screened initially
625 excluded after title/abstract/keyword
68 articles screened full-text
22 articles without indicators
46 articles with indicators
backward search: 299 sources included
1227 single & allocated indicators
indicator identification
indicator removal
1889 indicators after extraction
1091 indicators excluded due to:
• 436 dublicates removed
• 367 indicators on macro or meso level
• 192 too specific
• 91 no indicator due to definition
• 5 no access
798 indicators

F3 a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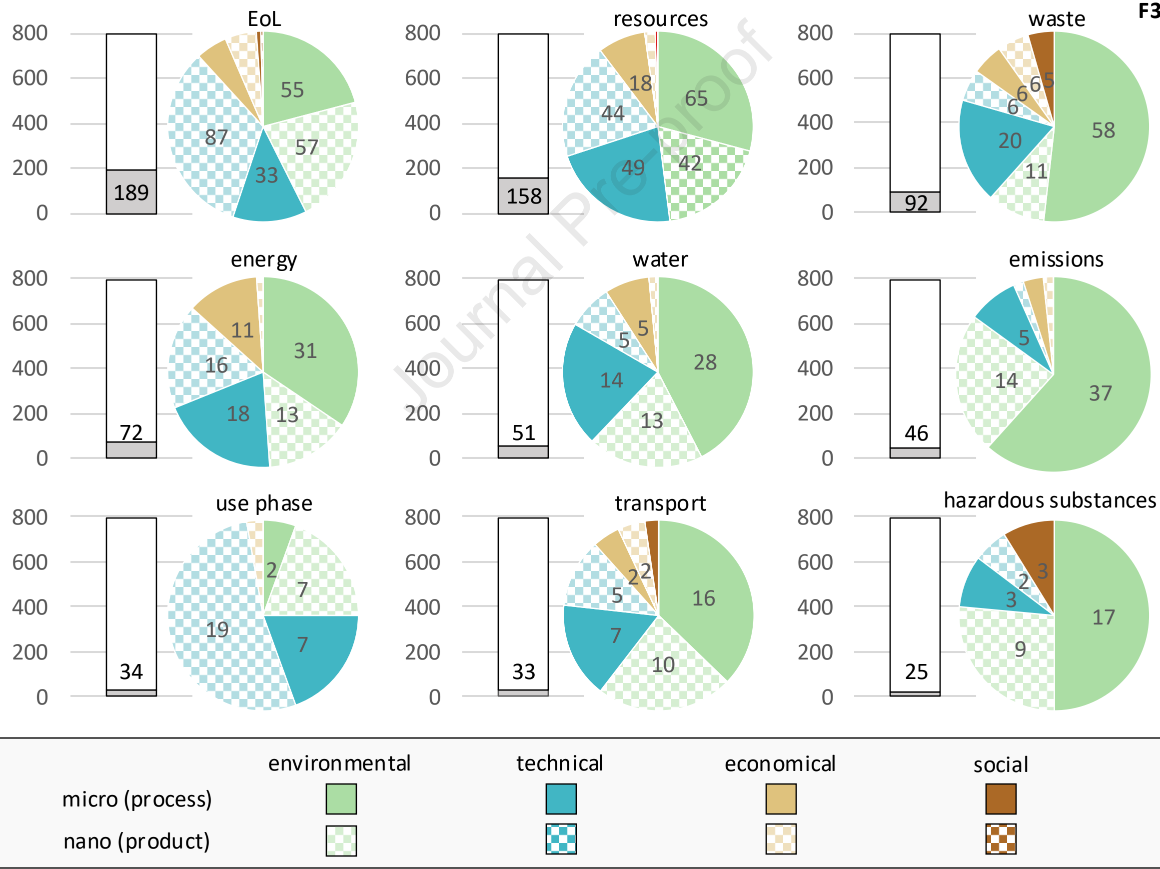
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use phase
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2
7
7
19
transport
33
16
10
7
5
2
2
hazardous substances
25
17
9
3
2
3
environmental
technical
economical
social
micro (process)
nano (product)

Highlights Techno-sustainable Analysis:

- Circular Economy Indicators can be categorized according to a Techno-Sustainable Analysis on hierarchy level, sustainability pillar, technical pillar, and life cycle stages
- 67 generalized CE indicators can be condensed from the indicator pool, and calculation recommendations are provided.
- The SMART+ Method is presented to evaluate the quality and case-specific viability of indicators.
- A four-step approach for the compilation of final indicator sets is proposed and demonstrated in the case of a producing company
- An Excel file with over 2,000 entries of CE indicators, tools, and questions from the literature is provided for further work.

Declaration of interests

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

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Florian Halter reports financial support was provided by Federal Ministry of Economic Affairs and Climate Action the German Federation of Industrial Research Associations (AiF). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.