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Review

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.

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 et al., 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

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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 Mosgaard, 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 (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 (Alamerew et al., 2020; De Oliveira et al., 2021; Kristensen and Mosgaard, 2020). Therefore, analyzing and evaluating existing indicators to derive potential simplifications may be helpful. Alamerew et al. (2020) additionally suggests a more in-depth consideration of the life cycle stages before end-of-life, while both Kristensen and Mosgaard (2020) and De Oliveira (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, and the creation of a use-case-specific indicator set from the derived indicator pool is demonstrated.

2. Method

Fig. 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.

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 as shown in Fig. 2. 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.

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, 1889 indicators are collected, of which 436 duplicates are removed. 367 indicators are assigned to

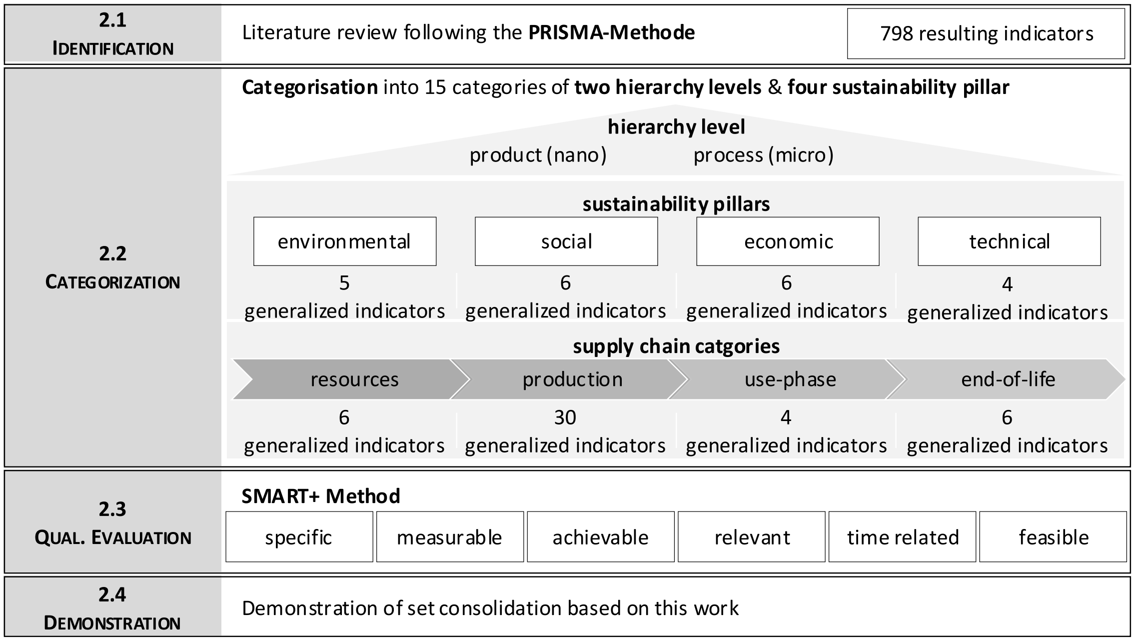

Fig. 1. Framework to assess circular economy indicators using the techno-sustainable analysis.

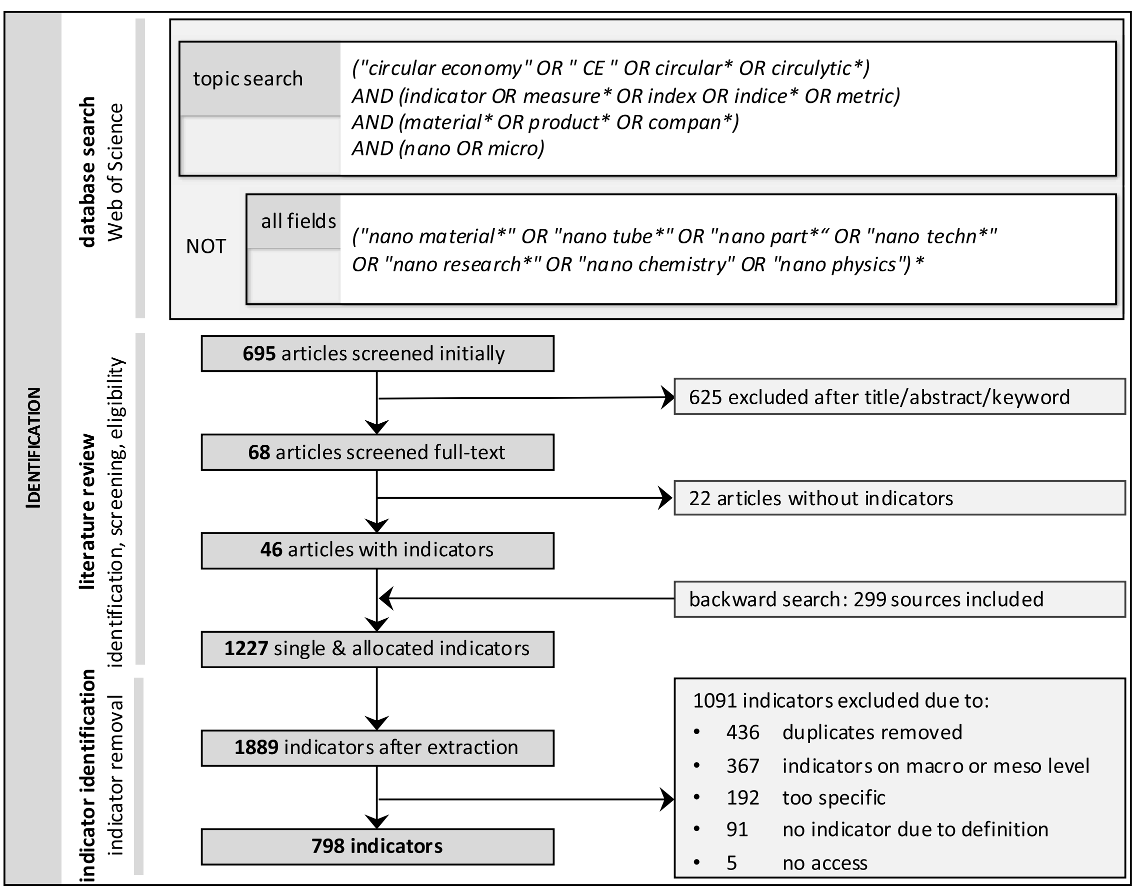

Fig. 2. Literature review and indicator pool.

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.

2.2.1. 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. *Product 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
Categorization criteria including the hierarchy level, sustainability pillar, and life cycle stage with description.

	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	
	economic	
	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

2.2.2. 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 4–5 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 and demonstrate the approach for an exemplary use case in Chapter 3.5:

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.

3. Results

3.1. Frequently used CE indicators

We identified 1889 indicators, of which 1091 are excluded, as described in Chapter 2.1. The largest group is 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.

Fig. 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.

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.

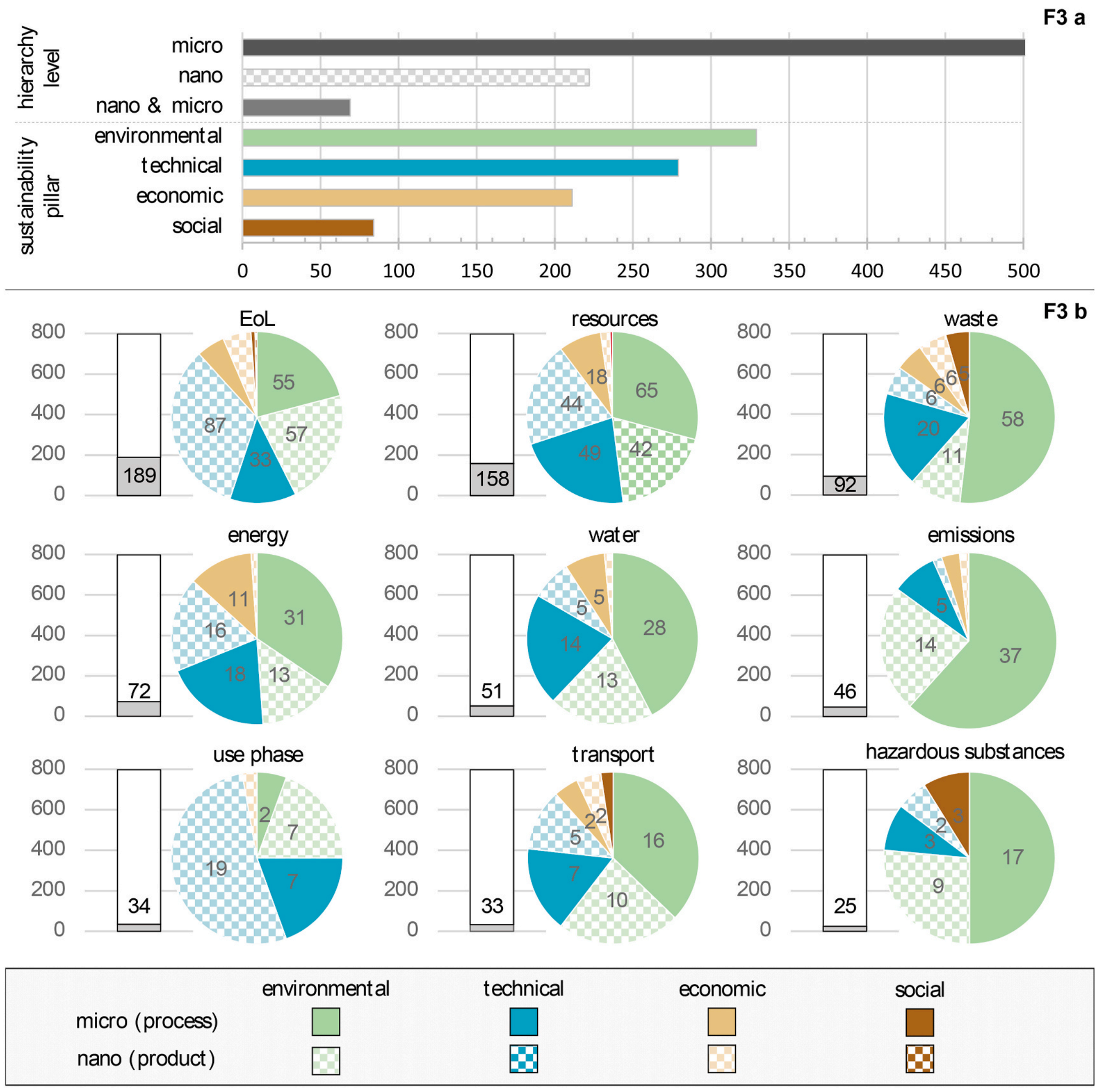

Fig. 3. Distribution of indicators

Fig. 3 a shows the distribution of the indicators in respect of their hierarchy level and their techno-sustainable pillar.

Fig. 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.

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*

Table 2
Generalized indicators of life cycle stages with mathematical formulas.

category	generalized indicator	#	formula [a]	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
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	

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

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. (2014). 23 Indicators are linked to *R1 Rethink as* the indicator *types of CE innovations* by 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 Graedel 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: 36 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).

Economic: 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 Fig. 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).

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 (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 in the demonstration case.

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**	**reasoning**
	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**	**formula**
resource	recycled content	$\frac{\sum_{\text{process steps}}(\textit{recycled input} + \textit{reused input})\ [t]}{\textit{total input}\ [t]}$
	resource efficiency	$\frac{\sum_{\text{process steps}}(\textit{recycled input} + \textit{reused input})\ [t]}{\textit{total input}\ [t]}$
	circular resource use	$\frac{\sum_{\text{process steps}}(\textit{reusable material} + \textit{recyclable material})\ [t]}{\textit{total material used}\ [t]}$
waste	waste generation	$\frac{\sum_{\text{process steps}}\textit{waste output}\ [t]}{\textit{product or process}}$
energy	energy input	$\frac{\sum_{\text{process steps}}\textit{energy used}\ [\textit{kWh or €}]}{\textit{product or process}}$
	renewable energy	$\frac{\sum_{\text{electricity,gas}}\textit{renewable energy consumed}\ [\textit{kWh or €}]}{\textit{total energy consumption}}$
emissions	climate change	LCA
Step 4	**indicators identified using SMART+ method**	**source**
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)

[a] 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 and Mosgaard, 2020; De Oliveira et al., 2021; Alamerew et al., 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 Oliveira 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 Oliveira et al. (2021), Kristensen and Mosgaard (2020), 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 Oliveira (2021), like this work, considers the share of environmental indicators to be the most significant, Kristensen and Mosgaard (2020) assign most indicators to the economic pillar. This difference may be favored by the absence of the technical pillar, as De Oliveira 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 et al. (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 Mosgaard (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 4–5 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 Oliveira et al. (2021) and Kristensen and Mosgard (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.

CRediT authorship contribution statement

Florian Halter: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lars Wietschel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization. **Andrea Thorenz:** Writing – review & editing, Project administration, Conceptualization. **Axel Tuma:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145078.

Data availability

Data will be made available on request.

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