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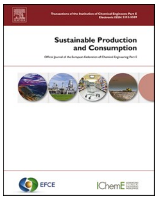

Review Article

A systematic literature review on circularity assessment indicators and frameworks in the built environment☆

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ABSTRACT

A wide range of circularity assessment indicators and frameworks for the built environment have been developed in recent years to support the transition to a circular economy (CE). However, few studies have systematically reviewed the available circularity assessment methods beyond the building scale, and there is limited analysis of non-quantitative assessment methods. Therefore, this systematic literature review of 66 studies identifies and analyzes existing circularity assessment indicators and frameworks for the built environment across building, neighborhood, and city (and beyond) scales, providing a comprehensive overview of the state of the art and key directions for future research. The analysis identifies 148 quantitative, 160 semi-quantitative, and 152 qualitative indicators, which are categorized based on their application in circularity assessment, either individually or as part of indicator sets in frameworks. The results show that existing indicators cover five key dimensions of circularity; however, the interrelationships between these dimensions remain unclear and are rarely addressed. Most indicators are applied at the building level, while larger spatial scales remain less developed. These findings highlight the complexity of the current state of the art, driven by the extensive number and fragmentation of existing indicators. Based on this, this review recommends future research directions to enhance circularity assessment methodologies, with an emphasis on refining existing methods, improving decision-support mechanisms, and moving toward standardization. By synthesizing current knowledge and identifying critical research needs, this study serves as a starting point toward standardizing circularity assessment and thus supporting the adoption of CE principles in the built environment.

1. Introduction

The built environment accounts for 37 % of total greenhouse gas (GHG) emissions, 34 % of global energy consumption (United Nations Environment Programme and Global Alliance for Buildings and Construction, 2024), and about 50 % of all extracted materials ("Buildings and construction," n.d.). In addition, the construction and demolition sector is responsible for over 35 % of Europe's total waste generation (Eurostat, n.d.-a, n.d.-b). The built environment plays a crucial role in achieving global climate goals. However, the widely applied linear "take-make-use-dispose" approach poses a critical barrier to progress. Transitioning to a circular economy presents a pathway to mitigate these impacts. Circular economy (CE) is defined as an economic system that uses a systemic approach to maintaining a circular flow of resources by recovering, retaining or enhancing their value, while contributing to sustainable development (International Organization for Standardization, 2024a). Countries around the world have introduced various policies and strategies to support the transition toward a circular economy. For instance, the National Recycling Strategy developed by the United States Environmental Protection Agency (2021) aimed at increasing

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recycling rates and reducing waste as part of its broader approach to advancing a circular economy. The new Circular Economy Action Plan of the European Union (European Commission: Directorate-General for Environment, 2021) aims to accelerate the transition to a circular economy and has identified the construction and buildings sector as one of the key areas for intervention. The recently revised Energy Performance of Buildings Directive (European Parliament, 2024) promotes resource efficiency and circularity in the building sector. In support of this transition, voluntary guidance tools such as the Circular Built Environment Playbook by the World Green Building Council (2023), as well as regulatory frameworks such as the Level(s) (European Parliament, 2020) have been developed to provide an entry point for applying circular economy principles in the built environment.

Despite the growing research on adopting the circular economy in the built environment, the concept is still in the early exploratory phase (Munaro et al., 2020; Ossio et al., 2023). One of the major challenges hindering the application of circular economy principles within the built environment is the lack of a standardized assessment method to effectively measure and track circularity progress (Harris et al., 2021; Tokazhanov et al., 2022). Circularity assessment has recently been defined in ISO 59004:2024 as the evaluation and interpretation of results and impacts derived from a circularity measurement (International Organization for Standardization, 2024a). In this case, circularity assessment is a multi-criteria problem, where the physical properties of circular strategies, such as the degree of circularity, should all be considered alongside their environmental, economic, and social impacts. Prior to the release of ISO 59004:2024, there were no internationally recognized standards specifically guiding circular economy implementation and assessment. Some national-level standards, such as the British BS 8001:2017 (British Standards Institution, 2017) and the French XP X30-901 (Association Française de Normalisation, 2018), offered early frameworks to support the adoption of circular economy principles, particularly within organizational settings. For example, XP X30-901 introduced a structured 7 × 3 matrix to guide project management for circular initiatives.

The European Commission has recognized the need for developing monitoring frameworks to assess progress toward a more circular economy and the effectiveness of action at the national level (European Parliament, 2023). In response, the European Union monitoring framework on the circular economy (Eurostat, n.d.-a, n.d.-b) has been developed to evaluate national progress toward a circular economy, consisting of five thematic areas, including production and consumption, waste management, secondary raw materials, competitiveness and innovation, and global sustainability and resilience. However, this framework is not specifically designed to capture sector-level performance. In the absence of a unifying international standard, researchers have conducted broader reviews to map existing circularity indicators. Saidani et al. (2019) summarized 55 existing sets of circular indicators for products, businesses, and nations. For instance, the Circular Economy Performance Indicator (Huysman et al., 2017) focuses on the measurement of circular economy performance of post-industrial plastic (i.e., polyethylene) waste treatments. However, these indicators are designed for general applications and may not fully capture the specific characteristics and complexities of the built environment. First, at the material level, construction materials, such as reinforced concrete, steel, and mass timber, differ from materials used in typical consumer products. They are used in large volumes and are usually bonded or layered with others. This makes disassembly, separation, and recycling far more complex than recycling plastic bottles. Second, buildings have long life spans and undergo renovations or even repurposing before reaching the demolition stage. As such, circularity indicators must not only focus on tracking the material flow, but should also be able to assess other aspects such as the design-for-adaptability potential. Third, the built environment involves multi-level interactions of resource flows. Buildings are part of larger urban systems, exchanging energy, water, and even waste with their surroundings. For example, a building may act as both a consumer and producer of energy (e.g., through solar panels), or reuse greywater for non-potable applications. Unlike assessments focusing on isolated objects, circularity in the built environment requires systemic indicators that can account for interactions across scales. Last, the built environment is shaped by multi-stakeholder decision-making, involving engineers, architects, facility managers, developers, policymakers, and end-users. Effective circularity assessment indicators should therefore be able to integrate diverse perspectives. A more focused examination of circularity assessment methods specifically tailored to the built environment is therefore essential.

Existing studies have developed and applied different circularity assessment indicators and frameworks for the built environment, such as the widely used Building Circularity Indicator (Verberne, 2016) at the building level. According to ISO 59020:2024 (International Organization for Standardization, 2024b), circularity assessment can be conducted at multiple system levels, including the product, organizational, interorganizational, and regional levels. In the context of the built environment, these can be interpreted respectively as the nano (material), micro (building), meso (neighborhood and community), and macro (city, region, and beyond) scales. Despite this increasing interest, relatively few studies have systematically reviewed the available circularity assessment methods (i.e., indicators and frameworks) across different scales in the built environment. Existing reviews focus narrowly on the building level. For instance, Segara et al. (2024) reviewed 32 existing building-level circularity assessment indicators and mapped their alignment with the Royal Institute of British Architects Plan of Work (The Royal Institute of British Architects, 2020). Similarly, Khadim et al. (2022) summarized and analyzed a set of 35 circularity assessment indicators, focusing on material and building levels. While such efforts provide valuable insights at the building level, several key research gaps can be identified. First, there is a knowledge gap in circularity assessment beyond the building level. To the authors' best knowledge, no particular review on circularity indicators and frameworks at neighborhood and city (and beyond) scales can be found. At these broader spatial scales, additional factors such as resource flows that extend beyond individual buildings (e.g., through energy sharing within local energy communities) need to be considered. As a result, the existing reviews' focus on building-level assessment methods fails to capture circular economy opportunities that arise at larger spatial scales. This gap not only limits a comprehensive overview of existing approaches but also hinders progress toward standardizing circularity assessment methods in the built environment. Second, there is a noticeable gap in the analysis of non-quantitative assessment methods. While some reviews acknowledge the existence of semi-quantitative and qualitative indicators, they often lack detailed explanations of how these indicators or frameworks are developed, applied, or evaluated. This is a significant omission, as non-quantitative approaches can be particularly useful in contexts where quantitative data is limited or unavailable. Moreover, they enable the assessment of those dimensions of circularity that are difficult to capture through numerical indicators alone, such as the social dimension. Therefore, a more balanced and comprehensive analysis of all indicator types is needed to better understand their respective roles, advantages, and limitations in circularity assessment. In summary, the research gaps in reviewing circularity assessment at larger spatial scales (i.e., neighborhood, city, and beyond), along with the limited attention to non-quantitative approaches, highlight the need for a more comprehensive understanding of how circularity is assessed across the built environment.

To address the research gaps, the general objective of this literature review is to investigate how circularity is assessed in the built environment across three spatial scales, namely building, neighborhood, and city (and beyond) levels. Specifically, this overall objective is further broken down into three specific objectives: (1) to identify indicators and frameworks developed for circularity assessment in the built environment, (2) to examine how these indicators are assessed and applied in circularity assessment, and (3) to map these indicators and frameworks based on the specific dimensions of circularity they assess. The novelty of this review lies in two key aspects: (1) expanded scope – instead of focusing only on the building level, this review also includes circularity assessment at urban scales (i.e., neighborhood, city, and beyond) to provide a more holistic understanding of indicator choices for different spatial scales, and (2) comprehensive inclusion – this review considers a wide range of assessment methods, including quantitative, semi-quantitative, and qualitative assessment indicators and frameworks to ensure a more comprehensive analysis. This review thus serves as a starting point for the standardization of circularity assessment in the built environment to support the transition to a circular economy.

This paper is structured as follows: Section 2 describes the research methodology, followed by Section 3, which presents the results and discussion in three subsections: content analysis, policy recommendation, and research limitations and future research directions. Finally, Section 4 concludes the study.

2. Methods

A systematic literature review (SLR) was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). The SLR approach was selected for its ability to comprehensively synthesize existing knowledge, ensuring a structured and unbiased review of the relevant literature (Tranfield et al., 2003). The objective of investigating how circularity is assessed in the built environment across three spatial scales, namely building, neighborhood, and city (and beyond) levels, guided the entire review process, helping to define the scope and criteria for selecting relevant literature. The next sections are structured based on the guidelines for reporting as recommended by PRISMA.

Studies that fulfilled the following inclusion criteria were eligible for inclusion in the systematic review: peer-reviewed journal articles and conference papers written in English, focusing on circularity assessment in the built environment at either the (1) building, (2) neighborhood, or (3) city and beyond scales. Studies published in other languages were excluded from the systematic review. Although initial discussions on circular economy in the built environment began around 2010, circularity in the built environment is a relatively recent research area, gaining increasing interest in the years following 2016 (Munaro et al., 2020). The first CE indicator was proposed in 2010 (Saidani et al., 2019); however, a widely applicable material-level indicator was developed by the Ellen MacArthur Foundation in 2015 (Goddin et al., 2019), which was tailored and applied for the built environment with adaptations at the building scale since 2016 (Verberne, 2016). Given this timeline, this review includes only more recent studies published within the past ten years from 2015 to 2024. Studies published before 2015 were excluded from the systematic review.

A set of keywords was searched within the title, abstract, and keywords using the online database SCOPUS, an online database of peer-reviewed articles, which is the largest of its kind (Chadegani et al., 2013). Keywords and Boolean operators were defined as follows: *(building OR neighborhood OR district OR community OR construction OR "built environment") AND ((circular OR circularity) W/5 (indicator OR indice OR index OR metric OR criteria OR framework OR assess* OR measur* OR quantif* OR evaluat*))*. The set of keywords consists of two main parts. The first part defines the research area and scope, covering levels from individual buildings to neighborhoods (districts and communities) and extending to the entire construction industry and built environment at broader spatial scales. The second part targets circularity assessment indicators or frameworks. The term "circular economy" has been extensively used in literature abstracts, often to provide background information without focusing specifically on circularity assessment. To exclude such literature and ensure the relevance of the results, a proximity search was applied. This search captured instances where "circular OR circularity" appeared within five words of "*indicator OR indice OR index OR metric OR criteria OR framework OR assess* OR measur* OR quantif* OR evaluat**."

Concerning the identification process, SCOPUS was last searched and consulted on the 4th of May 2024. Any new inclusions into the SCOPUS database that were added after this date were not considered for this systematic literature review. This resulted in 1751 records. Results were shortlisted using SCOPUS filters to include only peer-reviewed articles and conference papers in English published between 2015 and 2024. This step removed 664 records, narrowing the list to 1087 studies (826 articles and 261 conference papers) for screening.

The screening process was conducted independently by the first author, with Zotero used for reference management. In the first round, titles and abstracts were reviewed to determine whether they addressed circularity assessment at building, neighborhood, or city (and beyond) scales. This stage resulted in the exclusion of 958 studies, and 129 studies were sought for retrieval. All 129 full texts were successfully retrieved and assessed for eligibility. At this stage, the same inclusion and exclusion criteria used during the title and abstract screening were applied in more detail to the full texts. Specifically, two eligibility criteria were applied for assessing the full texts: (Criterion 1) the focus on scale, including only studies at the building, neighborhood, and city (and beyond) levels; and (Criterion 2) whether studies conducted circularity assessments, either by evaluating circularity, proposing new circularity assessment methods, or comparing circular options using case studies. After this eligibility assessment, a total of 65 studies (51 articles and 14 conference papers) were included for further analysis.

In addition to sources identified through keywords search, snowballing was conducted to identify any potentially relevant studies not captured by the search strategy. One additional study at the neighborhood scale was identified in this step, and this led to a total of 66 studies being selected for further analysis, as summarized in Fig. 1. Thereafter, data were collected from the identified studies. Data extraction was conducted manually by the first author. No automation tools were used. All relevant information from the 66 selected studies was reviewed independently. A structured Excel table and Notion workspace were used for documenting.

Concerning the data items, for each included study, the following information was extracted systematically: title, publication year, spatial scale of analysis (categorized as building, neighborhood, or city and beyond), number and names of indicators used, type of circularity assessment (categorized as quantitative, semi-quantitative, or qualitative), methods used for framework development, circularity dimensions addressed (categorized as environmental, economic, social, technical, and managerial), the specific aspects within these dimensions such as material efficiency, and whether a case study was applied. Additionally, a second structured Excel sheet was developed to document detailed characteristics of the indicators reported in each study. For each indicator, the following attributes were recorded: indicator name, dimension of circularity addressed (e.g., environmental), aspect (e.g., material efficiency), assessment method (e.g., qualitative), tool or framework used (if applicable), and any standard or benchmark referenced. All relevant results related to the identified outcome domains were extracted without any restrictions applied. Where information was unclear or missing, assumptions were avoided; data were only recorded when explicitly reported in the original study.

As this review aimed to collect existing frameworks and indicators, rather than evaluate the effectiveness of interventions or compare outcome data across studies, neither a formal risk of bias assessment nor effect measures were applied. Nevertheless, all included papers were peer-reviewed articles or conference papers, ensuring they were reliable sources for this review.

Studies were grouped for the syntheses based on assessment scale (i.e., building, neighborhood, or city and beyond) as well as type of assessment method (i.e., quantitative, semi-quantitative, or qualitative). For data presentation, descriptive information was organized in summary tables. Visual diagrams (such as charts or tables) were developed using Microsoft Excel to show overlaps and differences across studies.

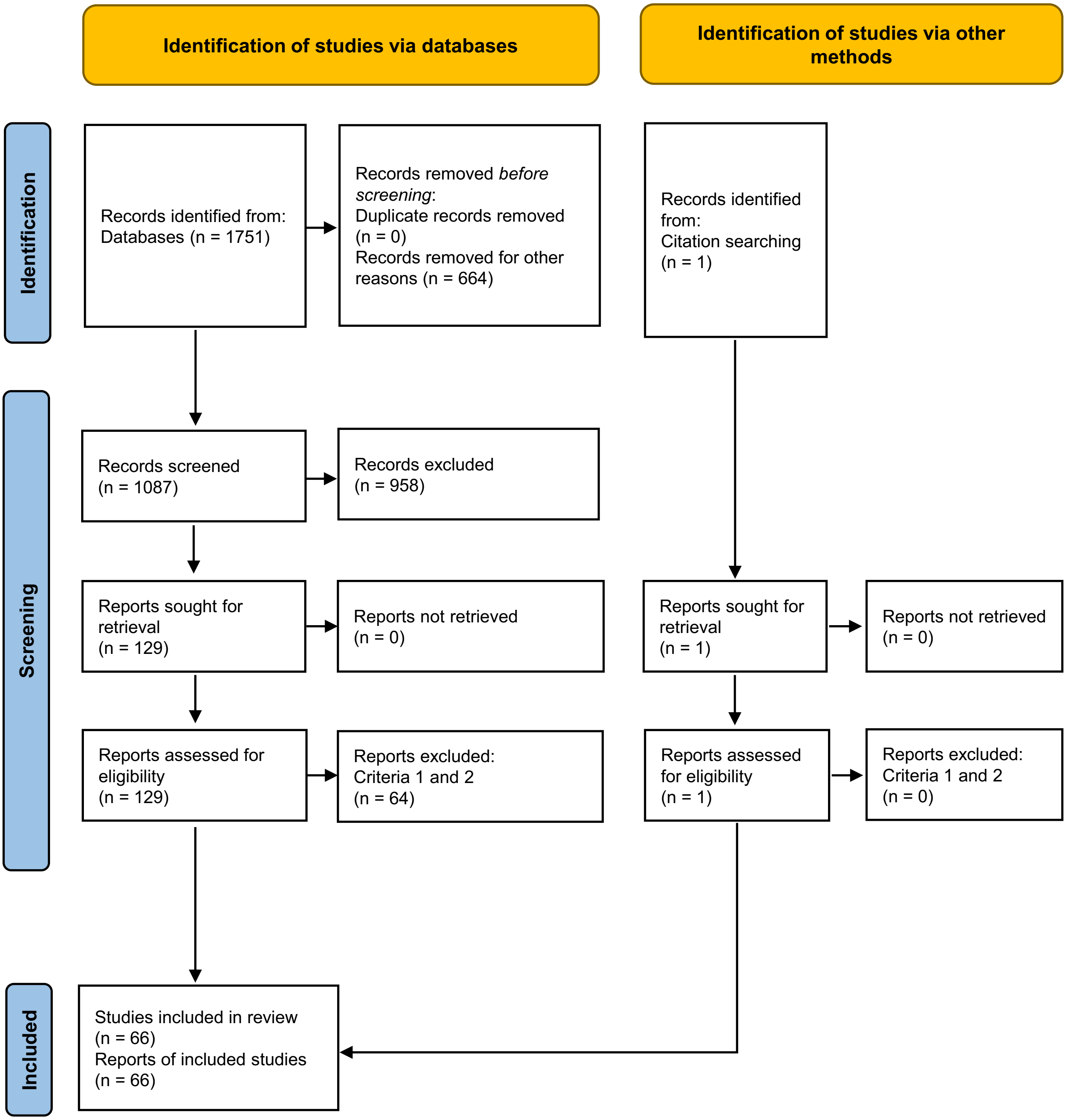

Fig. 1. Process flow of the systematic literature review conducted following the PRISMA 2020 guidelines, including identification, screening, and inclusion of studies.

No statistical synthesis, such as meta-analysis, was conducted as the included studies did not report standardized or comparable quantitative outcomes.

3. Results and discussion

This section presents the key findings of the review. Although the inclusion criteria targeted both journal articles and conference papers published between 2015 and 2024, research on circularity assessment at the building, neighborhood, and city (and beyond) levels remains relatively recent, with the earliest relevant publication appearing in 2019, as shown in Fig. 2. However, as Khadim et al. (2022) suggest, there were earlier contributions, including theses and reports. While those types of sources fall outside the scope of this review, they provide a groundwork upon which some recent scientific studies have applied, expanded, and adapted. Overall, there has been a growing interest in this research field, with the highest number of publications in 2022. In terms of application scale, the majority of studies (52 papers out of 66) focus on the building level, followed by studies at the city level or beyond with 11 publications.

This section comprises three main parts: content analysis (Section 3.1), policy recommendations (Section 3.2), and limitations and future

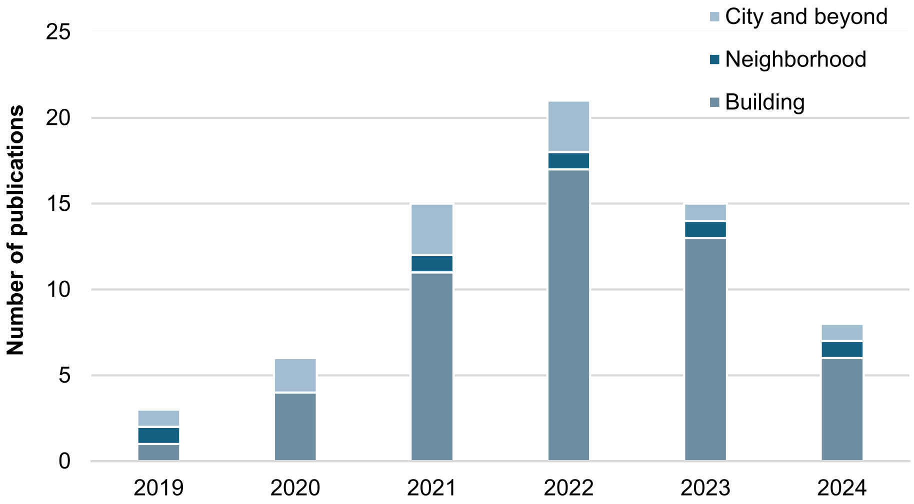

Fig. 2. Annual distribution of publications by spatial scale (building, neighborhood, city and beyond) for the period studied.

research directions (Section 3.3). The content analysis (Section 3.1) is further subdivided into detailed Sections focusing on the types of assessment indicators and frameworks applied in the reviewed studies, including quantitative, semi-quantitative, and qualitative approaches. Following the detailed analysis of assessment methods, Section 3.1.5 presents an integrated synthesis of how circularity dimensions, including environmental, economic, social, technical, and managerial, are addressed by identified indicators and frameworks. Additionally, Section 3.1.6 examines how circularity assessment is addressed across different spatial scales.

3.1. *Content analysis*

This section analyzes the indicators retrieved from the reviewed studies and used to assess circularity, focusing on their assessment methods and the aspects these indicators address.

3.1.1. *Overview of assessment indicators*

The collected circularity assessment indicators can be classified into three types: quantitative, semi-quantitative, and qualitative. A complete list of each type can be found in Supplementary material A. Quantitative indicators can be further divided into individual and composite indicators. Individual indicators measure a single aspect of circularity assessment. For example, Roberts et al. (2023) calculated the GHG emissions of a design-for-disassembly building through the indicator of Global Warming Potential (GWP). In contrast, composite indicators aggregate multiple dimensions (i.e., sub-indicators and factors) into a single quantitative value. Notably, although the final result is quantitative, the intermediate calculation process (i.e., calculation of sub-indicators or weighting factors) may not be entirely quantitative. This intermediate process can involve semi-quantitative assessments based on qualitative criteria, which are then translated into numerical values for the composite indicator calculation. For instance, Shin and Kim (2024) calculated the Building Circularity Indicator (BCI) for a timber building, which integrates material flows, design-for-disassembly potential, and the importance of each building layer into a composite indicator. The design-for-disassembly potential is used as a weighting factor, and it is assessed semi-quantitatively, relying on a scoring system for design criteria such as connection type and connection accessibility.

Semi-quantitative indicators use ratings or scores to evaluate the fulfillment of criteria, translating qualitative criteria into numerical values. For example, González et al. (2021) developed the Social Circularity Index (SCI), which measures the number of social impacts addressed within the new building or major renovation project to the total number of potential impacts potentially addressable. The assessment of whether the social criteria are met also depends on a scoring system.

Finally, qualitative indicators primarily consist of design criteria that are not yet quantified. For example, Abadi and Moore (2022) developed the PLACIT framework, which comprises 12 qualitative indicators within 5 themes, namely design for circularity in construction, reduced construction impact, sustainable utilization and maintenance, construction and demolition waste management, and CE management. The CE management theme consists of three indicators: (1) new business models and strategies, (2) planning and data management, and (3) education, training, and stakeholder awareness. This framework, however, is still in an early development phase and focuses on assigning weights to each theme and qualitative indicator to understand the relative importance rather than attempting to quantify them.

For all indicators identified across all reviewed studies, we analyzed the diversity (i.e., the number of indicators) of quantitative, semi-quantitative, and qualitative types. The level of diversity of these three types of indicators is similar, with quantitative indicators accounting for a slightly smaller proportion (32 %) of the total number of indicators. However, in terms of use intensity (i.e., the total number of applications across all reviewed studies), quantitative indicators are used far more frequently than both semi-quantitative and qualitative ones. This trend is likely due to the more standardized assessment methods associated with quantitative indicators. The top six most frequently applied indicators and their use intensity are summarized in Fig. 3. Notably, all of them are quantitative indicators, with 4 out 6 being based on Life Cycle Assessment (LCA). For instance, GWP is the most frequently used quantitative indicator because it is widely recognized and has a well-established calculation methodology (i.e., LCA). In addition, despite the absence of a standardized methodology for assessing the overall circularity degree of buildings, indicators such as the Building Circularity Indicator (BCI) and Predictive Building Circularity Indicator (PBCI) have been widely applied. The detailed methodologies for assessing these indicators are discussed in the following subsections.

3.1.2. *Quantitative indicators*

3.1.2.1. Overview of quantitative indicators. This subsection provides an overview and analysis of identified quantitative indicators, followed by a detailed analysis of these application approaches in Sections 3.1.2.2, 3.1.2.3, and 3.1.2.4.

A total of 148 quantitative indicators were used in circularity assessment in three ways: as a single indicator for a single result (nine studies), as a composite indicator for a single result (ten studies), and as

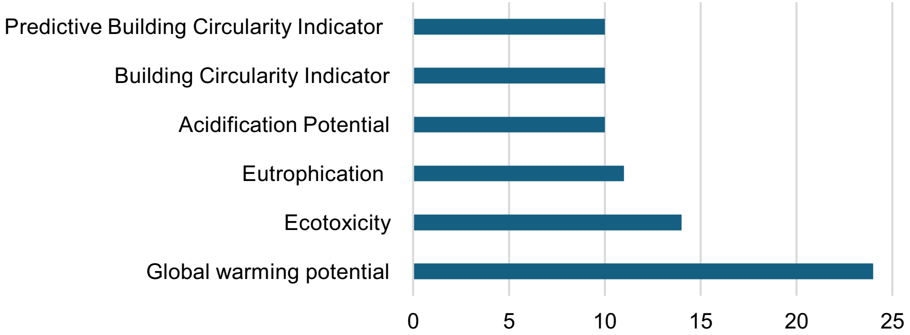

Fig. 3. Top six most frequently applied circularity indicators and their use intensity across reviewed studies.

part of a multi-indicator framework for multiple quantitative results (thirty studies). Figure 4 shows the distribution of these types across different application scales. Multi-indicator approaches are the most widely used, accounting for 62 % of studies. Overall, 74 % are applied at the building level. 20 % are applied at the city and beyond levels, where individual and sets of indicators are typically tailored to assess specific circular strategies within a particular region or city. 6 % are applied at the neighborhood level.

The 148 quantitative indicators are organized and discussed in the following paragraphs, which follow the structure presented in Fig. 5. First, environmental indicators are discussed, grouped by their methodological basis (i.e., whether they rely on LCA or not) and by specific aspects, including emissions, climate impact, land use, water use, energy use, and material efficiency. This is followed by economic indicators, then social indicators. Finally, we present indicators designed to assess an overall degree of circularity.

30 out of 148 quantitative indicators are based on LCA. Figure 6 summarizes these LCA-based indicators and their respective use intensity across all reviewed studies. The most commonly used indicators include GWP, ecotoxicity, and eutrophication potential, all of which are standard LCA indicators. In addition to these widely recognized ones, others such as carbon pricing and human health damage have also been identified. In general, they assess the impact of circular strategies on ecosystem and biodiversity, climate change, human health, resource depletion, land use, and energy use. Only one study (Balasbaneh and Sher, 2024) applied consequential LCA for assessment while the majority applied attributional LCA. The assessments were primarily guided by the ISO 14040 and ISO 14044 standards while Gravagnuolo et al. (2020) also considered the Level(s) framework when performing LCA for historic building conservation. The most frequently applied tools are SimaPro (four studies) and One Click LCA (four studies), and other tools, such as Open LCA (two studies), TOTEM (one study), and PLEIADES® (one study) have also been used. However, many studies did not specify the tools used. The Ecoinvent database (applied in six studies) and Environmental Product Declaration (EPD) (applied in three studies) have been used for life cycle inventory, though other studies did not mention the specific databases applied, which may limit the replicability and comparability of results. In terms of system boundary definition, six studies referenced EN 15804 and EN 15978 as guidance. However, the specific system boundaries applied differ across studies. Commonly, there is a focus on both production (A1-A3) and end-of-life (C1-C4) stages of buildings. Ahn et al. (2023) took a grave-to-gate approach, which analyzed the end-of-life stage of the first building and the production stage of the second building to assess the benefits of reusing post-use mass timber in new construction projects. Additionally, some studies have extended the boundary to include the construction stage (A4-A5), and the use stage (B). Within the use stage, some focus on the embodied impact of maintenance (B2) (Balasbaneh and Sher, 2024) and replacement (B4) (Kayaçetin et al., 2023) while others focus on energy and water use during operation (B6, B7) (Papadaki et al., 2022; Saadé et al., 2022). Furthermore, a cradle-to-cradle approach was applied in some studies to account for benefits and burdens beyond the system boundaries (stage D). Various allocation methods were used to distribute these benefits, including (i) 0–100 allocation, assigning 100 % benefits to the future life cycle, (ii) 100–0 approach, allocating 100 % impacts to the life cycle where the end-of-life occurs, and (iii) 50–50, dividing the benefits between the current and future life cycles.

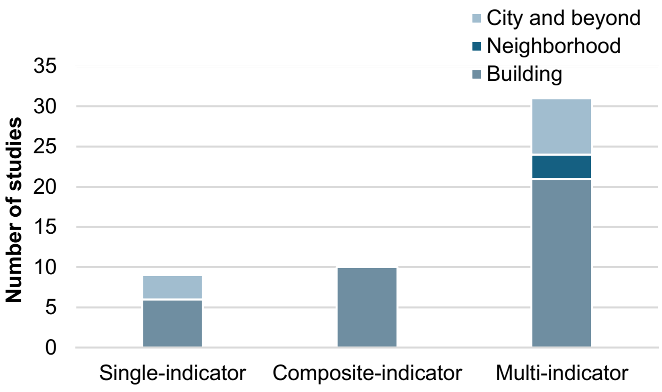

Fig. 4. Breakdown of quantitative circularity assessment indicators categorized by spatial scale, including building, neighborhood, and city and beyond.

In addition to LCA-based indicators, several other indicators within the emissions and climate change category have been identified. Some studies proposed indicators without detailing specific assessment methodologies. For example, Huovila and Iyer-Raniga (2021) selected core indicators from the 2030 Agenda through interviews and surveys, proposing "CO_2 emissions per unit of value added" as an indicator for regional circularity assessment. Other indicators (i.e., total CO_2 and GHG emissions) are all applied at the city (and beyond) levels. Unlike LCA-based indicators, which follow standardized methodologies, CO_2 and GHG emission indicators are calculated using a variety of accounting methods. For CO_2 accounting, Su and Urban (2021) applied the LEAP (Low Emission Analysis Platform) tool to calculate the energy demand for the built environment. They then calculated the total CO_2 emissions for this sector at the city level by multiplying energy demand by emission factors. For GHG emissions accounting at the city and regional levels, input-output analysis and consumption-based emission accounting were applied, relying on databases such as the Global Trade Analysis Project (GTAP) and local input-output datasets. Instead of quantifying the overall emissions of the building sector, Cader et al. (2024) proposed the indicator "share of new zero-emission buildings in the total number of new buildings" as a regional-level metric for evaluating progress in circular built environment.

Seven non-LCA-based land use indicators have been identified, all of which aim to assess the area of specific land uses. However, the indicators vary widely, reflecting a lack of standardization in this category. Different studies proposed their own indicators, including "area of

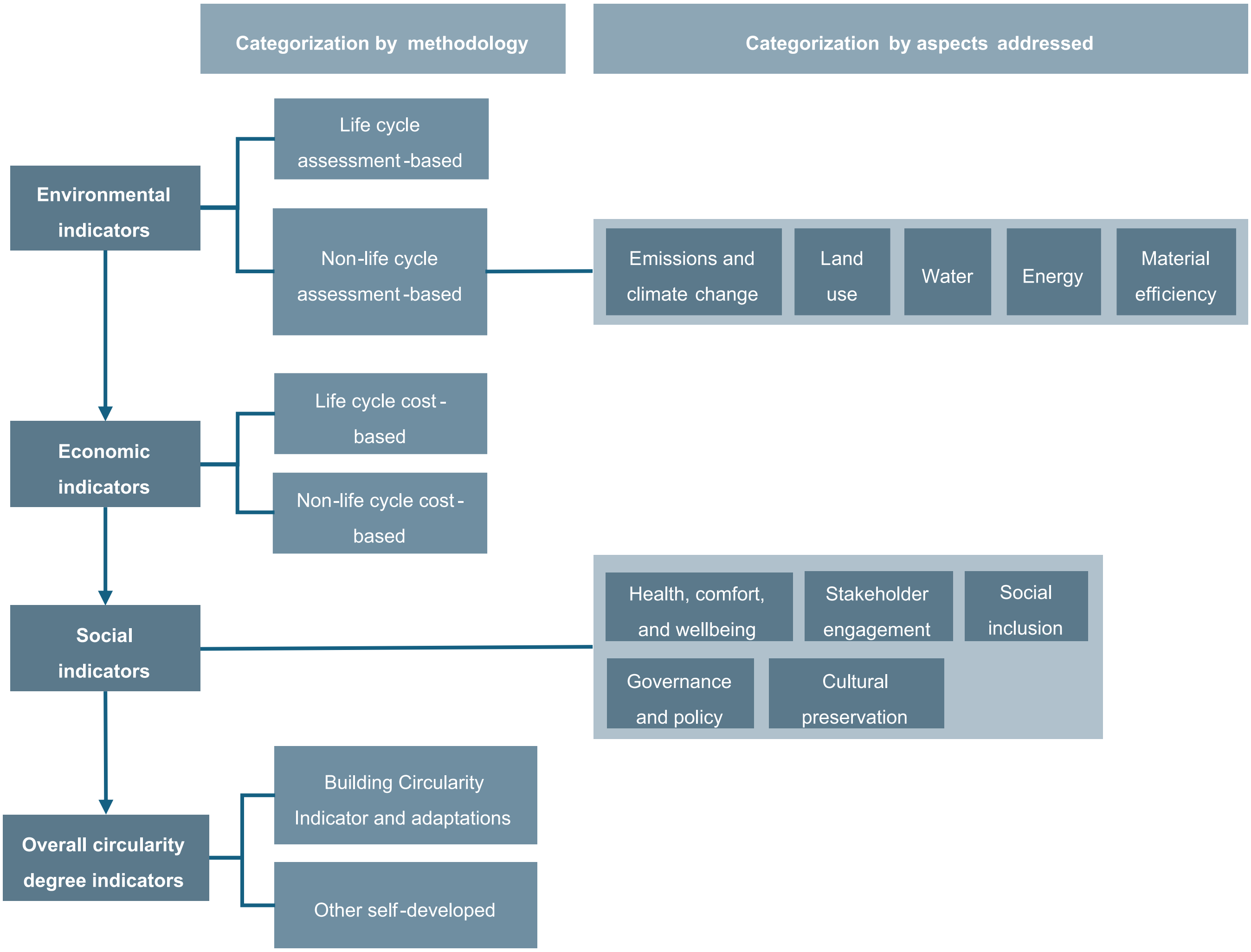

Fig. 5. Overview of the structure of the analysis of 148 quantitative indicators collected across reviewed studies.

farmland maintained or reduction in urban sprawl," "legally protected landscape area," "level of previous use of the site," "reduction in land use area due to adaptive reuse," "total area of new and recovered green land," "surface area covered with nature-based solutions," and "average amount of land needed for concrete production and debris association." Despite the diversity in indicators, the primary focus remains on applications at the building level, which may be influenced by data availability challenges at larger scales. Evaluating land use at broader spatial scales would provide more comprehensive insights into overall land use efficiency and urban planning. However, such assessments often require integrating multiple data sources, and data availability plays an important role in expanding beyond building-level assessments.

Water circularity has been recognized as part of circularity assessment. At the building level, two types of indicators measuring this aspect have been identified. The first type of indicators focuses on the amount of water, with several studies (Nocca and Angrisano, 2022; Roberts et al., 2023; Saadé et al., 2022) proposing basic indicators such as "use stage water consumption" and "onsite collected/stored/reused water volume," though without detailed calculation methods. The second type focuses on the circularity of water flows. González et al. (2021) introduced the "water circularity index," calculated as the ratio of circularly and on-site sourced water to total life-cycle water consumption (stages A-C). Similarly, Fagone et al. (2023) developed "water circularity rate," defined as the average of the circular water inflow rate and circular water outflow rate. Two indicators have been proposed at the regional level, focusing on the "water-use efficiency" and "proportion of domestic and industrial wastewater safely treated." While various indicators have been proposed for assessing the water aspect at both building and regional levels, most remain conceptual. These indicators lack calculation methods and tools, and application through case studies.

Indicators assessing the energy aspect of circular strategies have been identified across the three levels. At the building level, traditional indicators mainly address operational energy performance, including "annual operational energy consumption," "annual operational fuel consumption," and "annual heat gains and losses through surfaces." González et al. (2021) developed the "energy circularity index," assessing the percentage of total circular energy to total energy consumption throughout a building's life cycle (stages A-C), where circular energy is defined as the sum of renewable energy produced on-site or nearby and energy savings from both active and passive design strategies. While the majority of studies do not specify the tools used for energy modeling and simulation, building energy simulation tools such as DesignBuilder and TRNSYS18 have been applied (each in one study) to support these assessments (González et al., 2021; Honarvar et al., 2022). At the neighborhood scale, the focus shifts from individual energy demand to the interplay between operational demand and on-site renewable generation. This shift aligns with circular strategies applied at this scale, focusing on on-site renewable energy production and energy sharing within energy communities (Buildings Performance Institute Europe, 2022). Key indicators including "annual demand coverage ratio" and "annual renewable penetration ratio" have been proposed to assess the ratio of total self-consumed on-site renewable energy at each

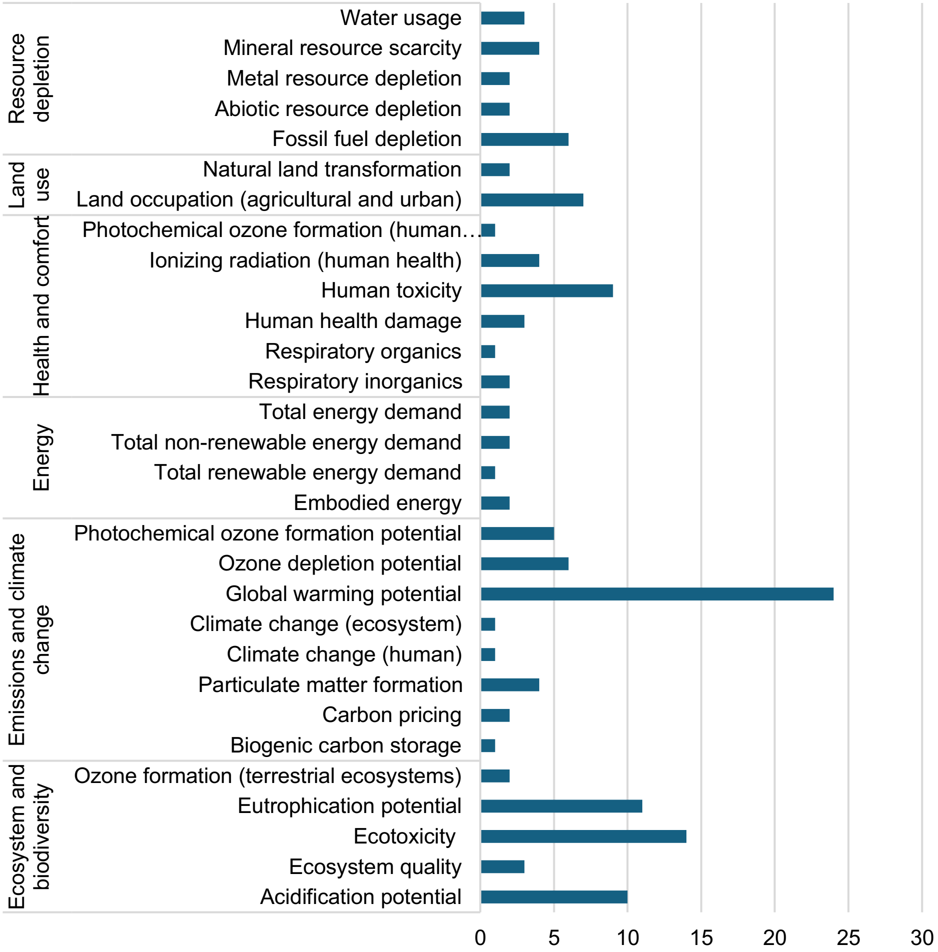

Fig. 6. Use intensity of LCA-based indicators within the reviewed studies.

time step to the total operational demand or total on-site renewable energy production. At the city scale and beyond, assessments prioritize total energy demand in the building sector and renewable energy generation capacity. For instance, Sevindik and Spataru (2023) applied building stock modeling using archetype-based approach to simulate regional building operational energy demand, while Su and Urban (2021) applied the LEAP tool to simulate the energy demand of the building sector at the city level. Furthermore, studies proposed renewable energy-related indicators at the city and beyond level, including “installed renewable energy-generating capacity in developing countries (in watts per capita)” (Huovila and Iyer-Raniga, 2021), “proportion of population with primary reliance on clean fuels and technology” (Huovila and Iyer-Raniga, 2021), and “renewable energy share in the total final energy consumption” (Cader et al., 2024; Huovila and Iyer-Raniga, 2021). It is worth noting that across the three scales, the assessment focus remains on operational energy. However, incorporating the evaluation of shared energy infrastructure at larger spatial scales (e.g., thermal and electrical networks at the neighborhood level) could provide a more comprehensive understanding of energy performance and support sustainable energy transitions.

The material efficiency aspect, further divided in three sub-aspects, namely material usage, waste generation, and circular flow connecting waste and materials, is covered by 26 % of the identified quantitative indicators. 15 indicators assess the first sub-aspect of material efficiency (i.e., material usage). They address material selection (i.e., the use of sustainable, locally sourced, renewable, and materials designed for disassembly, in the construction stage of buildings), total material consumption and savings, and transportation of materials. Additionally, 5 indicators have been identified to address the waste generation sub-aspect. Although with slight variations, they all aim to quantify the amount of construction and demolition waste generated as well as the share of specific waste types within the overall waste stream. The last sub-aspect of material efficiency (i.e., circular flow connecting waste and materials) is assessed by 19 indicators. These indicators evaluate the total mass of reused, recovered, or recycled materials both during construction and at the end-of-life stage of buildings. They also consider the share or rate of reuse, recovery, or recycling, whether through the integration of these materials into new construction or by assessing how much waste can be diverted from disposal. While the specific focus varies (whether they measure reuse, recycling, recovery, or a combination of these), all these indicators evaluate how effectively waste can be reintegrated into material flows, helping to close the material loop. In total, indicators addressing these three sub-aspects (i.e., material usage, waste generation, and circular flow connecting waste and materials) of material efficiency are distributed across the building (47 %), city and beyond (43 %), and neighborhood (10 %) scales. The circular flow sub-aspect is mainly evaluated at the building level, whereas indicators at the city and beyond scale more commonly focus on the material usage and waste generation sub-aspects. In terms of assessment methods, many studies focus on selecting and proposing indicators rather than detailing specific methods with clear spatial system boundaries. Temporal system boundaries vary significantly case by case, ranging from one year to 100 years. Among the identified methods, material flow analysis and input-output analysis are the most commonly applied. Building Information Modeling (BIM) is frequently applied for input data collection, as mentioned in 2 out of 18 related papers, along with others such as Eco2soft (1 paper) and One-Click LCA (1 paper). For final calculations, various tools have been used, including Python (applied in 1 paper), Excel (2 papers), and STAN 2.6 (1 paper). For instance, Honic and De Wolf (2023) applied the Excel templates provided by Level(s) to calculate the Level(s) indicator "2.1 bill of quantities, materials, and lifespans."

In addition to environmental indicators, a small proportion (10 out of 148) of quantitative indicators assess the economic impacts of circular strategies. Life-cycle cost-based indicators are the most frequently mentioned, including "net present value," "life cycle costs," "payback period," and "internal rate of return." Besides, economic indicators such as "cost saving due to reused materials," "direct material costs," and "waste management costs" have been assessed by Behúnová et al. (2023) using information retrieved from a BIM model at the building level. While some studies on economic indicators for circularity assessment focus on proposing and selecting indicators (5 out of 13 studies), the remaining studies (8 out of 13) apply them to case studies, though in most cases, a thorough description of the life cycle cost methodology (e.g., system boundary, functional unit) is lacking. In terms of assessment scale, the majority of economic indicators (7 out of 10) have been proposed for the building level.

13 out of 148 quantitative indicators assess the social dimension of circularity, with the majority (8 out of 13) focusing on health, comfort, and wellbeing. For instance, Nocca and Angrisano (2022) developed a framework to evaluate the cultural heritage regeneration projects, including 8 indicators assessing indoor air quality, thermal comfort, lighting and visual comfort, and occupant wellbeing, namely: "indoor ventilation rate," "indoor CO_2 concentration," "indoor particulate concentration," "indoor relative humidity," "useful daylight illuminance," "percentage of people feeling in a wellbeing condition inside the building," "time out of comfort range for the studied year," and "time out of comfort range in future year 2030." Apart from comfort and wellbeing, five other social indicators have been identified and categorized into three main areas: stakeholder engagement (represented by the "degree of diversity of stakeholders involved as co-producers of services"); social inclusion and community participation (measured by the "degree of diversity of community groups involved as users," the "number of associations, volunteers, and cooperative enterprises related to functional reuse projects," and the "proportion of the urban population living in slums, informal settlements, or inadequate housing"); and governance and policy (assessed through the "number of countries with nationally determined contributions, long-term strategies, national adaptation plans, and adaptation communications"). These indicators are quantified using either the total number of relevant entities or the percentage of the affected population. Furthermore, four indicators address the cultural dimension. This includes indicators such as the "legally protected cultural heritage buildings in m^2" (though the unit is not specified as total floor area or building footprint), "number of cultural sites and landmarks," "share of general government expenditure for cultural services," and "Cultural and Creative Cities Monitor index score," with the latter being calculated from data extracted from monitoring (Foster and Saleh, 2021). It is important to note that the number of indicators does not imply that social, socio-economic, and cultural aspects are less important for circularity assessment. Rather, the difficulty lies in quantifying these dimensions, which is why many indicators remain either semi-quantitative or qualitative. Furthermore, these indicators are not used individually for circularity assessment; instead, they are integrated into broader indicator frameworks that collectively evaluate circularity, as described in detail in Sections 3.1.3 and 3.1.4.

While the majority of quantitative indicators focus on one specific aspect of circularity, 17 out of 148 indicators assess the overall circularity degree at the building level integrating several aspects. Among these, nearly half are related to the Building Circularity Indicator (BCI). The Ellen MacArthur Foundation developed the Material Circularity Indicator (MCI) (Goddin et al., 2019) to measure the circularity at the product and company levels, considering virgin material input, uncoverable waste output, use intensity and service life. This MCI has subsequently been applied in the built environment (Honarvar et al., 2022; Saadé et al., 2022), evaluating the material circular flow of buildings and urban projects. Verberne (2016) was the first to introduce the BCI based on the MCI. The BCI is based on a four-step assessment. First, the virgin material input, uncoverable waste output in mass, use intensity, and service lifetime are considered for MCI calculation. Second, the MCI is aggregated through a weighted sum method to calculate the Product Circularity Indicator (PCI). The weights are obtained from the design-for-disassembly (DfD) score, determined based on pre-defined design criteria scoring tables related to the type of connection, connection accessibility, independency, and geometry of product edge. Third, the PCI is aggregated into the System Circularity Indicator (SCI) using mass share as weights. Fourth, the SCI is further aggregated into the BCI by weighting the importance of each building layer, determined through expert interviews and questionnaires. Even though the BCI is not a standardized metric for building-level circularity assessment, it has been extensively applied and several adaptations and modifications of the original BCI concept have been made, including the BCI of Alba Concept (BCI Gebouw, 2022), the Predictive BCI (PBCI) (Cottafava and Ritzen, 2021), the Predictive Building Systemic Circularity Indicator (PBSCI) (Antwi-Afari et al., 2022), the Whole Building Circularity Indicator (WBCI) (Khadim et al., 2023), and the Level of Circularity (LoC) (Braakman et al., 2021). The BCI of Alba Concept modified the original BCI to assess circularity across four levels: material, product, element, and building. The Whole Building Circularity Indicator (WBCI) (Khadim et al., 2023) expands the material scope by including not only the mass that ends up as product but also materials used during construction, maintenance, and repairs. The Level of Circularity (LoC) (Braakman et al., 2021) incorporates bio-based materials and recycling efficiency in the assessment of circularity. For a comprehensive understanding of these adaptations, the detailed formulas of these indicators can be found in Supplementary material B. In general, although these adaptations vary in the material input, internal levels, and application level of weights, they all share the same core concept of BCI. Additionally, studies (Cottafava and Ritzen, 2021; Shin and Kim, 2024) integrate environmental impacts into the calculation of BCI and PBCI by replacing the material input in mass with its environmental impacts such as global warming potential, embodied energy, and eutrophication potential. This integration shifts the focus from material quantity to the associated environmental impacts, allowing the BCI and PBCI to also reflect environmental considerations. Rather than focusing on modifications and adaptations of BCI, studies (Fernandes et al., 2022; Göswein et al., 2022; van der Zwaag et al., 2023) explore the use of BIM to enable an automated workflow to calculate BCI, through the development of databases for data input and BIM plugins.

Apart from the BCI and its adaptations, several studies have developed alternative indicators for building-level circularity assessment. Among these, the Technical Circularity Degree (Zhang et al., 2021), Express Building Circularity Indicator (EBCI) (Mazzoli et al., 2022), Madaster Circularity Indicator (Heisel and Rau-Oberhuber, 2020), and Circular Construction Indicator (Anastasiades et al., 2023) all include similar input parameters to the MCI, such as virgin material input, unrecoverable waste output, and DfD. However, their calculation formulas differ significantly, leading to distinct outputs despite relying on comparable foundational inputs. Some of these indicators adopt a more segmented approach, focusing on specific aspects of circularity for different life cycle stages. For example, the Madaster Circularity Indicator (Heisel and Rau-Oberhuber, 2020) evaluates circularity separately for the construction, use, and end-of-life (EoL) stages, while the Circular Construction Indicator (Anastasiades et al., 2023) assesses circularity separately for the design, construction, and EoL phases. Other studies have developed specialized indicators tailored to narrower objectives. Roithner et al. (2022), for instance, introduced the Relative Product-Inherent Recyclability indicator, which evaluates a building's inherent recyclability during the design phase. Similarly, O'Grady et al. (2021) proposed the 3DR indicator, a weighted sum that accounts for disassembly, deconstruction, and circular material flows. Moving beyond the widely applied deterministic calculation methods, Lei et al. (2022) introduced the Probabilistic Circular Economy Index (PCEI), which applies probabilistic modeling to integrate the MCI with embodied energy and carbon. These variations, whether in calculation formula, methodological approach (deterministic or probabilistic), life stage coverage, or parameter weighting, show the diversity in self-developed building-level circularity assessment indicators.

In summary, a total of 148 quantitative indicators have been identified for circularity assessment. The following Sections 3.1.2.2, 3.1.2.3, and 3.1.2.4 will provide a detailed analysis of how these quantitative indicators are applied in circularity assessment: as a single indicator for a single result, as a composite indicator for a single result, and as part of a multi-indicator framework for multiple quantitative results.

3.1.2.2. Single indicators. The first approach applies a single indicator for circularity assessment (applied by 14 % of the total reviewed studies), assessing only one specific aspect of circularity. For instance, Hoxha et al. (2022) calculated a single indicator, the global warming potential, to evaluate the benefits of a circular strategy (i.e., wood reuse in building) compared with traditional building construction solutions. An overview of the single-indicator assessment method is provided in Table 1. This single-indicator approach covers six indicators and provides valuable insights into a specific aspect of circularity, ranging from emissions to material efficiency (i.e., material usage and waste management). Although this approach is straightforward for evaluating and comparing circular strategies, its reliance on a single indicator fails to consider circularity assessment as a multi-criteria problem.

3.1.2.3. Composite indicators. The composite indicator-based approach applies a composite indicator for circularity assessment, and this approach is applied in 15 % of the total reviewed studies. Table 2 provides an overview of how this approach has been applied across the reviewed studies. Eight composite indicators have been found, and a significant portion of these composite indicators is based on the Building Circularity Indicator (BCI) and its adaptations. Five key aspects of circularity are commonly addressed, including material efficiency, lifetime and use intensity, design-for-disassembly (DfD), emissions, and energy. The first three aspects are the most frequently assessed, while emissions and energy considerations can be integrated into the calculation of the circular degree of material flows. This composite indicator-based approach considers circularity assessment as a multi-criteria problem and aims to integrate more than one aspect. This approach supports the decision-making process by allowing for easy comparison of final composite indicator scores. However, this approach has limitations. The composite indicators are not comprehensive enough to cover all critical aspects of circularity and may overlook key dimensions (Khadim et al., 2023; Lei et al., 2022; Roithner et al., 2022). Furthermore, although the formulas used to integrate several key aspects into one composite score have been defined, the interrelationships of the integrated aspects are still not well understood. For instance, it is unclear whether a significant improvement in one aspect, such as material efficiency, would lead to a proportional improvement in others. This makes it challenging to determine how to adapt these indicators to the subject of the assessment, where, for instance, the energy aspect may be significantly more critical than material efficiency, requiring a tailored assessment focus.

Table 1
Overview of single indicators for circularity assessment.

Reference	Application	Name of single indicator	Aspect addressed
Hoxha et al. (2022)	Building	Global Warming Potential	Emissions
Gravagnuolo et al. (2020)	Building	Global Warming Potential	Emissions
Dsilva et al. (2023)	Building	Global Warming Potential	Emissions
Ahn et al. (2023)	Building	Global Warming Potential	Emissions
Del Borghi et al. (2022)	City	Greenhouse Gas Emissions	Emissions
De Silva et al. (2023)	Building	Overall Circularity	Material efficiency
Sun et al. (2022)	Building	Recycling Potential	Material efficiency
Lederer et al. (2020)	City	Mass of Raw Materials Saved	Material efficiency
Ratnasabapathy et al. (2020)	Country	Waste Diversion Rate	Material efficiency

3.1.2.4. Multi-indicator frameworks. Multi-indicator frameworks are the most commonly used approach (applied by 45 % of the total reviewed studies) for quantitative circularity assessment in the built environment. This approach consists of a set of quantitative indicators aiming to evaluate different aspects of circularity. A total of 30 multi-indicator frameworks have been found. Although most studies did not specify the methods used to develop their assessment frameworks, several recurring approaches can be identified. Four studies (Cader et al., 2024; Foster et al., 2020; Hosseini et al., 2023; Papadaki et al., 2022) conducted reviews of existing scientific literature, policy documents, and national targets to collect relevant indicators and tools. Expert interviews and questionnaire surveys were used in three frameworks (Balasbaneh and Sher, 2024; Cader et al., 2024; Huovila and Iyer-Raniga, 2021) to support the selection of indicators. Additionally, four studies incorporated case studies (Hosseini et al., 2023; Papadaki et al., 2022; Saadé et al., 2022; Shin and Kim, 2024) to test and validate the developed assessment frameworks.

The number of indicators incorporated in each framework varies widely, ranging from 2 to 21, with 14 out of 30 frameworks using more than 10 indicators at the same time. When the number of indicators increases, it may be challenging to compare them and to prioritize design strategies. One potential solution to this challenge is the aggregation of multiple indicator values into a single score through methodologies such as the multi-criteria decision-making (MCDM) method, which assigns weights to each indicator.

Table 3 summarizes the number of indicators included in each framework and the specific aspects addressed. In some cases, multiple indicators address the same aspect; the corresponding number of indicators is shown in brackets. Additionally, some frameworks include composite indicators that cover multiple aspects, resulting in more check marks than indicators, as one indicator may span multiple categories. As a result, the number of check marks does not always match the number of indicators.

A total of 20 aspects have been identified to address five dimensions: environmental, economic, social, technical, and managerial. As previously mentioned, while some frameworks address each aspect with one single or composite indicator, others apply multiple indicators to assess a single aspect, particularly within the environmental dimension. For instance, the material efficiency aspect is assessed by a maximum of 14 indicators. Behúnová et al. (2023), for example, applied 6 indicators, namely "material consumption," "waste production," "reused material rate," "direct material costs," "cost saving due to reused material," and "waste management costs" to assess material efficiency and cost-related aspects. While three of these indicators are cost-related, they capture complementary information of the aspect, each providing a distinct insight into cost efficiency.

The top three most assessed aspects by the multi-indicator approach are emissions (assessed by 22 related frameworks), material efficiency (21), and energy (13). The frequent assessment of emissions can be partly attributed to the availability of standardized methods, such as

Table 2
Overview of composite indicators for circularity assessment.

Reference	Name of composite indicator	Application	Aspect addressed				
			Material efficiency	Lifetime & use intensity	Design-for-disassembly	Emissions	Energy
Gomes et al. (2022)	Building Circularity Indicator	Building	✓	✓	✓		
Fernandes et al. (2022)	Building Circularity Indicator	Building	✓	✓	✓		
Göswein et al. (2022)	Building Circularity Indicator	Building	✓	✓	✓		
van der Zwaag et al. (2023)	Building Circularity Indicator of Alba Concept	Building	✓	✓	✓		
Khadim et al. (2023)	Whole-Building Circularity Indicator	Building	✓	✓	✓		
Mazzoli et al. (2022)	Express Building Circularity Indicator	Building	✓		✓	✓	✓
Lei et al. (2022)	Probabilistic Circular Economy Index	Building	✓	✓		✓	✓
Roithner et al. (2022)	Relative Product-Inherent Recyclability	Building	✓		✓		
O'Grady et al. (2021)	3DR	Building	✓		✓		
Heisel and Rau-Oberhuber (2020)	Madaster Circularity Indicator	Building	✓	✓			

LCA. Material efficiency aspect includes both material input and output. This shows that material flow is widely regarded as a critical component in circularity assessment and the importance of closing material loops within the circular built environment. Energy, another commonly assessed aspect, is primarily evaluated in terms of energy demand or consumption, which directly influences the operational performance of buildings. Conversely, the least assessed aspects are managerial and cultural aspects, which aligns with the limited number of indicators available for evaluating these aspects.

The multi-indicator frameworks offer more transparency compared to a composite indicator-based approach, as they allow the performance of individual aspects to be assessed and interpreted separately. This enables stakeholders to pinpoint specific strengths and weaknesses of circular strategies across various aspects of circularity. However, the correlations (e.g., synergies or trade-offs) between indicators within the same frameworks are poorly understood. For example, it is unclear whether improved performance in material efficiency (e.g., a higher value in the BCI indicator) corresponds to lower or higher life cycle costs. Among the identified multi-indicator frameworks, only Braakman et al. (2021) investigated the correlations between assessed indicators, specifically the life cycle costs (LCC) and the level of circularity (LoC). The findings revealed that a higher LoC does not necessarily lead to higher LCC. When assessing and comparing multiple indicators for various design strategies to select the best alternative, understanding the correlations between indicators can reduce the complexity in the comparison process.

3.1.3. *Semi-quantitative indicators*

In addition to the quantitative indicators discussed above, a total of 160 semi-quantitative indicators have been identified. These indicators offer an important complementary approach, particularly for dimensions (e.g., social and cultural) that are complex and challenging to quantify using existing methodologies and tools. A total of 89 out of 160 semi-quantitative indicators are assessed through binary scoring while the rest (71 indicators) are evaluated using ordinal scoring. Based on whether the criterion is met or not, semi-quantitative indicators are assigned a score of either 1 or 0 by the binary scoring system. In terms of ordinal scoring, a score is assigned based on a pre-selected scoring scale. For example, Tokazhanov et al. (2022) developed a circularity assessment tool for construction projects, where the semi-quantitative indicator "design for deconstruction" is assessed by having experts and workers assign scores on a 0-to-5 scale. Various ordinal scoring scales have been applied across studies, such as 5-point, 3-point, and 2-point systems. However, it is often unclear what each score level represents (e.g., whether to assign 2 points or 3 points), as well as the specific thresholds that distinguish one level from the next. This may also explain why these indicators were developed by authors for application in their own case studies and are rarely adopted by other researchers. Well-defined scoring criteria are essential for the re-applicability of semi-quantitative indicators.

The breakdown of semi-quantitative indicators by categories is shown in Fig. 7. The design aspect is the most frequently assessed, including sub-aspects such as design-for-adaptability, design-for-disassembly, design-for-deconstruction, design-for-simplicity, and design-for-longevity. Material efficiency is the second most frequently assessed aspect, focusing on sub-aspects such as material usage, waste generation, as well as reuse, recycling, and recovery. Although the environmental dimension (e.g., energy, water, waste, emissions, and material use) is easily quantified and can be assessed by quantitative indicators, the semi-quantitative approach has also been applied to this dimension. For instance, the water sub-aspect is assessed using the semi-quantitative indicator "reducing external water use" on a 0–3 scoring scale by Nocca and Angrisano (2022). Other assessed aspects include the cultural dimension such as cultural heritage preservation and value creation, managerial dimension (e.g., business models, data management, skills training, awareness), social aspect (e.g., social inclusion, health and comfort), and construction (e.g., modular and prefabricated components).

Semi-quantitative indicators are applied within a semi-quantitative assessment framework, which consists of a set of semi-quantitative indicators or a mix of quantitative and semi-quantitative indicators. A total of eight semi-quantitative assessment frameworks have been identified, as summarized in Table 4. Five studies (Dufrasnes et al., 2024; Foster and Saleh, 2021; Gillott et al., 2023; Nocca and Angrisano, 2022; Tokazhanov et al., 2022) used reviews of literature and existing evaluation tools as a starting point for framework development. Four studies (Dufrasnes et al., 2024; Gillott et al., 2023; Gravagnuolo et al., 2024; Tokazhanov et al., 2022) applied participatory methods, including expert interviews, surveys, co-creation workshops, and focus groups to integrate the knowledge and perspectives of stakeholders and experts in the development process. Additionally, six of the eight frameworks (Dufrasnes et al., 2024; Foster and Saleh, 2021; Gillott et al., 2023; Gravagnuolo et al., 2024; Nocca and Angrisano, 2022; Tokazhanov et al., 2022) were tested and refined through application in case studies.

Based on the stage of framework development, these frameworks are categorized into four distinct phases, including identification of indicators, quantification, weighting calculation, and aggregation. Two semi-quantitative frameworks (Dufrasnes et al., 2024; Nocca and Angrisano, 2022) include only the indicator identification and quantification processes using self-defined scoring systems. Six frameworks (Dams et al., 2021; Foster and Saleh, 2021; Gillott et al., 2023; Gravagnuolo et al., 2024; Scialpi et al., 2022; Tokazhanov et al., 2022) further include the calculation of weighting for indicators; however, most of them do not specify the methods used. Only one (Gravagnuolo et al., 2024) applies the Technique for Order Preference by Similarity to

Table 3

Overview of multiple quantitative indicators for circularity assessment. The "Number of indicators" column shows the total number of indicators reported for each framework. Check marks indicate which aspects are addressed (when more than one indicator is used to measure the same aspect, the number is included in the brackets) (Al-Obaidy et al., 2021; Bherwani et al., 2022; Boeri et al., 2018; Cui, 2022; Kootstra et al., 2019; Ritzen et al., 2019; Song and Zhou, 2023; Tanthanawiwat et al., 2024).

			Environmental						Economic			Social						Technical				Managerial
Reference	**Application**	**No. indicators**	Emissions & atmosphere	Material efficiency	Ecosystem & biodiversity	Energy	Water	Resource depletion & land use	Return on investment	Cost-related	Macro-economic performance	Cultural conservation	Social & community development	Social inclusion	Health & comfort	Demographics	Policy & governance	Lifetime & use intensity	Design-for-disassembly	Design-for-adaptability	Other design & construction	Business model & innovation
(Braakman et al., 2021)	Building	2		✓					✓													
(Honic and De Wolf, 2023)	Building	2		✓(2)																		
(Bherwani et al., 2022)	City	2	✓	✓																		
(Anastasiades et al., 2023)	Building	3		✓														✓	✓			
(Ritzen et al., 2019)	Building	3	✓			✓				✓												
(Kayaçetin et al., 2023)	Building	3	✓	✓						✓												
(Cottafava and Ritzen, 2021)	Building	3	✓	✓		✓												✓	✓			
(Zhang et al., 2021)	Building	3	✓	✓						✓								✓	✓			
(Su and Urban, 2021)	City	3	✓		✓	✓																
(Kootstra et al., 2019)	Region	3		✓(2)				✓														
(Al-Obaidy et al., 2021)	Building	4	✓	✓															✓	✓		
(Song and Zhou, 2023)	Neighborhood	4	✓			✓(2)			✓													
(González et al., 2021)	Building	5		✓		✓	✓		✓				✓									
(Behúnová et al., 2023)	Building	6		✓(3)						✓(3)												
(Balasbaneh and Sher, 2024)	Building	7	✓		✓(2)	✓		✓		✓					✓							
(Cui, 2022)	City	8		✓(6)							✓					✓						
(Hosseini et al., 2023)	Building	10	✓(3)		✓(3)			✓							✓(3)							
(Tanthanawiwat et al., 2024)	Building	11	✓(2)	✓	✓(4)			✓(3)		✓								✓				
(Honarvar et al., 2022)	Building	11	✓(4)	✓	✓(2)	✓(3)		✓										✓	✓			
(Fagone et al., 2023)	Building	12		✓(8)		✓	✓	✓(2)														
(Cader et al., 2024)	Region	12	✓	✓(6)		✓(2)															✓(3)	
(Shin and Kim, 2024)	Building	14	✓(6)	✓(14)	✓(4)			✓(2)										✓(14)	✓(14)			
(Huovila and Iyer-Raniga, 2021)	Global	14	✓	✓(4)		✓(3)	✓(2)									✓	✓(3)					
(Saadé et al., 2022)	Building and neighborhood	15	✓(2)	✓(4)	✓(5)	✓	✓	✓							✓							
(Antwi-Afari et al., 2022)	Building	16	✓(4)	✓	✓(5)	✓		✓(2)							✓(3)			✓	✓			
(Boeri et al., 2018)	Neighborhood	16	✓(2)	✓(5)				✓	✓				✓(4)	✓(2)								✓
(Papadaki et al., 2022)	Building	17	✓(5)		✓(6)			✓(5)							✓							
(Roberts et al., 2023)	Building	18	✓(4)		✓(7)		✓	✓(3)							✓(3)							
(Foster et al., 2020)	Building	20	✓(3)	✓(4)	✓(3)	✓(4)	✓(3)	✓(2)				✓										
(Sevindik and Spataru, 2023)	Region	21	✓(5)		✓(6)		✓	✓(5)		✓(3)					✓							

Ideal Solution (TOPSIS) method. Furthermore, five assessment frameworks (Dams et al., 2021; Foster and Saleh, 2021; Gillott et al., 2023; Scialpi et al., 2022; Tokazhanov et al., 2022) proceed to aggregate all quantified indicators into a single score based on the calculated weighting.

Regarding assessment methods, four frameworks applied a single method, replying on either ordinal scoring or binary scoring. These approaches are useful in contexts where quantitative data is limited. The other four frameworks, which consist of a mix of quantitative and semi-quantitative indicators, used a combination of methods. They combined ordinal scoring with quantitative data, obtained through methods such as calculations (e.g., LCA) or empirical monitoring.

The number of indicators included in the analyzed semi-quantitative frameworks varies widely, ranging from 2 to 86. Gillott et al. (2023) developed the Regenerate framework, which consists of 86 semi-quantitative indicators. The high number of indicators is due to the framework's comprehensive approach, assessing circularity across five building layers (i.e., site, structure, skin, services, and space). Each layer requires specific considerations regarding design-for-adaptability, design-for-disassembly, and material efficiency. Through self-assessment, each semi-quantitative indicator is assigned one credit if the corresponding criterion is met, and the total credits are summed to obtain the final circularity score. Regarding the aspects covered, a total of 20 aspects have been identified as shown in Table 4. Each framework can cover a maximum of 12 aspects, with at least half of these frameworks addressing six or more. Material efficiency is a fundamental aspect addressed by all semi-quantitative assessment frameworks. Furthermore, there is an increasing focus on integrating cultural conservation and managerial (i.e., skills, awareness, and knowledge) aspects.

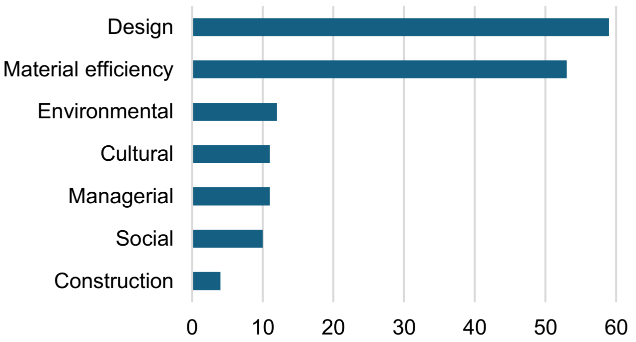

Fig. 7. Breakdown of semi-quantitative circularity assessment indicators by categories and their use intensity.

Semi-quantitative frameworks are developed by different authors and are rarely re-applied by other researchers, even within similar contexts. A key challenge is the lack of consensus on semi-quantitative indicators and self-defined scoring systems for quantification. Different frameworks use varied scales to assign scores, and there is limited transparency regarding the methodologies used in developing these scoring systems, such as whether stakeholder consultations are involved in the process. This issue is also identified in the scoring methodologies used for renewable energy assessments within green building and neighborhood rating systems by Zhang et al. (2019). The absence of clear guidelines for indicator selection and scoring makes it challenging to establish frameworks that can be broadly adopted and adapted to different cases and contexts.

3.1.4. Qualitative indicators

In addition to quantitative and semi-quantitative indicators, 152 qualitative indicators have been identified. While semi-quantitative indicators attempt to translate qualitative criteria into measurable values through scoring systems, qualitative indicators are further divided into two types. The first type consists of 115 indicators proposed by researchers to conceptualize circularity assessment. However, they lack specific assessment methods and they are not applied to case studies for qualitative evaluation. Instead, they serve as theoretical framework to identify or suggest the criteria and sub-criteria that should be included in circularity assessment. The second type includes 37 indicators assessed using non-numerical scales. Tools such as questionnaires and self-assessment tables have been applied to evaluate these indicators through various qualitative scales, including binary options (i.e., yes/no) in two studies, agreement levels (i.e., agree/neutral/disagree) in one study, and level of intensity (i.e., very high/high/medium/low/very low) in two studies. In this case, there is a possibility to transform these qualitative indicators into semi-quantitative by assigning numerical values to non-numerical scales. However, ensuring consistence to avoid misinterpretation is still challenging. Indeed, both types of qualitative indicators are proposed by individual authors and are rarely re-applied or adopted by other researchers. This lack of consensus has resulted in a wide variety of qualitative indicators with limited use intensity, hindering both their applicability and comparability.

Figure 8 presents the various aspects addressed by qualitative indicators. Similar to semi-quantitative indicators, the top assessed is related to design aspects. Additionally, qualitative indicators place great importance on the social aspect, and this includes sub-aspects such as health and comfort, accessibility, community benefits, social cohesion, and community-building. The other widely assessed aspects are the environmental and managerial aspects, including new business models (e.g., product-as-service), planning, skills/knowledge/awareness development, data management, and innovative technologies (e.g.,

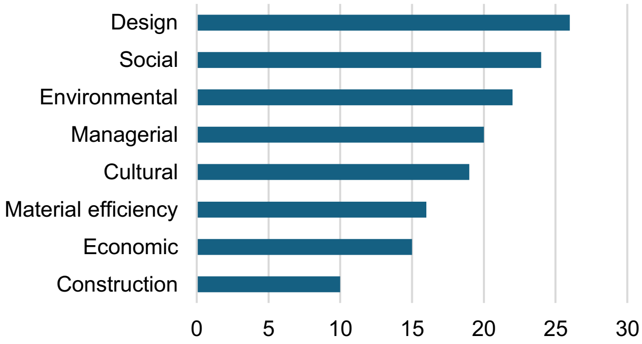

Fig. 8. Breakdown of qualitative circularity assessment indicators by categories and their use intensity.

Table 4
Overview of semi-quantitative frameworks for circularity assessment. The “Number of indicators” column shows the total number of indicators reported for each framework. Check marks indicate which aspects are addressed (when more than one indicator is used to measure the same aspect, the number is included in the brackets).

Reference	Application	Framework development				Assessment method	No. indicators	Environmental					Economic			Social						Technical				Managerial	
		Indicator identification	Quantification	Weighting calculation	Aggregation			Emissions & atmosphere	Material efficiency	Ecosystem & biodiversity	Energy	Water	Return on investment	Cost-related	Job creation	Cultural conservation	Social & community development	Social inclusion	Health & comfort	Demographics	Policy & governance	Lifetime & use intensity	Design-for-disassembly	Design-for-adaptability	Other design & construction	Business model & innovation	Skills, awareness & knowledge
(Dufrasnes et al., 2024)	Building	✓	✓			Ordinal scoring, quantitative data	5	✓	✓(2)					✓													✓
(Nocca and Angrisano, 2022)	Building	✓	✓			Ordinal scoring, quantitative data	37	✓	✓(3)		✓(2)	✓(3)		✓	✓	✓(14)	✓(2)	✓	✓(9)								
(Gravagnuolo et al., 2024)	Building and neighborhood	✓	✓	✓		Ordinal scoring, quantitative data	20	✓	✓	✓(2)	✓	✓	✓(3)		✓	✓(2)	✓(2)	✓(3)								✓	✓(2)
(Dams et al., 2021)	Building	✓	✓	✓	✓	Ordinal scoring	14												✓				✓(3)	✓(4)	✓(6)		
(Foster and Saleh, 2021)	City	✓	✓	✓	✓	Ordinal scoring, quantitative data	15		✓							✓(7)				✓(2)	✓(3)					✓	✓
(Tokazhanov et al., 2022)	Building	✓	✓	✓	✓	Ordinal scoring	31		✓(9)		✓(4)	✓										✓(4)			✓(4)	✓(8)	✓
(Scialpi et al., 2022)	Building	✓	✓	✓	✓	Ordinal scoring	2		✓															✓			
(Gillott et al., 2023)	Building	✓	✓	✓	✓	Binary scoring	86		✓(43)														✓(19)	✓24)			

material passport). Cultural aspect is explored, focusing on the cultural value preservation and state of conservation of cultural heritage buildings. Others include material efficiency, the economic aspect, such as job creation and local return on investments, and construction (i.e., innovative construction methods such as off-site construction).

Qualitative indicators are never used alone for circularity assessments. Instead, they are typically applied within a qualitative assessment framework, which consists of a set of qualitative indicators. In total, 8 qualitative assessment frameworks have been identified, as summarized in Table 5. Similar to semi-quantitative frameworks, methods used for developing qualitative assessment frameworks include literature reviews, applied in 6 framework development (Abadi and Sammuneh, 2020; Amarasinghe et al., 2024; Bakos and Schiano-Phan, 2021; Bosone et al., 2021; Hasheminasab et al., 2022; Pelicaen et al., 2021), expert interviews, applied in 3 frameworks (Amarasinghe et al., 2024; Ikiz Kaya et al., 2021; Pelicaen et al., 2021), questionnaire surveys (2 frameworks) (Abadi and Moore, 2022; Amarasinghe et al., 2024), and case studies (2 frameworks) (Bakos and Schiano-Phan, 2021; Hasheminasab et al., 2022).

Based on the stage of framework development, we categorized these frameworks into three distinct phases, including identification of qualitative indicators, identification of correlations between indicators, and weighting calculation. Four frameworks (Abadi and Sammuneh, 2020; Bakos and Schiano-Phan, 2021; Bosone et al., 2021; Pelicaen et al., 2021) are in the early stages of development, focusing only on the identification of qualitative indicators through literature reviews and expert interviews, which serves as a foundational basis for further development. In addition to identifying qualitative indicators, one framework analyzes the correlations between indicators. Specifically, Ikiz Kaya et al. (2021) identified 23 qualitative indicators for assessing the adaptive reuse of heritage buildings, covering environmental, economic, social, technical, and managerial aspects. To evaluate these indicators, an online questionnaire was conducted, collecting 53 responses where participants rated their agreement (agree/disagree/neutral) with the indicators based on given cases. The results were analyzed using the Multiple Correspondence Analysis (MCA) to summarize the correlations among the indicators. For instance, when respondents agreed with the indicator "improved service life of the building," there was a high likelihood of agreement with the indicator "enhanced creativity and innovation," indicating a strong co-occurrence between them. Furthermore, three frameworks prioritize calculating the weighting of qualitative indicators to determine their relative importance. Various methods are used for this purpose, including the Analytic Hierarchy Process (AHP) (Abadi et al., 2021; Abadi and Moore, 2022; Hasheminasab et al., 2022), Combined Compromise Solution (CoCoSo) (Hasheminasab et al., 2022), Multiple Correspondence Analysis (Ikiz Kaya et al., 2021), and Fuzzy Analytic Hierarchy Process (FAHP) (Amarasinghe et al., 2024). Since qualitative assessment frameworks are still in the early stages of development, only one framework reported an assessment method. It applied a questionnaire-based approach, in which respondents were asked to indicate their level of agreement.

The number of indicators included in the analyzed frameworks varies widely, ranging from 12 to 40. However, the majority (6 out of 8 frameworks) consist of 12 to 23 indicators. Regarding the aspects covered, 20 aspects have been identified across five pillars, as shown in Table 5. Half of the frameworks can cover between 9 and 14 aspects. Notably, the material efficiency aspect is addressed across all frameworks, highlighting its importance in circularity assessment. There is a significant shift toward addressing the managerial dimension (i.e., business model and innovation, and skills, awareness, and knowledge), which is included in 6 out of 10 frameworks.

Similar to semi-quantitative frameworks, qualitative frameworks are typically developed by different authors and are rarely re-applied by other researchers. For instance, researchers developed their own qualitative frameworks for assessing the adaptive reuse of buildings (Bosone et al., 2021; Ikiz Kaya et al., 2021). One potential reason for this limited re-application is the varying development stages of these frameworks; most of them remain in the early phases and require future work for further development. For example, studies primarily focused on identifying indicators may need to explore methods for quantifying indicators. Another contributing factor is the lack of consensus in qualitative indicators. Authors typically develop their own indicators, resulting in a non-standardized and inconsistent process. This lack of standardization presents significant challenges in creating frameworks that can be easily adapted and re-applied to different cases and contexts.

3.1.5. Assessment across circularity dimensions

Following the detailed analysis of quantitative, semi-quantitative, and qualitative assessment methods, this subsection presents an integrated synthesis of how circularity dimensions, including environmental, economic, social, technical, and managerial, are addressed by identified indicators and frameworks. As illustrated in Fig. 9, the total number of studies addressing each dimension is presented by the grey line (corresponding to the right Y-axis). The environmental dimension is the most extensively addressed, with 62 studies including at least one environmental indicator. This is followed by the technical dimension, which is addressed in 29 studies. The economic and social dimensions are considerably less addressed, both appearing in 19 studies. The managerial dimension is the least addressed, with only 11 studies incorporating this dimension.

Table 5
Overview of qualitative frameworks for circularity assessment (when more than one indicator is used to measure the same aspect, the number is included in the brackets).

Reference	**Application**	**Framework development**			**No. indicators**	**Environmental**						**Economic**				**Social**				**Technical**				**Managerial**	
		Indicator identification	Correlation identification	Weighting calculation		Emissions	Material efficiency	Ecosystem & biodiversity	Energy	Water	Resource depletion & land use	Return on investment	Cost-related	Job creation	Economic growth	Cultural conservation	Social & community development	Social inclusion	Health & comfort	Lifetime & use intensity	Design-for-disassembly	Design-for-adaptability	Other design & construction	Business model & innovation	Skills, awareness & knowledge
(Pelicaen et al., 2021)	Building	✓			12		✓(2)														✓(4)	✓(3)	✓(3)		
(Abadi and Sammuneh, 2020)	Building	✓			12	✓	✓(5)													✓			✓(2)	✓(2)	✓
(Bakos and Schiano-Phan, 2021)	Neighborhood	✓			30	✓	✓	✓(4)	✓(2)	✓	✓			✓							✓(2)	✓(5)	✓(2)	✓(9)	✓
(Bosone et al., 2021)	Building	✓			40	✓(2)	✓(2)	✓(4)	✓	✓(2)		✓(2)	✓(2)	✓	✓(5)	✓(5)	✓	✓(5)	✓(6)					✓	✓
(Abadi et al., 2021; Abadi and Moore, 2022)	Building	✓		✓	12	✓	✓(5)														✓	✓	✓	✓(2)	✓
(Hasheminasab et al., 2022)	Building	✓		✓	16	✓	✓(3)		✓	✓			✓			✓	✓		✓(5)					✓	
(Ikiz Kaya et al., 2021)	Building	✓	✓		23		✓	✓(2)	✓(2)			✓		✓	✓(2)	✓	✓(4)	✓	✓	✓(2)		✓		✓(2)	✓(2)
(Amarasinghe et al., 2024)	Building	✓		✓	15		✓(5)														✓		✓(9)		

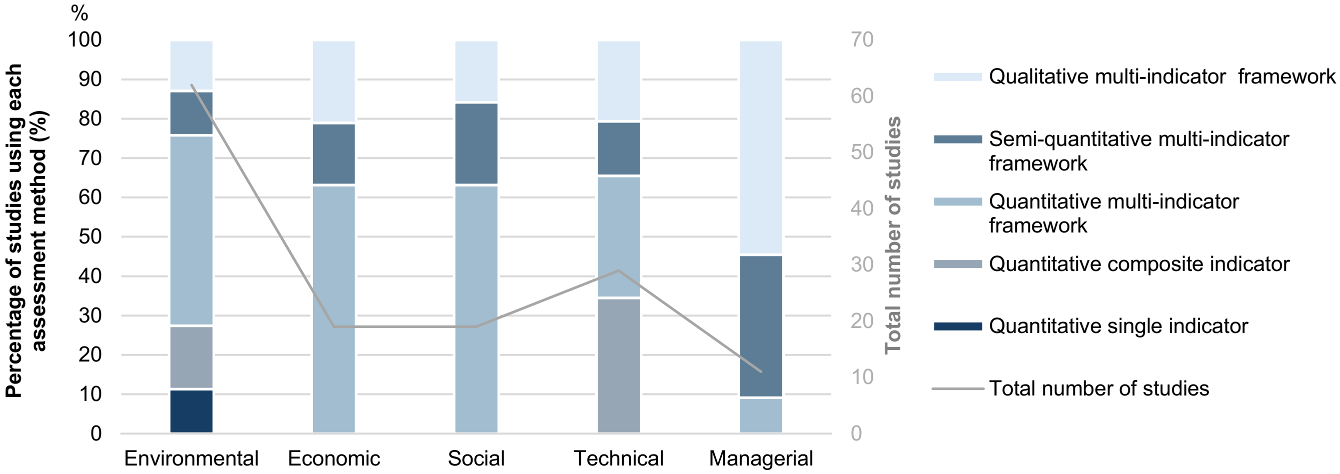

Fig. 9. Total number of studies (line graph, right Y-axis) addressing each circularity dimension and percentage distribution of assessment methods (stacked columns, left Y-axis) per circularity dimension.

The stacked columns in Fig. 9 show the percentage distribution of the different assessment methods applied to each dimension (corresponding to the left Y-axis). All five assessment methods have been applied to the environmental dimension, with the quantitative multi-indicator framework accounting for the largest share (48 % of all studies addressing this dimension). The technical dimension has been addressed by four of the five approaches, with quantitative methods (i.e., composite indicators and multi-indicator frameworks) applied in 65 % of the studies. The economic, social, and managerial dimensions have only been evaluated using three approaches: the quantitative multi-indicator framework, the semi-quantitative framework, and the qualitative framework. Among these, qualitative frameworks are the most frequently used approach for assessing the managerial dimension, accounting for 55 % of the total studies addressing this dimension.

Out of the 66 studies reviewed, the majority (60) focus on addressing only one to three circularity dimensions. Only five studies cover four dimensions, with four of these including the environmental, economic, social, and managerial dimensions, and just one study addresses all five. Among the six studies that assess four or more dimensions, only two (Gravagnuolo et al., 2024; Hasheminasab et al., 2022) apply weighting methods to determine the relative importance of each dimension. For instance, Hasheminasab et al. (2022) applied the Analytic Hierarchy Process to assign weighting not only to circularity dimensions but also to specific aspects within each. The results show that the environmental dimension is considered the most important, with a weighting of 0.48, followed by the economic dimension (0.39). In contrast, the social and managerial dimensions receive much lower weighting of 0.07 and 0.06, respectively. While these approaches compare and prioritize dimensions, the ways in which the dimensions influence one another remain unclear. For instance, managerial strategies, such as implementing circular economy training programs or raising awareness among employees and stakeholders, may also influence social outcomes, such as social inclusion and community engagement. Similarly, technical strategies, such as design-for-disassembly, can also have economic implications. Despite these potential interdependencies, assessment frameworks treat dimensions as separate components, without analyzing how changes in one dimension may enable or constrain progress in another. This reflects a significant gap in current circularity assessment methods: while efforts are made to incorporate multiple dimensions, their interactions are rarely explored in depth.

3.1.6. *Assessment across spatial scales*

This subsection investigates how different spatial scales have been assessed using quantitative, semi-quantitative, and qualitative methods. As illustrated by the grey line in Fig. 10, the total number of studies varies significantly across spatial scales. Most of the collected studies focus on the building level (51 studies), followed by city and beyond scales (11 studies), and the neighborhood scale (5 studies). The stacked columns in Fig. 10 further show the percentage distribution of studies using each assessment method per spatial scale.

At the building level, all five identified assessment methods have been applied. Among these, the quantitative multi-indicator framework is the most used method, accounting for 41 % of building-level studies, followed by the quantitative composite indicator approach, which represents 20 %. The remaining three methods, namely quantitative single indicator, semi-quantitative framework, and qualitative framework, each account for 12 % to 14 % of building-level studies. At the neighborhood scale, frameworks comprising multiple indicators, whether qualitative, semi-quantitative, or quantitative, are generally preferred. Notably, the quantitative multi-indicator framework method is the most widely applied, accounting for 60 % of the neighborhood scale studies, while both qualitative and semi-quantitative methods each represent 20 %. The city (and beyond) scale is assessed using the semi-quantitative framework, quantitative multi-indicator framework, and quantitative single indicator methods. The quantitative multi-indicator framework method is the most commonly applied (64 % of studies at this scale). The quantitative single indicator approach is the second most commonly used, accounting for 27 %. This is particularly noteworthy given that circularity assessment at larger scales often involves increased complexity, including integration of diverse urban systems (e.g., district heating networks) and the involvement of multiple stakeholders. Despite these complexities, the quantitative single-indicator method remains popular, likely due to its simplicity and ease of interpretation.

In conclusion, circularity assessment methods vary across spatial scales. While the building level is the most commonly studied, a range of fragmented methods has been applied. In contrast, the neighborhood and city and beyond scales are significantly less explored. This imbalance highlights the need for more targeted development and application of assessment methods at broader spatial scales to better support circular transitions at urban and regional levels.

3.2. *Policy recommendation*

This subsection outlines key considerations for policy recommendations. It is important to note that the keyword search was conducted prior to the publication of the ISO 59000 family of standards, the first set of international definitions and rules for the circular economy. As a result, none of the identified indicators explicitly referenced this newly released standard. The only widely cited standards among the reviewed quantitative indicators are ISO 14040 and ISO 14044, in the context of

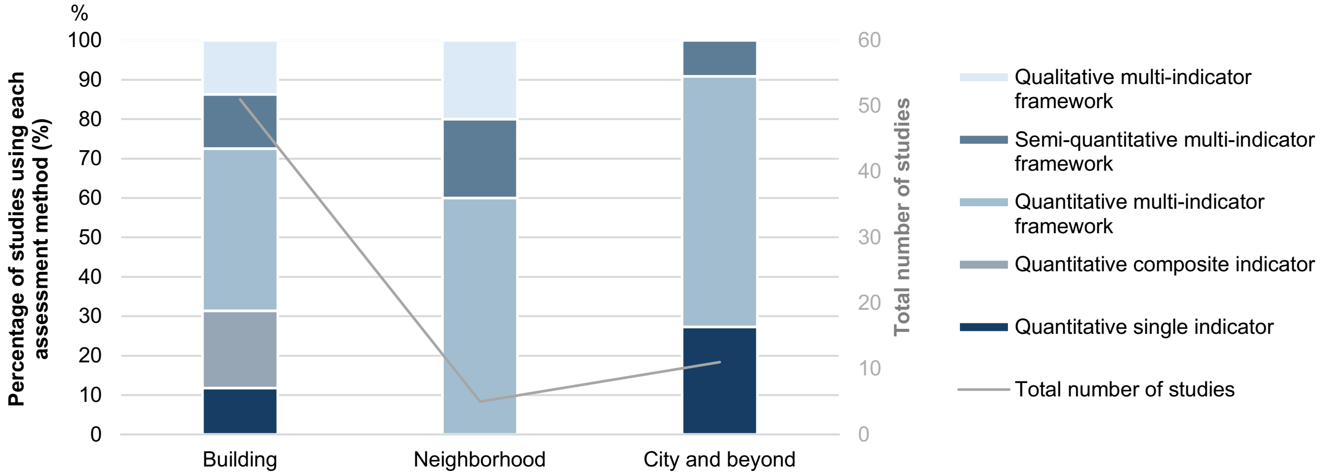

Fig. 10. Total number of studies (line graph, right Y-axis) and percentage distribution of assessment methods (stacked columns, left Y-axis) at each spatial scale.

LCA. This absence of a unifying framework, such as the ISO 59000 series, at the time likely contributed to the observed diversity in indicator development. To enhance consistency across future work, we recommend that policymakers actively promote the adoption of relevant international standards, particularly the ISO 59000 series, in both academic research and public-sector project evaluations.

There is a relatively low number of studies that focus on the reflections of circularity assessment on existing and future policies. Two studies (Cader et al., 2024; Foster et al., 2020) provided an analysis of existing policy documents on regional and global levels. Cader et al. (2024) reviewed 22 regional CE strategy plans published in the European Union (EU) between 2016 and 2021, which are currently in force in several member states, including Austria, Belgium, Finland, Italy, the Netherlands, Portugal, and Spain. Most of these CE strategy plans are cross-sectoral and only three of them do not include any indicators. Foster et al. (2020) aimed to develop a framework for adaptive reuse of cultural heritage and compare micro-level indicators with macro-level policy initiatives in the EU, such as EU resource efficiency scoreboard. There are two takeaways from these studies: (1) indicators included in EU policy documents are too narrow and a bottom-up approach is necessary, (2) the success of these policies depends on the integration of the CE model across consolidated socio-economic sectors and stakeholder engagement. Furthermore, two studies include semi-quantitative indicators addressing policy and governance (Foster and Saleh, 2021; Kayaçetin et al., 2023). Foster and Saleh (2021) presented an index designed to help policymakers and urban managers benchmark their cities. When rephrased, the EU requires a large scope of indicators that are consolidated in socio-economic sectors via co-creation with stakeholders. Then, there is also a need for integrating decision-support mechanisms to enhance this process.

The decision-making process for implementing CE principles in the built environment is a multi-criteria problem involving environmental, economic, social, technical, and managerial dimensions. However, current methods often neglect social and managerial dimensions, such as the BCI. Only a limited number of studies (Dams et al., 2021; Foster and Saleh, 2021; Gillott et al., 2023; Scialpi et al., 2022; Tokazhanov et al., 2022) incorporate several dimensions into a single index to support decision-making. This limitation is partly due to the lack of consistent, accessible, and well-structured data that captures these dimensions. To address this gap, policies should encourage the integration of circularity assessment data into structured repositories, such as building or material passports, to facilitate transparency and traceability. For example, the Madaster online platform (Heisel and Rau-Oberhuber, 2020) enables the generation and registration of materials passports and the calculation of a building-level circularity indicator. Supporting the adoption of such tools through regulatory frameworks would enhance the practical applicability of circularity assessments and support more informed, data-driven decision-making in a circular built environment.

To complement academic progress in circularity assessment, the development of policies that encourage the real-world application and testing of circularity indicators and aggregation methods is recommended. Several city-level case studies demonstrate how urban environments can serve as testbeds for circularity assessment. For instance, Bucci Ancapi et al. (2022) provided a review of policy instruments to develop a circular built environment toolbox. They highlighted the prominence of regulation levers (among other levers such as incentives, provisioning, and capacity building), which is considered a sign of immaturity of circular city development. They advise for exploration of missing dimensions in circular cities. On this front, several cities adopt a case study approach. Madhu and Pauliuk (2019) integrated LCA for the impact assessment of urban systems. Their study considered buildings as well as infrastructure in Masdar city for several impact categories on human health, ecosystem, and resources. In 'Karma' Interreg Project (Interreg Europe, n.d.), Hamburg city was utilized as a role model for circular cities. The project aims to improve housing and the restoration of buildings via improved business models, procurement, and governance of construction waste. Four implementations were planned: material reuse portals with a physical demonstration, eco-labeling process in HafenCity Living Lab, an interactive strategic discourse with workshops, and a pop-up circular hub for increasing publicity. The case studies display the need for a variety of indices and indicators to tackle circularity at an urban level. Drawing from these case studies, future policy frameworks should actively support pilot initiatives that enable the practical application and refinement of circularity assessment tools in real-world urban settings.

3.3. *Research limitations and future research directions*

3.3.1. *Limitations of the research*

A few limitations of this study can be highlighted. First, the scope of the review focuses on the building, neighborhood, and city (and beyond) scales. This focus was chosen because material-level assessments are often integrated within these broader spatial levels, particularly for evaluating material efficiency. However, a more detailed examination of how circularity is assessed at the material level could provide valuable insights, especially since different material types may require distinct end-of-life processes, recovery strategies, or reuse pathways. For example, Wiprächtiger et al. (2020) investigated thermal insulation materials by coupling dynamic and prospective material flow analysis with life cycle impact assessment to evaluate their environmental impact. Second, there is a possibility that not all relevant indicators and frameworks have been identified through this systematic literature review, as only peer-reviewed journal articles and conference papers were included to ensure source credibility. Existing grey literature, such as white papers, technical reports, and guidelines, has not been reviewed. The exclusion of these sources may limit the comprehensiveness of the findings, given that grey literature contributes to 19 % of the studies according to the critical review conducted by Khadim et al. (2022). Future research could benefit from incorporating grey literature more systematically, provided that robust and clear criteria are established for assessing the quality and credibility of different sources, such as the citation analysis suggested by Luukkonen (1990). Additionally, while this study excluded indicators related to infrastructure, such as bridges or roads, these indicators could provide valuable insights, particularly for circularity assessments at larger spatial scales. Future research should consider incorporating such indicators for a more comprehensive review.

3.3.2. Future research directions

Methodological fragmentation in circularity assessment of the built environment leads to incomparable results across varying contexts. This highlights the need for guiding instruments for circularity assessment in the built environment, such as standardized guidelines, to support (1) the selection of an appropriate indicator or set of indicators for specific contexts, for instance, based on project phase (e.g., design vs. decommissioning), geographic context, or circularity goals (e.g., closed-loop vs. regenerative systems) and (2) the implementation of circularity assessment results to bridge the gap between evaluation and actionable decision-making. The two proposed directions address different but related challenges arising from methodological fragmentation during circularity assessment of the built environment. First, there are no standards for indicator selection, which leads to different and often incomparable results of assessments across different studies and contexts. The need for a structure to support the selection of indicators specific to project conditions (e.g. project stages, including design, construction or demolition; spatial or socio-economic context; circularity target such as closed-loop material flows or regenerative systems) would allow for increased methodological consistency during assessments, but would also improve the comparability and relevance of assessment findings. Second, gaps could persist between the production of results and their use even though a robust assessment is undertaken. This highlights the need for tools and frameworks that support the translation of complex assessment outputs into actionable strategies. Such strategies may take various forms, such as integrating assessment findings into a decision-making statement, developing a policy, or creating a strategy (e.g. an operational plan), all of which ultimately support concrete actions. Together, these two directions constitute an integrated approach to the problem of methodological fragmentation: the first strengthens the rigor and context sensitivity of measurements, while the second ensures their operational utility and impact.

Hence, future research should focus on two main key directions. First, rather than developing entirely new circularity assessment methods, future efforts should be directed toward refining existing ones. Semi-quantitative and qualitative assessments should be further investigated and their scoring system validated through the use of practical case studies. Additionally, their application should be adapted to the less-explored neighborhood scale, and incorporate a more comprehensive multi-criteria circularity assessment system. Second, there is a the need for developing decision-making instruments to support the assessment process as well as the implementation of assessment results. This includes the possibility to select appropriate methods for circularity assessment based on contextual factors, such as key policy targets, urban and neighborhood features, end-user typologies and stakeholders' involvement. To address the first research direction, various studies to be conducted within the scope of the Urban-CoLLaR project (European partnership in Driving Urban Transitions, Grant Agreement No. 101069506) will highlight how circularity can inform urban regeneration strategies and promote broad-based adoption of circular solutions in a variety of urban settings. Furthermore, these studies will further develop the method based on practical case studies, exploring digital methods for real-time data integration, and strengthening policy recommendations to balance scientific knowledge with practical application. To address the second research direction, through a co-creation approach and the use of urban living labs, the project will develop a replicable and translatable decision support tool that municipalities and developers can use to tackle circularity in urban regeneration. The tools will help not only achieve key policy targets, such as carbon neutral and circular building stock targets for 2050, but also resilient, resource-efficient and socially inclusive cities. This approach includes the creation of the Attitudes Towards Circularity Questionnaire (ATCQ) to determine a baseline measure of stakeholders' attitudes and knowledge on circularity. For instance, the ACTQ results will be used for cluster analysis, thus identifying various end-user typologies and providing some insight into engagement approaches. In addition, cross-cultural validation will ensure comparability between findings across national contexts and facilitate the project's ability to contribute to more general policy and practice frameworks. In addition, expanding stakeholder engagement (especially with policy makers, local businesses, and civil society organizations) will be key to long-term impact and scalability in European cities.

In summary, future research should focus on developing and validating composite indices that demonstrate the capacity to aggregate multiple circularity indicators into a coherent and interpretable format. These indices can simultaneously represent the stakeholder's overall circularity performance, while also being able to be broken down into components (e.g. material efficiency, adaptability, life cycle) when necessary, particularly when developed with transparent aggregation techniques (e.g. weighted sums, multi-criteria decision analysis) (Wang et al., 2009). Methods for calculating relative weighting, such as Shannon Entropy and the CRiteria Importance Through Intercriteria Correlation, can be applied to determine the relative importance of a set of indicators, as demonstrated by Salah et al. (2023) in the context of sustainability assessment of construction projects. In addition, discussion of aggregation methods can clarify assumptions in circularity assessments and increase comparability of results and guidance across projects and geographies. Future research could also explore context-adaptive aggregation frameworks where the importance of indicators is context-adjusted (e.g. inputs are modified according to stakeholder priorities or project phases). Also, they need to be positioned to consider more material specific assessments, for example with regard to number, density or life cycle stage of material to provide more informative conclusions regarding reuse, recovery and environmental consequences.

4. Conclusions

To support the circular transition of the built environment, this study systematically reviewed 66 studies to investigate the existing circularity assessment methods in terms of indicators and frameworks for the built environment across three spatial scales, namely building, neighborhood, and city (and beyond) levels. A total of 148 quantitative, 160 semi-quantitative, and 152 qualitative indicators have been identified and analyzed. Their application for circularity assessment has been categorized as either a single quantitative indicator, a composite quantitative indicator, within a set of quantitative indicators, or semi-quantitative or qualitative assessment frameworks. In general, quantitative assessments are much more applied due to the availability of relatively well-established assessment methods of indicators, such as material flow analysis, building energy simulation, and LCA. In contrast, semi-quantitative and qualitative assessment frameworks remain in the early stage of development, hindered by methodological ambiguities, such as inconsistencies in the development of scoring systems.

Circularity dimensions addressed by existing indicators and frameworks include environmental (e.g., material efficiency, GHG emissions, energy), economic (e.g., return on investment), social (e.g., social inclusion, cultural value preservation), technical (e.g., design-for-disassembly, design-for-adaptability), and managerial (e.g., CE business model) dimensions. Among these, environmental aspects, particularly material efficiency and GHG emissions, are the most commonly addressed. In contrast, integrating social and managerial dimensions into quantitative assessments remains challenging due to the difficulty in measuring these impacts. Regardless of this variety, there is still a lack of knowledge regarding how different indicators and circularity dimensions interact and potentially trade off against one another. The lack of knowledge in these interrelationships creates significant challenges to the development of circular strategies that balance multiple dimensions of circularity.

Furthermore, circularity assessment methods vary significantly across scales. While the building level receives the most attention, the existing approaches are often fragmented. In contrast, the neighborhood and city and beyond scales are significantly less explored. This imbalance highlights the need for more targeted development and application of assessment methods at broader spatial scales to better support circular transitions at urban and regional levels.

Results highlighted the complexity of the state of the art in circularity assessment of the built environment due to the extensive number of indicators and their significant fragmentation, both individually and grouped in sets. This fragmentation complicates the indicator selection process during assessments, making it difficult to identify which indicators are most appropriate for specific contexts or scales. As a result, assessments risk being incomplete and inconsistent. This highlights the need for a comprehensive and centralized database of circularity indicators tailored to the built environment. This would enhance the comparability and transparency of circularity assessments and support the development of standardized assessment methods. In addition, few circularity assessment methods successfully incorporate decision-support mechanisms that effectively facilitate the decision-making process in prioritizing interventions and comparing alternatives. Approaches such as weighting and aggregation are recommended to reduce the complexity of the final results.

CRediT authorship contribution statement

Qiuxian Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Dirk Saelens:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Nuri Cihan Kayaçetin:** Writing – review & editing, Conceptualization. **Rengin Aslanoğlu:** Writing – review & editing. **Joost van Hoof:** Writing – review & editing. **Chiara Piccardo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT for proofreading. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

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.

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Appendices. Supplementary data

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