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Key indicators to assess construction supply chains from an environmental perspective: taxonomy and critical insights

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ABSTRACT

The construction industry heavily impacts the environment, with issues like resource use, emissions, and waste. Quantifying these impacts with suitable indicators is vital for sustainable development. Yet, selecting these indicators for construction supply chains is complex due to environmental system intricacies. Our study aims to address this by reviewing existing indicators and proposing a taxonomy. Through systematic literature review following PRISMA guidelines, indicators were extracted and a taxonomy with three categories (i.e., indicator type, assessment level, area) was developed. This research reveals a variety of indicator sets, aiding in evidence-based sustainability assessments for the construction sector.

1. Introduction

The impacts arising from the construction industry have frequently been looked at due to the important environmental consequences that the activities associated with this sector have. Construction supply chains are responsible for high levels of resource and energy consumption (34 % of energy demand in 2021), the emission of several harmful gasses (37 % of energy and process-related CO_2 emissions in 2021), as well as the production of high volumes of waste [1,2]. Recent studies indicated that emissions in the building sector are estimated at 17 % of global greenhouse gas emissions [3] and, while decarbonisation is high on the agenda of this sector, the UNEP has highlighted that it is not right on track to achieve the 2050 objectives [1].

Recent recommendations to improve sustainability in the construction sector have involved a stronger emphasis on the calculation and monitoring of environmental impacts by different stakeholders [2]. For governments, developing and deploying environmental regulations requires that the current state and potential impact of responses are well understood quantitatively. For businesses, making and implementing zero-emissions plans involves relying on evidence. For citizens, a better understanding of the impacts that their decisions have can help change their behaviour towards a more environmentally friendly one. Thus, there is a strong interest by different stakeholder groups in having quantitative evidence of the environmental impacts arising from the construction.

Therefore, given the significance of the impacts of construction supply chains and the need to evaluate them, it is essential to have metrics allowing stakeholders to measure and interpret the impact of construction supply chains on the environment. While the relationships between human behaviour and the environment are complex, the communication of the effects and the development of appropriate policies to mitigate them demand that easy-to-understand indicators are available. As emphasised by [4], appropriate indicators could provide the basis for informed decisions and proper policies. Representative indicators are essential to compare future strategies (such as circular economy strategies) and to assess their impacts.

In fact, over the last two decades, considerable attention has been given to the development of environmental indicators, which has led to an extensive pool of such metrics [5,6]. However, there are still challenges linked to the use and selection of indicators which are attributable to several issues. On the one hand, some sets of indicators might fail to appropriately consider the complexity that is inherent to environmental systems [7]. The methods followed for selecting indicators frequently place an emphasis on the selection of individual indicators rather than on the overall picture that a collection of indicators can provide. In fact, according to several authors, very often, the selection of indicators is not sufficiently grounded within evidence-based frameworks [8].

Even though it is complicated to capture such complexity in a set of indicators, a collection of consistent indicators can help adequately

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describe the characteristics of environmental systems. Additionally, the use of indicator frameworks instead of individual indicators is a useful means for identifying the inherent relationships that exist among different environmental indicators [9,10].

On the other hand, in some cases, indicators are selected without a clear objective and with no consideration of the characteristics of the object under assessment. Different indicator frameworks and indicator types might be more suitable for certain contexts and objects of assessment; thus, the properties of such entities need to be considered in the process of selecting indicators. Also, some new sustainability paradigms are arising (e.g., circular economy) that require including assessment indicators in addition to the ones that have traditionally been used [11].

In addition to the above challenges, while several frameworks defining environmental indicators have been developed until the present (see, for instance, [12]), there has not been an agreement of a robust and exhaustive framework specific to the construction sector [13]. Even though some indicators may be applicable to multiple products and processes, it is crucial to recognise that the supply chains of different sectors involve distinct process which thus generate different impacts that require unique assessment approaches.

Considering the above, this article aims to address the identified challenges by establishing a comprehensive taxonomy of indicators that enables the assessment of environmental impacts within construction supply chains at various levels. This main objective translates into two specific objectives. On the one hand, through an extensive literature review, the article examines the primary challenges associated with existing indicator frameworks. On the other hand, the article proposes a taxonomy with recommendations for groups of indicators to be used for different purposes.

2. Conceptual background

This section presents some preliminary concepts that are key for the review performed. In particular, construction supply chains are defined and briefly described and then, the definition of indicators used in this article is presented.

2.1. Construction supply chains

A construction supply chain refers to the network of entities involved in the production and delivery of materials, equipment, and services required for construction projects [14]. As [15] describe, the initial stages of the construction supply chain spans include the design, procurement of raw materials and components from suppliers and manufacturing of by-products. Then, the products and materials move through the hands of contractors and subcontractors, who use them to build and complete construction projects. The last stages included in the concept of construction supply chains are the maintenance, operation, and end of life.

Construction supply chains may be seen from different levels, ranging from smaller (e.g., the supply chain of a construction material) to wider levels (e.g., nation or worldwide levels) [16]. These are often referred to as micro and macro levels, respectively [17]. This has been represented in Fig. 1.

Construction supply chains have certain peculiarities that supply chains in other sectors (e.g., manufacturing) do not possess [18]. suggest that the products from construction are usually unique and the organisations tend to be temporary. Further, [19] emphasise the great number of participants in construction supply chains (e.g., manufacturers, distributors, wholesalers, contractors, subcontractors, logistics providers).

Effective management of the construction supply chain at different levels is crucial for ensuring that materials and equipment are delivered on time, in the right quantities, and at the right locations. However, the characteristics described above pose challenges to attaining high efficiencies in the processes. By optimising the different processes involved in construction, it is possible to improve overall environmental efficiencies and performance of projects. In this regard, indicators are key to evaluate and monitor these aspects.

2.2. Key indicators and their characteristics

This article deals with key indicators to assess construction supply chains from an environmental perspective. In this context, key indicators refer to performance indicators that evaluate critical aspects of a system [20,21].

Indicators can be classified according to different groups of features. A key feature is the type of data used, which will affect the way in which the indicator is measured (i.e., quantitative, qualitative, hybrid). Detailed information of this is provided in Table 1 and described below.

First of all, as described by [22], quantitative indicators are

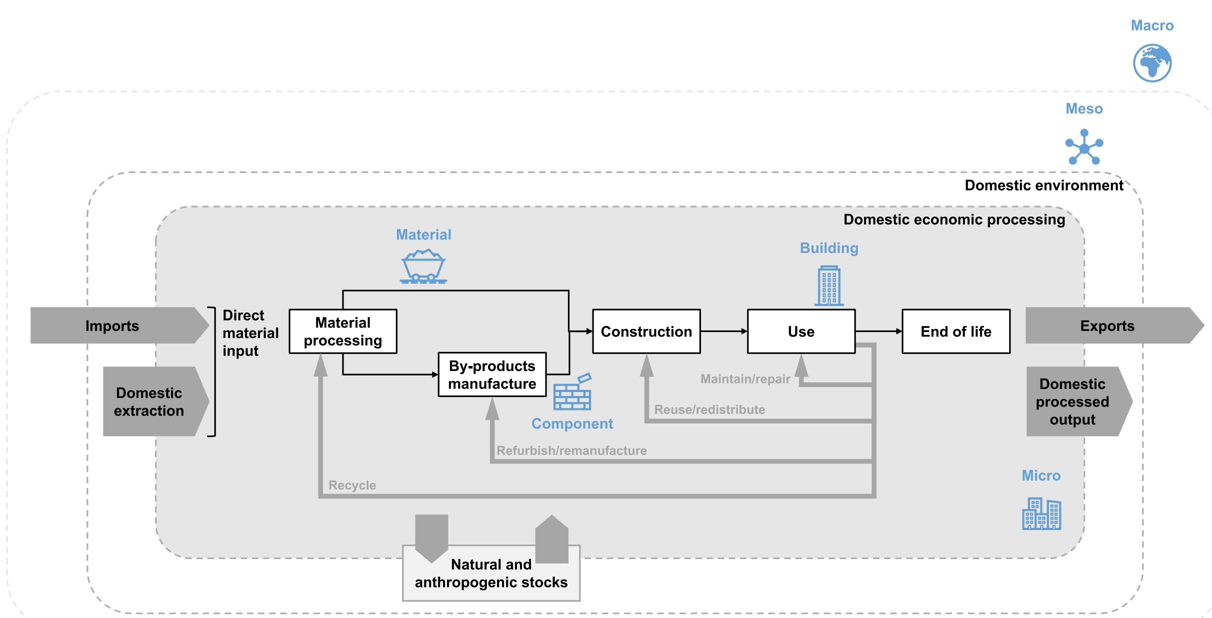

Fig. 1. Diagram of a generic construction supply chain and its different stages, levels and flows.

Table 1
Classification of indicators according to type of data.

Type of data	Way of measurement	Sub-level of measurement
Quantitative	Absolute	–
	Relative	Rate Ratio Proportion
	Composite	Weighted aggregation Formula
Qualitative	–	–
Hybrid	Nominal Ordinal Interval (and ratio)	– – –

indicators that are measurable and numerical in nature. They can be classified into absolute, relative, and composite indicators, as described next.

- Absolute indicators are those that provide the intrinsic value of the object of assessment without comparing it to other values.
- Relative indicators are based on the division between two values. Rates are those indicators where the numbers or quantities being divided do not have the same units. A common case is the occurrence of event during a given time period (e.g., waste generated per year). Ratios are obtained by dividing numbers or quantities that have the same units. Lastly, proportions are a specific case of ratios where the numerator is a subset of the denominator.
- Composite indicators are mathematical combinations (or aggregations) of a set of indicators. This can include weighted aggregations or more complex aggregations, where formulas are used to obtain the value of the indicator.

Secondly, qualitative indicators are those that are descriptive and subjective in nature. The information they provide is not easily quantified or measured numerically. Examples are written comments, in-depth conversations, etc.

Then, hybrid indicators are those that combine both quantitative and qualitative elements [23]. classify them into nominal, ordinal, interval and ratio indicators:

- Nominal indicators correspond to variables that are classified qualitatively with levels that do not have any quantitative meaning.
- Ordinal indicators comprise those variables that are grouped into categories that have a natural order (e.g., Likert scales).
- Interval indicators use variables that are grouped into categories that have a natural order with a known and equal distance between each value in the scale.
- In ratio indicators, variables are grouped into categories that have a natural order with a known and equal distance between each value in the scale and a natural zero (e.g., weight, temperature in Kelvin). Given that these are a special case of interval indicators and the consideration of the difference between interval and ratio indicators is not fundamental for the case of the assessment of construction supply chains, in this study they are grouped together as shown in Table 1.

In addition to the classification by nature of the indicators, indicators can be classified according to other criteria, such as source of data (i.e., primary and secondary indicators), and observability (i.e., direct and indirect indicators) [24].

3. Methods

The methodology followed in this study consisted of a literature review followed by an analysis of the articles selected as shown in Fig. 2. This section describes the several steps that were followed to perform the literature review and the analysis, and discusses the limitations associated with the methodology employed in this study.

3.1. Data collection

A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [25,26].

Records were initially identified using the databases Scopus and Web of Science. The search was performed on the 14/02/2023, and articles published until that date were included. The search was limited to journal articles written in English, not including review articles.

The keywords used were related to the object of the study. In particular, three groups of keywords were used. The first one indicated the focus of the study (i.e., construction) and it included the combination of the words infrastructure OR construction OR building. The second group of keywords referred to the indicators, and it included indicator OR metric. Then, the words sustainab* OR environment* were used to focus metrics on environmental aspects. The character * was used to allow for variations of these words (e.g., sustainable, sustainability). The final group of keywords was used to indicate that groups of indicators were being searched. For this purpose, the following keywords were used: framework OR method* OR guideline OR standard OR collection OR set.

Because the above combination of words yielded a great number of articles, the search was refined by defining proximity operators between the keywords.

Overall, this search yielded 880 and 642 papers in Scopus and Web of Science respectively, among which 514 were duplicate between the two databases. After duplicates were removed, the titles and abstracts of the articles were screened, and those articles not fitting the criteria for inclusion were excluded. The following criteria were used to select the articles during this screening process: (1) information from the title and abstract indicate that environmental indicators are used in the context of construction supply chains at any level; and (2) the full text is available.

This reduced the total number of articles to 458. Then, the full records were screened and those articles that did not fit with the selection criteria were excluded. In this case, full articles were searched to ensure that at least one indicator was used to assess an aspect of a construction supply chain from an environmental perspective. In the end, a total of 226 studies was selected for the review.

At this point, it needs to be noted that the use of the terms “environment” and “metrics” as keywords when searching databases led to obtaining multiple metrics dealing with indoor environments and with public health and safety, which were excluded.

On the one hand, indoor environment metrics refer to the quality and conditions within indoor spaces (e.g., buildings or enclosed environments), and typically include aspects such as air quality, thermal comfort, lighting levels, and acoustic performance. Differently, the metrics under consideration in this study take a broader perspective and consider the external environment surrounding buildings or construction sites, which includes the aspects that were reviewed in this article.

On the other hand, public health and safety indicators typically involve assessments of risks, exposure levels, compliance with regulations, and adherence to safety standards. Even though these are crucial considerations in any construction project or the built environment, they are distinct from environmental indicators, which focus on the ecological and environmental aspects of sustainability.

3.2. Data processing

The information from each selected paper was extracted in a systematic way, and recorded in a dedicated spreadsheet, which was used to facilitate the analysis by coding and categorising the data.

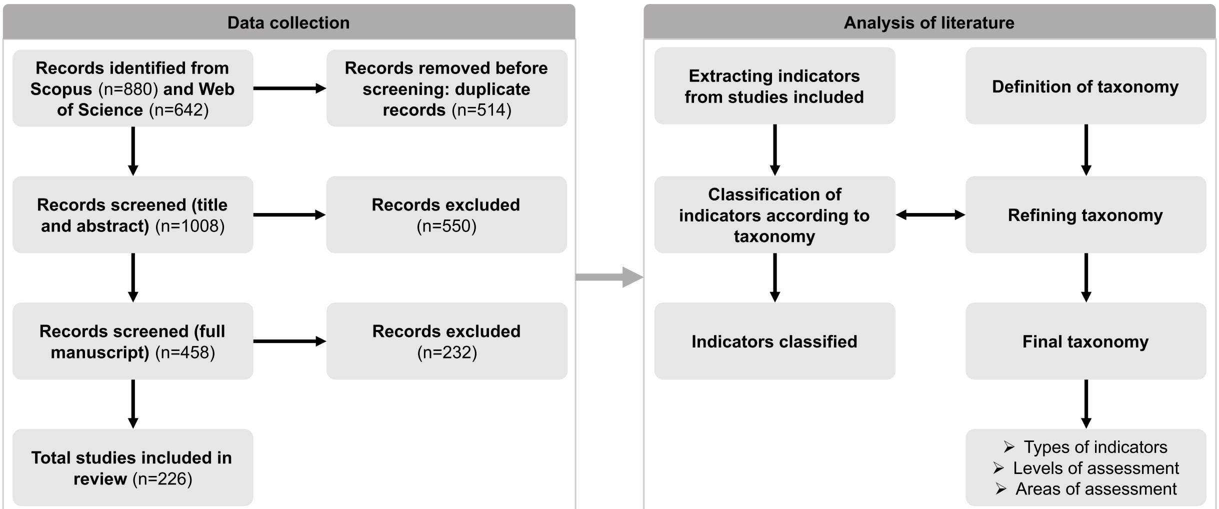

Fig. 2. Flow diagram of the literature review process.

On the one hand, for each publication, the information that was retrieved was the level at which the indicators were used, whether a specific framework was used for the indicators (e.g., life cycle assessment - LCA, building rating systems) and the list of indicators contained in the article.

On the other hand, for individual indicators, first, each indicator was transcribed verbatim. Second, information on the indicators was noted. This included a description of the indicator as given by the authors, units (if specified, e.g., kg CO_2eq, m^3 of water), and group(s) of indicators, if defined by the authors. This process allowed developing a comprehensive list of final indicators, provided in the Supplementary File.

3.3. Analysis of literature

In addition to the information directly extracted from the articles, to facilitate the analysis of the data, a systematic characterisation process was conducted. This involved classifying each indicator based on its type and the corresponding environmental area it addresses. The types of indicators were defined according to the literature (see Table 1). Additionally, it was found that standardised labels for the assessed environmental areas are not yet established in the literature. Therefore, a taxonomy was built in an iterative manner, involving multiple iterations of categorisation and refinement to ensure comprehensiveness and meaningfulness of the classification of environmental areas assessed. Such process has been used by other researchers in the past to build taxonomies iteratively [27]. Each indicator was then mapped to the taxonomy developed.

Once all the information of the indicators was extracted as described above, data was analysed using frequency analyses of year of publication, indicator level, type of indicator, and environmental aspects assessed. Spreadsheets were used to analyse the results by filtering data according to the labels assigned. Diagrams were then prepared using Excel.

3.4. Limitations

There are several limitations in this study that warrant careful examination. From the perspective of the methodology used, despite using a rigorous search protocol, there is an inherent possibility that some relevant studies were inadvertently overlooked due to search engine limitations, indexing delays, or human error. This study relied primarily on Scopus and Web of Science, two widely recognized databases for scientific publications. However, these platforms may not fully capture all literature, such as emerging preprints, which could provide additional insights. The use of keyword-based filtering may also have excluded studies that use different terminologies or non-standardised phrasing for similar environmental indicators. However, although this study aims to provide a representative overview of indicators used in construction supply chains, it does not claim to be exhaustive.

From the perspective of the study's outcomes, The labelling and categorisation process involved manual classification of indicators based on iterative refinement. While this method ensures transparency and adaptability, it introduces potential subjectivity. To mitigate bias, an iterative validation process was implemented, allowing for cross-checking and refinement of categories of the taxonomy over multiple review cycles.

From the perspective of the particularities of the construction sector, the applicability of certain indicators varies based on regional regulatory frameworks, material supply chains, and construction practices. For instance, indicators relevant in European construction markets (e.g., EPD-based carbon footprinting) may not be directly transferable to regions with less developed LCA infrastructures. This study provides generalised insights but does not delve into detailed regional comparative analyses, which could be a valuable avenue for future research.

4. Results and discussion

This section describes and discusses the results obtained in the literature review. This was done by giving an initial overview across time of the literature reviewed, followed by a description of the literature grouped according to the type of indicator used, level of assessment, and area assessed.

4.1. Literature overview

Fig. 3 shows the yearly evolution of the selected articles and shows information of the level at which the indicators were developed or used. Key milestones (e.g., standards, conventions, frameworks) for the definition and application of environmental indicators have been included in the plot. In the top part, generic milestones are represented, while milestones related to construction are shown at the bottom of the timeline.

As it can be seen, the levels for which more articles were found are infrastructure (19 % of the total number of articles) and building levels (45 % of the total number of articles). In both cases, the increase in number of articles is particularly noticeable in two points in time, namely in 2005 and as from 2019. The period comprising the last years of the previous millennium and the beginning of the current one was

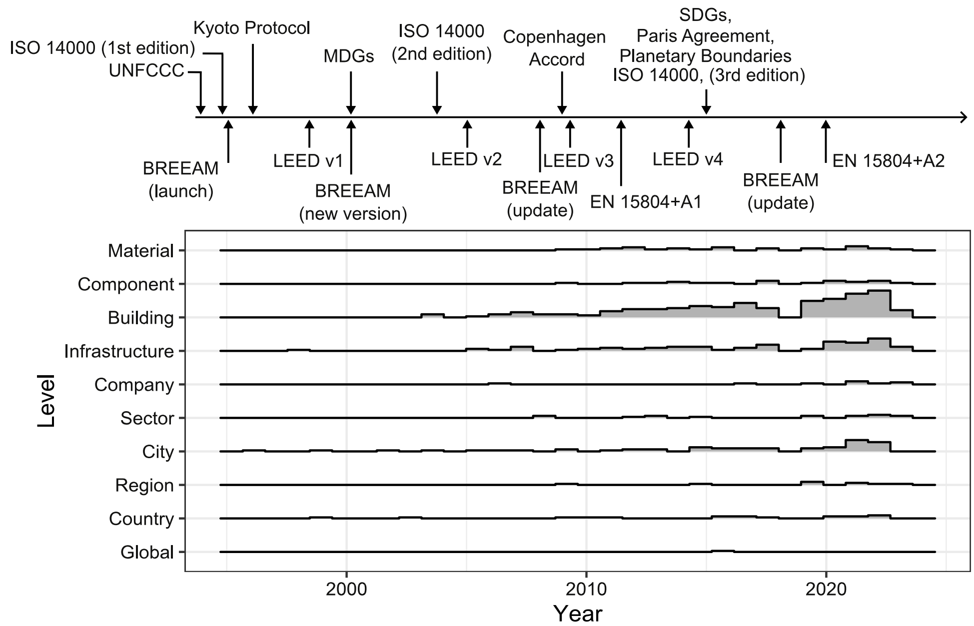

Fig. 3. Evolution of selected articles and relationship to sustainability milestones related to construction (bottom) and generic (top).

characterised by the development of several standards that have a close relationship with the sustainability of the built environment (such as the LEED certification, which began in 1993, or BREEAM, which was first launched in 1990). The frameworks and guidelines that these standards provided led to an increased attention and research in this field. In addition to this, globally, there was a growing concern regarding the environment (e.g., the MDGs), which emphasised the need for more sustainable practices across different sectors, including the construction sector.

Later, in 2015, there were several relevant global events and initiatives, including the adoption of the SDGs, the Paris agreement, and the publication of the planetary boundaries [28]. All these marked a turning point in terms of environmental sustainability priorities worldwide, including an increased research and interest regarding environmental aspects of construction supply chains, as stakeholders in this sector recognised the need for addressing sustainability challenges using comprehensive approaches.

4.2. Descriptive analysis

This section presents the results by type of indicator, level of assessment and environmental area assessed. Additionally, the alignment of the reviewed indicators with construction supply chain stages is presented in the last subsection.

4.2.1. Type of indicator

Fig. 4 shows the proportion of indicator types found in the literature according to the classification that was presented in Table 1. The proportion of quantitative, hybrid and qualitative indicators found was of 39, 20, and 1 %, respectively.

The remaining 40 % of indicators did not explicitly define the type of indicator and have thus not been included in Fig. 4. This corresponds to cases where authors proposed an area to be assessed but did not define how to perform such assessment. An example of this is the work by Stanitsas et al. [29], who proposed a framework of indicators that addressed conceptual aspects but did not offer practical guidance on

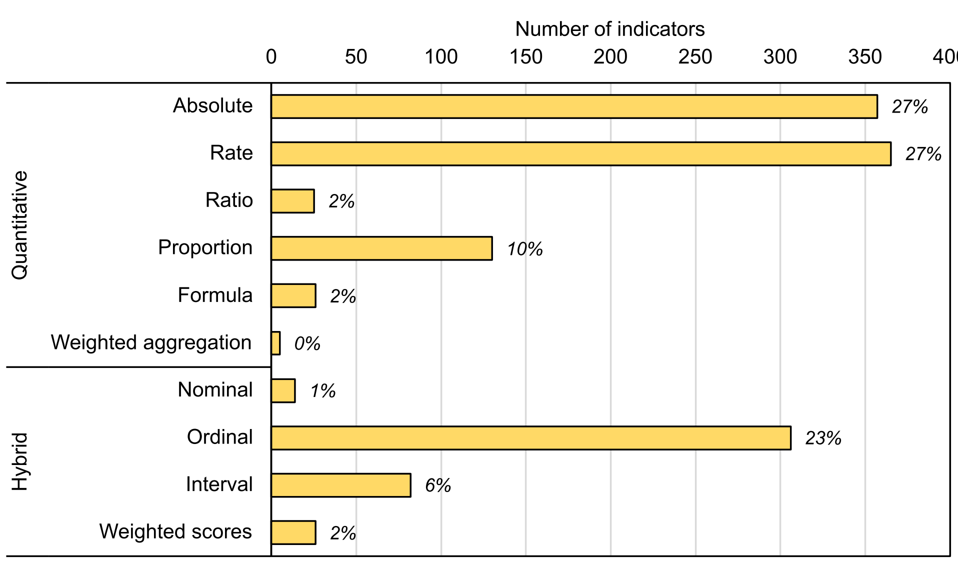

Fig. 4. Types of indicators in the reviewed literature.

their measurement. Another common approach found in the literature is the development of frameworks accompanied by expert consultations to determine the significance or weights assigned to the proposed indicators (see, for instance, [30,31]).

Quantitative indicators seem to be slightly more widely used than hybrid indicators in the context of construction supply chains to quantify and evaluate the environmental impacts of the different aspects of construction supply chains (39 % of indicators reviewed were quantitative). They offer a quantitative basis for decision-making, target setting, and performance monitoring.

Among quantitative indicators, more relative indicators (39 %) than absolute (27 %) and composite (2 %) ones were found. Relative indicators (including rates, ratios, and proportions) offer a comparative perspective by relating environmental performance to a reference point or benchmark, facilitating comparisons across different projects or time periods. While these indicators provide a comparative perspective, their effectiveness strongly depends on choosing an appropriate reference point. As it can be seen, rates represent a large part of the quantitative indicators reviewed (27 %) as they are commonly expressed per functional unit (e.g., as seen in LCA indicators) or per time.

Differently, absolute indicators provide a direct measurement of a specific environmental aspect, such as energy consumption or CO_2 emissions, enabling a clear assessment of the magnitude of impact. However, they may lack comparability, as they do not embed a reference point or benchmark and, therefore, they do not allow interpreting the significance of absolute values and assessing the performance in relation to targets or industry standards.

Lastly, composite indicators (which can involve the use of formulas or weighted aggregations) combine multiple quantitative measures into a single metric. This allows obtaining a comprehensive view of environmental performance. Constructing effective and meaningful composite indicators requires considering carefully the weights used and the aggregation method, as these could introduce subjectivity and bias into the assessment and affect the interpretation of results. Examples of such indicators in the literature reviewed include the power indicator in [32], where the masses of different materials are multiplied by the power needed for their production, or the circularity indicator in [33], where a formula that depends on the fractions of recycled materials, rapidly renewable materials and reused products and/or components is used.

Regarding hybrid indicators ordinal scales were found to be more common among the indicators reviewed (23 %) (see, for instance, [34, 35]). Ordinal scales allow for the ranking or categorisation of data based on their relative importance or level of performance. In fact, they are commonly used in building rating systems, such as LEED and BREEAM, where different sustainability criteria are assessed and assigned a specific score or rating.

4.2.2. Level of assessment

Fig. 5 provides an overview of the distribution of articles reviewed based on the level at which indicators were applied. The analysis reveals that a considerable number of articles focus on the micro level, specifically on buildings. This emphasis on buildings can be attributed to their significant environmental impact throughout their life cycle, including construction, operation, and demolition phases. Buildings have a high potential for energy consumption, resource depletion, and emissions generation; thus, they appear as a focal point for research within the construction supply chain.

First, when looking at the micro level, there are significantly less publications dealing with sets of indicators at material and component levels (14 %) than at building and infrastructure levels (65 %). Materials and components play a fundamental role in shaping the overall environmental performance of construction supply chains. In fact, there are specific standards to assess their environmental performance (e.g., EN 15804). These standards allow to produce Environmental Product Declarations (EPDs), which provide transparent and comparable information about the environmental impacts of products throughout their life cycle. However, despite the existence of these standards, there is still a need for further research in this area to bridge the current gap in knowledge and ensure a comprehensive understanding of sustainability implications at the micro level.

Regarding the meso level, interestingly, the analysis reveals a relatively higher number of articles at the city level (10 %) than at company and sector levels (2 and 3 %, respectively). This finding aligns with the growing recognition of cities as critical hubs for sustainable development and the need for comprehensive assessments of their environmental impact [36] given the concentrations of population, infrastructure, and intensive resource consumption in cities.

In comparison to micro and meso levels, a smaller proportion of articles (6 %) focused on indicators at the macro level. The reasons for this could be attributed to factors such as data availability, the inherent challenges of conducting assessments at higher levels, or a relative lack of research interest in exploring macro-level impacts.

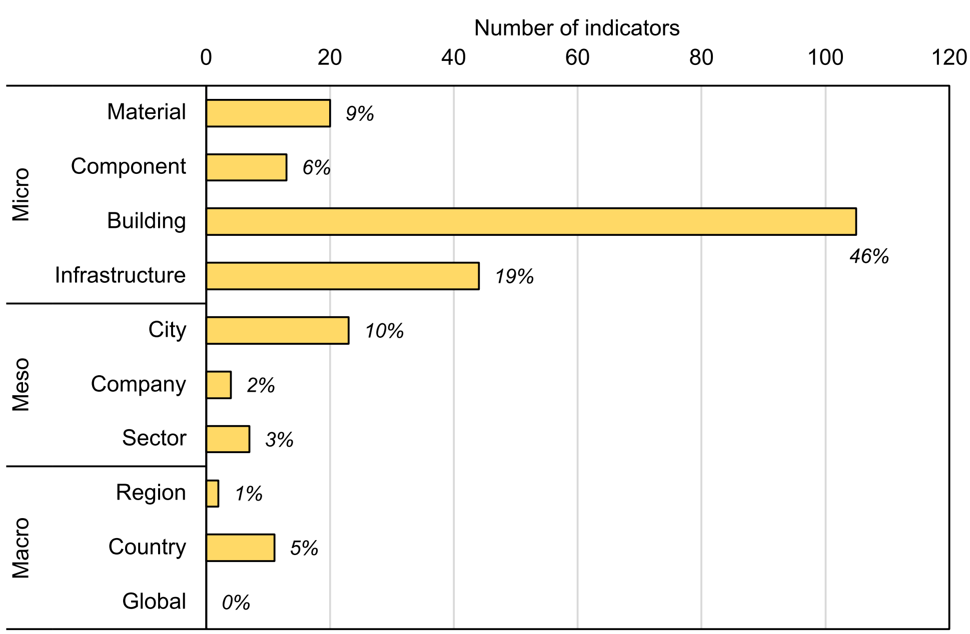

Fig. 5. Levels of assessment in the reviewed literature.

4.2.3. Area of assessment

The review process allowed refining the taxonomy for the areas of assessment of indicators shown in Table 2. These areas are grouped into two main dimensions, namely natural and anthropogenic. This distinction has already been made in the past [37,38].

Note that, while the taxonomy presented here adopts specific dimensions and groups, the complex nature of socio-environmental systems allows for alternative approaches to organising the areas of assessment for indicators.

On the one hand, the natural dimension refers to specific elements or components of the natural environment that can be influenced or impacted by human activities. This includes Materials/natural resources, Land and soil, Water, Air, and Ecosystems. Each of these is further sub-grouped in pressures, states and impacts. The nomenclature in the DPSIR framework [39] was used to structure each of these areas into pressures, states, and impacts, as described below.

Pressures represent the demands that are directly exerted on the environment and that are caused by the driving forces [40,41], such as emissions, oil extraction, or waste disposal. Then, states represent the conditions of the environment that are changed as the effect of pressures. They describe the actual condition of the environment, including the quality and quantity of natural resources, and they need to be quantified for a given area and at a certain moment in time [41–43]. Lastly, impacts represent the effects on ecosystems that result from changes in the states [40].

On the other hand, the anthropogenic dimension considers those processes that take place mostly in the technosphere, encompassing human-made systems and activities. This dimension captures the anthropogenic inputs, outputs, stocks, and flows that contribute to the environmental impacts of construction supply chains.

Anthropogenic inputs refer to the resources and materials used in construction activities which are not directly obtained from natural resources, such as reused materials or components. These inputs are essential for the production and operation of buildings and infrastructure. Anthropogenic outputs entail the waste generated during construction activities, as well as its characteristics and destination. Then, stocks and flows refer to the flows of anthropogenic material and components, as well as the characteristics of these elements.

Fig. 6 shows the number of indicators reviewed for the different environmental areas, and further detail regarding their distribution among the categories defined is presented in the diagrams in Fig. 7. In what follows, the results obtained are discussed for each of the environmental areas and sub-areas.

Table 2
Taxonomy of indicators – areas of assessment.

Dimension	Group	Sub-group	Sub-groups
Natural	Materials/ natural resources	Pressures	Resource consumption, resource extraction, energy consumption, energy generation
		States	Resource quality, resource scarcity
		Impacts	Depletion of abiotic resources
	Land and soil	Pressures	Land use, land use change, soil discharge
		States	Location, land state
		Impacts	Land/soil degradation, Terrestrial acidification, Terrestrial eutrophication, Terrestrial ecotoxicity
	Water	Pressures	Water withdrawal, Water discharge/release to water, Water consumption
		States	Water quality, Water scarcity
		Impacts	Water depletion, Water acidification, Water eutrophication, Water ecotoxicity
	Air	Pressures	Particulate matter (PM) emissions, Gaseous emissions (GHG), Gaseous emissions (non GHG)
		States	Air quality, CO_2 concentration, PM concentration, Aerosol optical depth, Total ozone concentration
		Impacts	Ozone depletion, Climate change, Photochemical ozone formation, Particulate matter formation
	Ecosystems	Pressures	Introduction/invasion of new species, Physical changes to fauna/flora, Noise/disturbances
		States	Fauna quality, Flora quality, Ecosystem quality
		Impacts	Habitat loss, Loss of ecosystem services, Impacts on ecosystems
Anthropogenic	Anthropogenic inputs	Recirculated inputs	Primary vs secondary content, Recirculated water, Recovered energy
		Inputs characteristics	Toxicity, Resource criticality, Origin, Other sustainability considerations
	Anthropogenic outputs	Outputs characteristics	Waste generated, Residual value
		Destination of outflows	Waste treatment and disposal, Potential for recirculation
	Stocks and flows	Stocks characteristics	Longevity, Value change
		Management	Energy management, Water management, Other resource management
		Resource efficiency	Recirculation efficiency, Material efficiency, Water efficiency, Energy efficiency

4.2.3.1. *Materials/natural resources.*

For materials and resources, the literature reviewed emphasises the significance of indicators that capture the use of energy (12 % of indicators). This is usually done in the literature by evaluating the total energy consumption, which some authors further classify according to its nature, such as renewable and non-renewable energy [44].

Following energy consumption indicators, indicators related to extraction and consumption of materials and resources are also frequently utilised (5 % of indicators). These indicators provide insights into the quantities of materials used or extracted and are often measured in terms of weight or volume. Considerations are often made regarding the characteristics of materials, such as their scarcity/non-scarcity, renewability, local or non-local sourcing, and other relevant attributes. For example, [45] measure the use of local materials and the use of materials from sustainable resources.

Apart from quantitative indicators of resource consumption, some authors have used in the past hybrid indicators to assess the use of resources. For instance, [46] use a severity scale that ranges between 1 and 5 to assess embodied energy and material consumption.

When assessing the state of materials and resources, researchers commonly employ indicators that focus on resource quality and scarcity

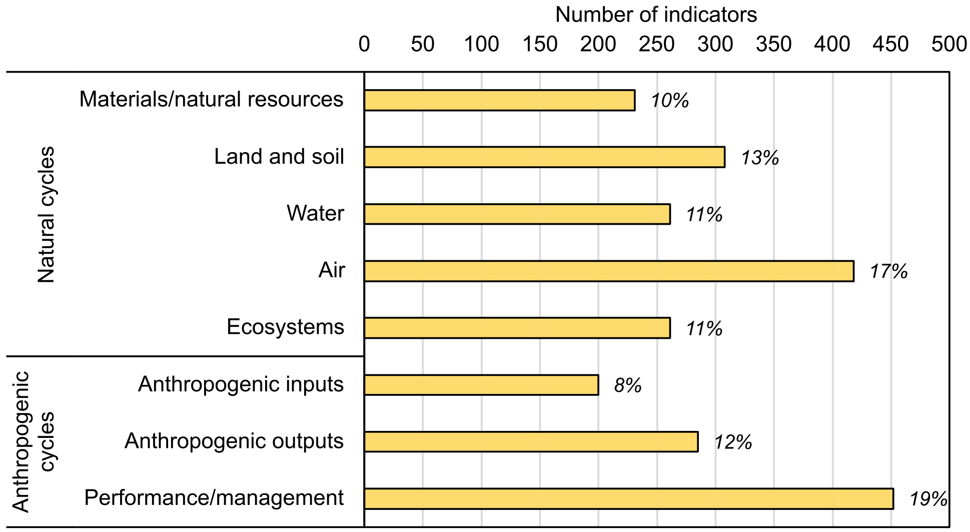

Fig. 6. Environmental areas assessed by the reviewed indicators.

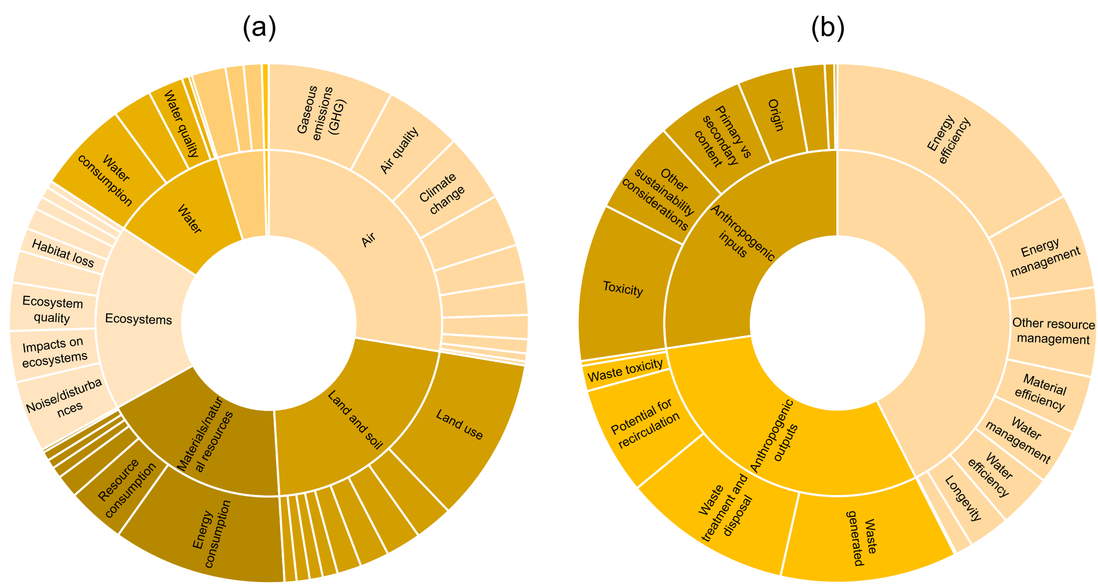

Fig. 7. Detail of areas of assessment in the reviewed indicators, for (a) natural and (b) anthropogenic dimensions.

(see, for example, the indicator "Red list materials" proposed by [47]. However, the literature does not provide detailed guidance on how to measure these indicators, indicating the need for further research and standardisation in this domain.

Regarding the impacts on materials and resources, the most frequently used indicator is the depletion of abiotic resources. This indicator is often measured following impact categories in LCA studies and expressed in kilograms of antimony equivalent (kg Sb-eq). It provides valuable information about the potential depletion of non-renewable resources associated with specific activities or processes.

4.2.3.2. Water. Pressures related to water are commonly evaluated in the literature considering three aspects: water withdrawal, releases to water, and water consumption [48–50]. While the former corresponds solely to <1 % of the total indicators collected, releases to water and water consumption indicators make up a 3 % and 6 % of indicators, respectively. The three of them are usually measured in volume units and can be broken down by water sources (e.g., groundwater, surface water, seawater) or by water body characteristics (e.g., areas with water stress).

The two most important metrics to evaluate the state of water are water quality and water scarcity [51,52]. Indicators of water quality include pH, turbidity, dissolved oxygen and the presence of nutrients and heavy metals, among others. The reader is referred to [53] for a complete list of such indicators.

Regarding impacts, the most important indicators found in the literature are water depletion, acidification, eutrophication and ecotoxicity. These are indicators that are commonly assessed as part of LCA impact categories.

4.2.3.3. Air. When considering air, the literature highlights various types of emissions associated with construction activities. These include process emissions, fugitive emissions, emissions from the combustion of fossil fuels in stationary and mobile plants, as well as emissions from traffic or dust generated during materials handling. To assess the pressures on air quality, the indicators that are used by authors can be classified in particulate matter (PM) emissions and gaseous emissions, which can be greenhouse gas or non-greenhouse gas emissions [54–56].

Among the three groups of emissions, GHG emissions are the ones that are more present among the indicator groups reviewed (8 %). They are most measured in mass of CO_2eq (either kg or tons) [57] and frequently given as a ratio between the emissions and a functional unit like mass of product or component [58], surface area [59] or service life [60]. Less frequently present are non GHG emissions (3 %), which usually include NO_x and SO_2 emissions [45]. Similar to GHG emissions, these indicators tend to be measured through mass units.

Particulate matter (PM) emissions (2 % of indicators reviewed) can be quantified using specific measurement techniques and are typically expressed in terms of mass concentration, such as micrograms per cubic meter (μg/m^3). Gaseous emissions encompass a range of pollutants, including nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), volatile organic compounds (VOCs), and other relevant gases. These emissions are typically reported in terms of concentration or emission rates, such as grams per kilogram of fuel burned or grams per kilowatt-hour (g/kg or g/kWh).

Even though less frequently, some authors use hybrid indicators to assess the level of emissions. For instance, [61] measure the change in emissions using a scale that goes from 0 (no influence on the reduction) to 4 (very high influence).

In terms of the state of air, many countries employ air quality indices to assess the overall conditions of air in specific regions. These indices provide a comprehensive measure of air pollution levels, taking into account multiple pollutants and their respective thresholds or standards. Additionally, other indicators such as atmospheric CO_2 concentration, aerosol optical depth, and total ozone concentration are also mentioned in the literature as metrics for assessing air quality conditions.

When considering the impacts related to air, four key indicators are frequently discussed in the literature: ozone depletion, climate change, photochemical ozone formation, and particulate matter formation. These indicators highlight the potential environmental consequences of emissions on atmospheric composition, global warming potential, and air pollutant formation processes. While there are other impacts, these four are very frequently used because they belong to the standard LCA framework.

4.2.3.4. Land and soil. Indicators related to land and soil represent a proportion of 11 %. Pressures on land and soil are related to activities from construction such as land clearing and excavation, soil contamination due to disposal of substances, conversion of green spaces into built environments, soil compaction due to heavy machinery and equipment, disruption of soil structure (e.g., soil texture, composition, drainage characteristics) due to excavation and earthmoving activities, and the conversion of agricultural land or natural habitats into urban or industrial areas, which leads to land fragmentation and land use change. It is worth noting that indicators related to Land and soil are closely linked to the broader category of "Ecosystems," as alterations to the land and soil can significantly impact various ecosystem functions.

Pressures on land and soil are typically assessed through the following main categories: land use, land use change, and discharges to soil. Land use changes are particularly relevant in the context of construction supply chains. These changes involve transformations in land use, including the conversion of natural areas to residential, commercial, industrial, agricultural, recreational, or amenity land uses, along with the construction of buildings, structures, or other infrastructure. These pressures are commonly measured in area units, such as square meters (m^2).

Regarding states, the two indicators that are mainly used are the location of the construction activities [62] and the land state [63], understood as the set of physical, chemical and biological properties of the land and soil.

Indicators commonly found for assessing the impacts on land and soil include terrestrial acidification, eutrophication, and ecotoxicity. These indicators are often obtained through LCA methodologies, providing valuable insights into the potential environmental impacts associated with different activities. Additionally, some authors choose to evaluate impacts on land and soil using more generic indicators that capture the overall degradation of land and soil resources.

4.2.3.5. Ecosystems. In comparison to the previous categories, indicators found related to ecosystems correspond to 11 % of all indicators. Most indicators related to other environmental areas have an impact (direct or indirect) on ecosystems. Therefore, even when ecosystems indicators are not explicitly included in indicator frameworks, they are often implicitly addressed through indicators that assess the state or impacts of other environmental areas. For instance, activities like vegetation clearing, excavation, and land grading can lead to habitat destruction, habitat fragmentation, biodiversity loss, and disruption of ecological processes. Similarly, alterations in water flow and water pollution can significantly impact aquatic ecosystems.

The literature reviewed highlights several key indicators that pertain to the pressures, state, and impacts on this vital environmental area. One of the primary pressures is the introduction or invasion of new species, along with physical changes to the fauna or flora and disturbances such as noise and vibrations [64]. However, assessing indicators related to ecosystems can be challenging due to their inherent complexity and the need for subjective judgments. For instance, measuring the introduction of new species can involve various approaches, including quantifying the number of different species introduced, the total number of new individuals introduced [65], or the extent of the affected area [66].

When evaluating the state of ecosystems, researchers often focus on indicators that reflect the condition of the fauna and flora, as well as the overall quality of the ecosystem. These indicators provide insights into the health and functioning of ecosystems, allowing for the assessment of their ecological integrity. For instance, [67] assess the preservation of the ecosystem quality by evaluating the functions of terrestrial habitats and wetlands through a hybrid indicator.

In terms of impacts on ecosystems, the literature encompasses indicators that highlight the loss of habitats and ecosystem services. Some studies take a broad approach to assessing negative impacts, such as the "Impacted ecosystem area ratio" proposed by [68]. This indicator offers a measure of the proportion of the ecosystem that has been affected or compromised.

4.2.3.6. Anthropogenic inputs. Recirculated inputs, including the use of secondary resources as well as recirculated water, have received attention in the literature as important aspects of sustainable construction supply chains. Primary content refers to materials and resources that are extracted directly from the environment, while secondary content refers to materials that are recycled or reused. Metrics related to recirculated inputs focus on quantifying the proportion of primary and secondary content used in construction activities. This has been measured in the literature using indicators such as the percentage of recycled materials used in construction projects or the ratio of recycled content to total content in building materials [67].

Additionally, the assessment of recirculated water involves measuring the percentage of water that is sourced from recycled or treated sources, rather than relying solely on freshwater withdrawals [35,69]. These metrics help evaluate the extent to which construction supply chains are reducing reliance on virgin resources and minimising the extraction of raw materials, while also conserving water resources.

Another important sub-category under anthropogenic inputs is the characterisation of input characteristics, which includes metrics related to toxicity, resource criticality, origin of the resource, and other sustainability considerations.

Toxicity metrics assess the potential harmful effects of materials and substances used in construction, such as the presence of hazardous chemicals or pollutants. Resource criticality metrics aim to identify materials that are scarce or have limited availability, helping prioritise the use of sustainable and readily available resources.

Metrics related to the origin provide information about the geographical source of materials, allowing for assessments of transportation distances, carbon emissions, and considerations of local sourcing. Furthermore, sustainability considerations encompass metrics that evaluate the social, economic, and environmental aspects associated with the production and use of construction inputs. These metrics can include LCA indicators, such as carbon footprint or embodied energy, which provide a comprehensive assessment of the environmental impacts associated with the entire life cycle of construction materials.

4.2.3.7. Anthropogenic outputs. The characteristics of the outputs can be measured through the amounts of waste generated (12 %) and the residual value of the outputs (<1 %). Waste generated in construction activities can be solid waste or liquid effluents [70]. Examples of the former are construction debris, packaging material, and demolition waste [71]. Examples of liquid effluents are wastewater from construction processes, such as concrete production or site dewatering [72]. These can be measured in mass units, and a breakdown of this total by the composition or type of the waste can be made.

Residual value at end of life is the estimated value of the outputs or materials at the end of their useful life. It represents the economic potential or value that can be recovered through recycling, reusing, or recovering materials from the construction waste stream.

The destination of outflows is measured in the literature through indicators related to waste treatment and disposal (11 %), and the potential for recirculation (7 %). For waste treatment, the proportion of waste diverted and directed from disposal can be measured. Waste diverted from disposal refers to those resources that are recycled, reused, or recovered in some way. Regarding waste directed to disposal, the following operations can be considered: incineration (with or without energy recovery), landfilling, and other disposal scenarios.

Recirculation potential refers to the ability to reintroduce materials or resources back into the supply chain or production processes. It assesses the extent to which waste materials can be recycled, reused, or repurposed, reducing the need for virgin resources and minimising waste generation.

4.2.3.8. Performance/management. The performance/management of the technosphere component of construction supply chains are assessed in the literature according to the characteristics of the stocks, the management of stocks and flows, and the efficiency of resource use.

Results showed that the characteristics of stocks have been measured in the past through longevity (3 % of indicators) and value change (1 % of indicators). Longevity may be measured as the lifespan or durability of the stocks, indicating how long they can remain in use before being replaced or becoming obsolete. Value change can be assessed by considering the depreciation or appreciation of the stocks over time, reflecting changes in their monetary value or market demand.

Regarding efficiency, several authors use indicators to measure the efficiency of processes within the supply chains, including recirculation, material, water, and energy efficiencies. These indicators assess the extent to which resources are effectively utilized, recycled, or conserved throughout the construction processes, minimising waste, and optimising resource allocation. It needs to be noted that indicators relating to energy efficiency are highly common in the literature, composing 18 % of all indicators reviewed.

Results for management indicators are common (16 % of the total indicators), but there is high dispersion in terms of what and how they are measured. These tend to be hybrid indicators such as indicator “Energy management system” [73], which is measured using a scale from 0 (not achieved) to 100 % (achieved).

4.2.4. Alignment of indicators with construction supply chain stages

To provide more granularity on where and how each indicator can be deployed, the four major stages of construction activities—(1) Inception and Design, (2) Construction, (3) Operation and Maintenance, and (4) End of Use—as proposed by Thanu et al. [74]. Each stage has distinct environmental pressures, opportunities, and decision points, making it essential to consider a tailored set of indicators at every phase. Table 3 in the Appendix presents illustrative examples showing which indicators are most relevant to each of these stages.

First, in the Inception and Design stage, design decisions about materials, technologies, and site placement can “lock in” environmental impacts for decades. Indicators such as embodied energy [75], GHG emissions intensity [76], and material circularity [77,78] are especially pertinent here because they inform whether a project pursues lower-impact materials (e.g., recycled steel vs. virgin steel, as Zhong and Wu [78]) or integrates design features that cut future resource demands (e.g., passive cooling strategies, Roostaie and Nawari [61]). While cost and time pressures often dominate at this phase, incorporating life cycle thinking (e.g., via resource scarcity or land use change indicators) ensures that environmental trade-offs are evaluated alongside immediate budget constraints. This can prevent scenarios in which cheaper initial options lead to higher impacts or maintenance burdens later on.

Second, during Construction, indicators that capture energy consumption by machinery, dust and particulate (PM) emissions, and waste generation take centre stage [59,79]. Monitoring these provides real-time feedback, prompting interventions like more efficient equipment, optimised logistics (reducing transport miles), and on-site sorting of construction waste to improve recycling rates. This stage also introduces social or health-related dimensions—excessive noise [80], local traffic disruptions [31], or chemical spills [81]—that may not be fully visible at the design stage. While predominantly environmental indicators (e.g., PM emissions [80], water withdrawal [71]) are tracked here, practitioners should also consider hybrid or qualitative metrics (e.g., risk management measures [82], impact on local ecosystems [79]) to ensure construction activities remain safe and minimally intrusive.

Third, regarding Operation and Maintenance stage, it must be considered that buildings often exist for decades, making operational indicators critical for sustained environmental performance. Operational energy use [83], GHG emissions (from HVAC or electricity) [83], and water efficiency rate (e.g., graywater systems) [84] allow stakeholders to pinpoint inefficiencies that can be remedied through retrofits, technology upgrades, or behaviour change initiatives. Operational impacts can change over the building’s lifespan (e.g., expansions, new tenants, evolving local regulations). Indicators like ecosystem disturbance, air quality, and maintenance resource consumption [69,85] should be revisited periodically to capture shifts in usage patterns or environmental conditions. In this sense, the operation stage demands continuous monitoring rather than a one-time audit.

Lastly, for the End of Use stage, historically overlooked, the demolition (or deconstruction) phase can become a pivotal moment for recovering valuable materials and minimising landfill. Indicators such as demolition waste generation [80,86], landfill diversion rate [71,86], and reusability/salvage potential [22,71], highlight whether a project successfully closes material loops and reduces the burden on natural resources. While the building ceases operation here, local air pollution (from dust or truck traffic) and potential soil or water contamination remain concerns. End-of-life GHG emissions (e.g., from hauling debris) [87] and hazardous materials in demolition (e.g., asbestos or lead) [88] help ensure safe, responsible end-of-life practices that align with broader sustainability goals.

A key lesson from these four stages is that life cycle interdependencies profoundly shape a project’s overall performance. Early decisions during inception often set the stage for subsequent impacts, influencing construction methods and the ease or difficulty of salvaging materials at demolition [74]. In practical terms, data availability and consistency across stages becomes paramount: measuring indicators like GHG emissions or water consumption in a uniform, reliable way is crucial, yet record-keeping can be especially scattered during dynamic phases such as construction or demolition. To address this, project teams should establish robust data protocols from the outset, thereby enabling seamless information flows over the building's lifetime. In addition to quantitative measures, some issues—such as ecosystem disruption or cultural heritage preservation—require hybrid indicators that combine numeric data with qualitative stakeholder input. This dual approach can uncover subtleties that purely numerical metrics might miss. Likewise, engaging all relevant actors—whether architects, contractors, facility managers, or demolition crews—in the measurement process clarifies roles and fosters shared accountability. Finally, adaptive management should remain an ongoing priority, since indicators and thresholds must evolve alongside changes in technology, regulation, and best practices, ensuring that construction supply chains continuously improve rather than remain static.

5. Challenges and recommendations

This section provides critical insights into the main challenges associated with selecting, using, and applying indicators to measure environmental issues in construction supply chains. These insights have been grouped in the main areas discussed in this review; namely, the definition of metrics, the types of indicators and data collection method, the level of assessment, and the area assessed. For each of these areas, three transversal topics are key, as shown in Fig. 8.

5.1. Challenges by topic

5.1.1. Definition of indicators

The review revealed that, often, the indicators proposed and used in studies lack clear definitions. This was evident from the fact that a high percentage of indicators reviewed (68 %) did not provide a clear description of what they meant (i.e., just a label or name of the indicator).

Failing to provide sufficient information can be detrimental to the transparency and reproducibility of the assessment, hinders comparability, and impedes stakeholders' understanding of the context and limitations of the indicators [89,90]. Therefore, it is important to establish precise definitions and boundaries for each indicator category. Clear definitions help in selecting appropriate indicators that align with the objectives of the assessment and provide meaningful insights. These definitions should include, if possible, information regarding the underlying assumptions made and the data's origin. Examples of underlying assumptions for the case of construction supply chains are the considered location of the study, the timeframe, or the transportation distances of materials or equipment.

As for data's origin, indicators rely on data to quantify and assess environmental impacts and, as such, it is essential to specify the origin of the data used. This includes explicitly stating whether the data is based on primary data collection (e.g., information provided by manufacturers, distributors, etc.), secondary data sources (e.g., public statistics and databases, literature), or models (e.g., emission factors, dispersion models). Recent international endeavours have highlighted ways to improve data quality and deal with issues arising from missing or highly uncertain data [91–93].

Nevertheless, data availability and reliability can be a challenge, especially when the entire construction supply chain is considered, which involves data from both upstream and downstream processes. Specific challenges may arise upstream in the supply chain, where data on raw material extraction, manufacturing processes, and transportation can be fragmented or difficult to obtain. In the case of downstream processes, challenges might arise when collecting data for waste management, recycling rates, or other end-of-life processes of products and materials. In both cases, primary data providers may not want to deliver data when/if it is perceived to be sensitive [94].

Recent EU-driven initiatives have sought to address these limitations. For example, the UNEP [95]'s "Roadmap for National LCA Database Development" provides a structured approach to harmonizing LCA datasets across different countries. Similarly, the Italian LCA database (BDI-LCA) developed through the Arcadia project [96] has demonstrated a national-level effort to create consistent, sector-specific datasets. This project has been instrumental in producing high-quality LCA datasets for the steel construction industry, as documented in Sesana et al. [97]. Their work emphasises the importance of a cradle-to-gate approach in assessing steel product sustainability and ensuring data alignment with international methodologies.

Despite these advancements, further efforts are needed to enhance data transparency and accessibility. One promising direction is the development of open-access national LCA databases that integrate sector-specific data while ensuring compatibility with existing international databases such as Ecoinvent and GaBi. This approach would facilitate broader adoption of LCA in green public procurement (GPP) and decision-making for sustainable construction.

Regarding assumptions, indicators should explicitly state the system boundaries and processes that are considered. System boundaries define the scope of the assessment, identifying which stages of the supply chain and associated activities are included or excluded. Construction supply chains involve multiple interconnected processes, which can make it challenging to define comprehensive enough system boundaries and the

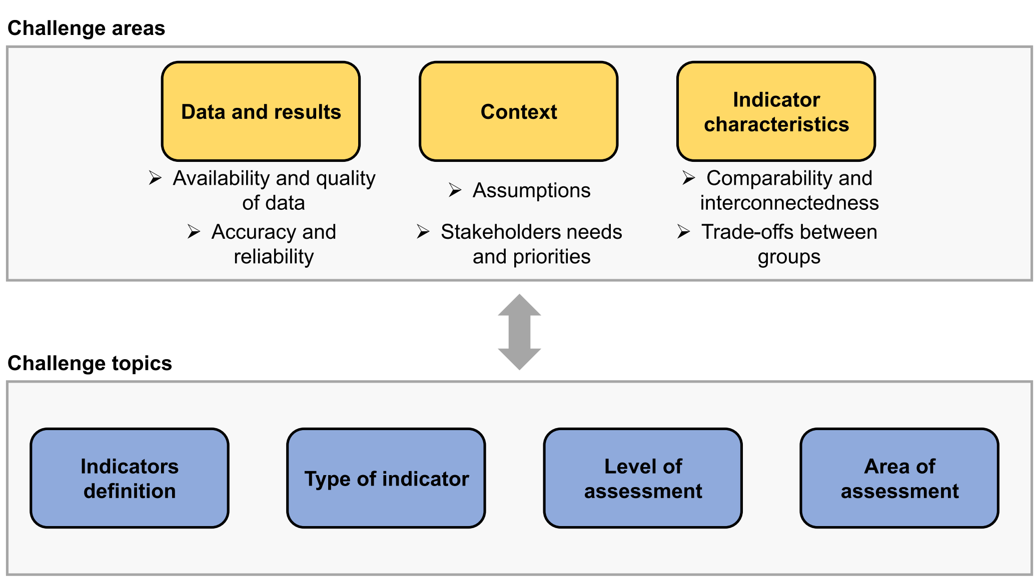

Fig. 8. Summary diagram of the main challenges involved with environmental indicators to assess construction supply chains.

impact allocation method. For example, the extraction and production of raw materials used in construction can have significant environmental impacts that extend beyond the boundaries of the construction site itself [98].

5.1.2. Type of indicator

It is essential to assess the data requirements and evaluate the data availability and reliability before deciding on the indicator type [99]. If comprehensive and high-quality data is available (i.e., detailed and accurate data on relevant parameters and processes), quantitative indicators can provide valuable insights into environmental impacts. However, when data limitations exist or certain impacts are difficult to quantify, hybrid indicators can be employed to capture information in a semi-quantitative form [100]. If no numerical evaluations are necessary, qualitative indicators can fill the gaps by narrating subjective or contextual information [100].

In addition to aspects related to data, the selection of the type of indicator should be well aligned with the intended goals of the assessment and the information needs of stakeholders [22,101]. Quantitative indicators are well-suited for the measurement of tangible environmental impacts, such as energy consumption or waste generation. Qualitative indicators are useful to capture subjective or non-measurable aspects, such as stakeholder engagement or perception of sustainability practices. Hybrid indicators combine both quantitative and qualitative elements to provide a comprehensive assessment, leveraging the strengths of both approaches.

Moreover, different stakeholders may need (or want) to prioritise different aspects of environmental performance and report them in a different way. Quantitative indicators are often preferred by stakeholders seeking measurable and comparable results to evaluate and compare different processes, products, or systems; they allow to track performance over time and to benchmark against sector standards or goals. Qualitative indicators are useful for narrative descriptions of environmental situations, as is done in the case of Environmental Impact Assessments (EIAs). They can facilitate engagement, dialogue, and decision-making processes.

5.1.3. Level of assessment

Firstly, regarding data, analysing different levels of the construction supply chain can present different challenges or barriers [102]. For example, it might be easier to collect data on material production processes than to track the environmental impacts of a building over time due to the different levels of complexity of data collection process. The level of assessment at which the analysis is conducted might define the indicators and methodology employed to evaluate them. For instance, at a micro level, quantitative indicators can be obtained following the LCA framework. At a macro level, more holistic approaches ought to be used to capture the whole system; for instance, the principles of EEIOA can be used to evaluate the indicators as they allow for consideration of interdependencies and flows across different sectors of the economy.

Apart from the availability of data, the accuracy and reliability of results may vary depending on the level of assessment. For example, assessments at the material or component level may be more precise in measuring the environmental impacts of specific processes or products but may not capture the full life cycle impacts of the construction supply chain. In fact, it is important to consider the limitations of the assessment level when interpreting the results and drawing conclusions. For instance, assessments at the building or sector level may provide a more comprehensive view of the impacts but may rely on assumptions or generalisations due to data limitations.

Secondly, it is crucial to recognise the variability in assessment outcomes depending on the level at which environmental performance is evaluated within the construction supply chain. Different levels of assessment—ranging from material, component, and building levels to sector-wide evaluations—can yield distinct insights, but also pose challenges in prioritisation and integration. For instance, while building-level assessments provide a holistic view of a structure's environmental footprint, they may overlook the environmental burdens embedded in upstream material production. Conversely, material-level assessments may have a more direct influence on supply chain sustainability, particularly if high-impact materials are substituted with more sustainable alternatives. Consequently, determining which level of assessment has the most significant leverage in improving the overall environmental performance of construction supply chains remains a critical challenge.

Lastly, a key issue in construction supply chain assessments is the comparability between different levels of analysis, as well as the potential trade-offs and synergies that arise when transitioning from one level to another. Focusing solely on the building level, for example, may obscure the upstream and downstream supply chain impacts, leading to incomplete assessments of environmental burdens. Likewise, improving the sustainability of a specific material could paradoxically increase environmental impacts at the building level if the material requires greater energy inputs for production, transport, or installation.

While the reviewed articles examined various levels of the construction supply chain—including materials, components, buildings, and sector-wide assessments—these levels are not inherently comparable due to differences in scope, data granularity, and modelling assumptions. Therefore, it is imperative to contextualise each level of assessment when comparing results across different studies. Furthermore, as assessments shift from simpler systems (e.g., individual materials) to more complex systems (e.g., entire buildings or sector-wide evaluations), the uncertainties related to data availability, measurement methodologies, and system boundaries increase significantly. This underscores the need to exercise caution when scaling results between levels, as oversimplification or overgeneralisation may lead to misinterpretations (e.g., directly comparing the impact of concrete as a material with that of an entire concrete building without accounting for contextual factors such as functional performance, lifespan, and structural dependencies).

Additionally, a broader examination of construction supply chain dynamics is necessary to fully capture the distribution and relevance of indicators across different supply chain links. Given the complex and multi-tiered nature of construction supply chains, it is essential to clarify how sustainability indicators are distributed across their various levels. A discussion around this topic is included in Section 5.2.

5.1.4. Environmental area assessed

The availability and quality of data may vary across different environmental areas, making it challenging to develop indicators for certain areas of focus [102]. For instance, data on biodiversity may be less readily available than data on air quality. Thus, it is important to understand well what data is available and to optimise it.

Related to the above question is the lack of standardisation of some indicators. Standardisation of indicators can help ensure consistency and comparability of results [103]. However, some of the indicators reviewed lack standardisation (e.g., biodiversity, circularity indicators), making it difficult to compare results across studies or regions.

While it is important to consider different areas of assessment separately, it is crucial to recognise the interconnectedness and interdependence of these areas. For example, addressing air pollution can also positively impact soil quality and biodiversity. Therefore, a holistic approach to environmental assessment that considers the multiple areas of assessment may be more effective than solely focusing on a few key indicators.

At the same time, prioritisation of environmental areas for assessment should be based on the most pressing environmental challenges and potential impacts. For example, if a construction supply chain is located near a sensitive ecological area, biodiversity may be a critical area of focus for assessment.

Given that pressure indicators define issues such as the release of substances (e.g., physical and biological agents) or the use of resources (e.g., land, water), in order to measure them, indicators describing construction activities, like inventory data, are useful. At an entity level, this can be evaluated using an LCT approach and applying adequate system boundaries for the object under study. At a system level, aggregated data is necessary. Additionally, given the extent of the environment, measuring the state differently for the three sublevels defined at an entity level is not easy.

The context is not only important for the definition of system boundaries and assumptions, but also for the selection of a set of indicators. Environmental challenges and priorities vary by region and sector, making it important to consider the local context when selecting indicators for assessment. For example, water scarcity may be a more pressing concern in some regions compared to air pollution.

5.2. Overarching challenge: construction supply chain dynamics

Indicators rely on data to quantify and assess environmental impacts, and in the case of construction supply chains, these data may originate from multiple tiers—ranging from raw material extraction and manufacturing to on-site assembly, operation, and end-of-life processes. Each tier involves distinct actors (e.g., designers, contractors, subcontractors, logistics providers, and demolition contractors) who may have differing priorities, data standards, and reporting practices [104,105]. This complexity underscores the need for a broader supply-chain perspective.

For instance, a material supplier is often concerned with resource extraction rates, embodied energy, and production emissions, while a demolition subcontractor focuses on waste sorting, salvage value, and end-of-life impacts. Gaps in data exchange or inconsistencies in measurement approaches across these actors can create bottlenecks for accurate indicator usage.

Moreover, supply-chain dynamics can alter data availability and reliability. Lower-tier suppliers might not systematically track indicators like water consumption or GHG emissions, whereas larger, well-established contractors may have sophisticated systems for energy or waste monitoring [106,107]. Accordingly, constructing a complete environmental profile of a single construction supply chain—encompassing micro, meso, and macro levels—requires orchestrating and harmonising different data collection methodologies, ensuring consistent system boundaries, and establishing robust protocols for data sharing.

These challenges emphasise the importance of a cohesive indicator framework that accounts not only for the inherent complexity of multi-tiered supply chains but also the potential for overlapping indicators among diverse levels of assessment. By aligning stakeholders on shared metrics and clarifying the responsibilities of each actor within the chain, project teams can more effectively coordinate environmental data collection, interpret aggregated results, and inform targeted improvements at the appropriate supply-chain link.

6. Conclusions

In this review, indicators assessing environmental aspects of construction supply chains were reviewed following the PRISMA guidelines. Quantifying and monitoring these indicators allow for a better understanding of the environmental impacts associated with construction supply chains and facilitate the development of targeted mitigation strategies.

A total of 226 articles were selected after database searching and screening processes, from which several indicators were extracted. The extraction of indicators allowed iteratively composing a taxonomy that can be used to describe and select indicators. This taxonomy builds on the types of indicators (i.e., quantitative, qualitative, hybrid), levels of assessment (i.e., micro, meso, macro), and areas of assessment (i.e., natural and anthropogenic dimensions).

The results of the review highlight several key challenges and recommendations that can be used to guide future research and practice in this area. The definition of metrics emerged as a crucial aspect. Clear definitions and boundaries for each indicator category are essential to ensure transparency, comparability, and meaningful insights. It is important to explicitly state the system boundaries, processes considered, and the origin of data, including whether it is based on primary data collection, secondary data sources, or models.

Regarding the type of indicator used, the most common indicator type is quantitative, within which ratio, absolute and proportion indicators are predominant. Among hybrid indicators, results showed that the most commonly utilised indicators are ordinal and interval scales. Selecting the appropriate type of indicator depends on the specific objectives of the assessment, the availability and quality of data, and the stakeholders' information needs. Quantitative indicators provide measurable and data-driven insights, while qualitative indicators capture subjective and contextual aspects. Hybrid indicators can offer a comprehensive assessment by combining quantitative and qualitative elements. Balancing the indicator types ensures meaningful insights and effective communication of environmental performance.

When comparing different levels of assessment, the results showed that some of the levels are underrepresented in the literature. Macro-level indicators, such as city-level or regional-level assessments, are less common. These require more comprehensive data collection and integration compared to assessments at the material or component level.

The level of assessment presents important considerations. Comparability across different levels of assessment requires careful attention to differences in scope, data granularity, and modelling assumptions. Trade-offs and synergies between different levels should be examined to identify potential impacts and prioritize assessment areas. The accuracy and reliability of results may vary depending on the level of assessment, and it is important to consider the limitations and data availability specific to each level.

The assessment of environmental concerns in construction supply chains has traditionally focused on a small number of indicators (i.e., GHG emissions, energy generation and efficiency, waste generation). Even though these indicators can provide important insights into currently pressing issues, comprehensive approaches that consider other environmental areas could enhance assessments and allow stakeholders to develop more robust and effective strategies to promote sustainable construction practices that minimise environmental impacts. In fact, the environmental area assessed must recognise the interconnectedness and interdependence of different areas. While focusing on specific areas is important, a holistic approach that considers multiple areas of assessment may be more effective. Standardisation of indicators is necessary to ensure consistency and comparability, and the local context should be considered when selecting indicators to reflect regional and sector-specific environmental challenges and priorities.

Looking ahead, there is a strong need to integrate internationally recognised data frameworks into useable assessment methods—whether at micro, meso, or macro levels—to improve comparability of results and ensure robust environmental accounting. Future work could also examine how advanced data-sharing platforms can build on these references, enabling consistent supply chain traceability and dynamic real-time updates, ultimately empowering construction stakeholders to make well-informed, lower-impact decisions. By combining a taxonomy-based approach to indicator selection with verified LCA data protocols, the construction sector can progressively overcome data barriers and evolve toward a truly transparent and sustainable supply chain culture.

CRediT authorship contribution statement

Irene Josa: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aiduan Borrion:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Irene Josa reports financial support was provided by UK Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100824.

Appendix

Table 3
Examples of environmental indicators aligned with each stage of the construction supply chain.

Stage	Major activities*	Key environmental aspects*	Example indicator	Typical units/ methods	Relevance	Scaling considerations
Inception & Design	Determine goals / aims / objectives. Develop project initiation proposal. Conduct feasibility studies. Carry out preliminary and detail design.	Selection of site, biodiversity, natural habitat. Potential land use, changes to local ecosystems	Embodied GHG emissions	kg CO_2-eq per m^2 (or per functional unit)	Highlights "cradle-to-gate" carbon footprint of materials and processes, guiding design teams to choose low-impact or recycled materials.	Difficult to scale from material level to whole-building impacts due to variations in material mix and energy sources.
			Resource scarcity indicator	kg Sb-eq (or other LCA-based measure)	Assesses depletion potential of abiotic/ critical resources; fosters careful selection of materials (e.g., less scarce metals, lower-impact minerals).	Scaling up requires national/global resource availability assessments; downscaling requires product/material-specific data.
			Land use (life cycle perspective)	m^2·year (or m^2) per functional unit	Evaluates land occupation and potential habitat disruption from sourcing materials or site preparation, encouraging minimal environmental footprint.	Land use impacts scale differently between project-level and regional/ global assessments; complex due to indirect land use change effects.
			Recycled content ratio	% of recycled/ reused content in design	Incentivises circular approaches from the start by specifying secondary or reused materials wherever feasible.	May not capture supply chain impacts; upscaling requires integration with circular economy strategies.
			Material toxicity potential	Qualitative screening or LCA-based (e.g., Comparative Toxic Unit)	Identifies hazardous substances in proposed materials, pushing for safer, lower-toxicity alternatives early in the project lifecycle.	Challenging to compare across different material systems; impact depends on exposure levels at product and site levels.
			Renewable vs. Nonrenewable energy inputs	% share of renewable energy in upstream processes	Encourages design teams to favour materials/ processes powered by renewable sources, reducing lifecycle emissions.	Material-specific analysis may not translate well to regional or national energy grid comparisons.
Construction	Mobilize resources. Transport resources to site. Carry out construction & installation (shell and core, finishes, etc.).	Atmosphere emissions (e.g., dust, GHG). Releases to water, landfill. Resource consumption, local issues. Risks of spills/accidents	On-site energy consumption	kWh or MJ used for site activities	Helps track electricity/ fuel demands of construction machinery and equipment, guiding energy-saving measures.	Micro-level tracking at the site may not be indicative of total project energy impacts; variations in machinery types add complexity.
			Dust & particulate matter emissions	μg PM_{10} or $PM_{2.5}$ per m^3 air; or total PM mass	Measures local air-quality impacts; important for mitigating worker exposure and neighboring communities' health risks.	Local air quality effects are highly site-specific; may not align with broader urban or regional pollution metrics.
			NOx and SOx emissions	kg NOx (or SOx) released per project or per unit of output	Captures combustion-related pollutants from equipment, ensuring	Requires downscaling from national emissions factors or real-time equipment

(continued on next page)

Table 3 (*continued*)

Stage	Major activities*	Key environmental aspects*	Example indicator	Typical units/ methods	Relevance	Scaling considerations
					compliance with air-quality regulations.	monitoring for accurate tracking.
			Process water consumption	m^3 of water used during construction	Tracks fresh water withdrawals for concrete mixing, dust suppression, etc.; encourages water-saving techniques onsite.	Difficult to compare across construction types; scaling up may require sector-wide water benchmarking.
			Construction waste generation	kg or tonnes of waste produced during project	Highlights leftover materials, packaging, offcuts, prompting on-site waste minimization and better resource management.	Micro-level tracking of waste may miss regional/ national circular economy trends.
			Hazardous waste proportion	% of construction waste that is classified as hazardous	Identifies presence of chemicals/paints/solvents requiring special handling or disposal.	Regional variations in hazardous waste classifications create challenges in comparability across projects.
Operation & Maintenance	Project management. Building operation and maintenance.	Resource consumption (energy, water). Pollutant emissions. Ongoing site impacts on flora/fauna.	Operational energy use	kWh or MJ per year (often normalized by floor area)	Monitors long-term energy demand for HVAC, lighting, equipment; key to evaluating building efficiency and retrofit needs.	Must be normalised for climate variations and occupancy patterns. Building-level assessments may underrepresent supply chain energy dependencies.
			Operational GHG emissions	kg CO_2-eq per year or CO_2-eq/m^2/ year	Addresses climate impacts of in-use phase; often the largest share of building's life-cycle emissions.	Downscaling must account for regional energy mix. Dependent on efficiency of building systems, and maintenance practices.
			Water efficiency rate	Ratio of reused/ treated water to total water consumption	Encourages greywater systems, rainwater harvesting, or closed loops to cut operational water footprint.	Scaling depends on site-specific reuse potential and infrastructure availability for water treatment. Requires regional consideration of water scarcity levels
			Pollutant emissions (operation)	E.g., kg CO, NOx per year from fossil-based heating/cooling	Tracks local air-quality impacts, indicating whether more sustainable energy systems or building upgrades are needed.	Difficult to scale across different building types; emissions intensity depends on site energy sources.
			Maintenance resource consumption	kg or tonnes of replacement/ repair materials per year	Reflects the need for ongoing upkeep or refurbishment, prompting use of long-lasting materials and strategic maintenance planning.	Impacts depend on building age, material durability, and quality of preventive maintenance. Up-scaling requires long-term monitoring and LCA forecasting.
			Stormwater management indicator	% of stormwater captured or infiltration rate (m^3 infiltration / m^2)	Encourages systems to manage runoff onsite, reduce flooding risk, and protect local water bodies from pollution.	Stormwater effects are highly dependent on local hydrological conditions; requires site-level calibration.
Demolition	Demolition and disposal of building components	Waste disposal, landfill. Operation of demolition. Potential for salvage / recycling.	Demolition waste generation	kg or tonnes of debris per building or infrastructure asset	Quantifies total volumes at end-of-life, highlighting possibilities for resource recovery or landfill burden.	Varies widely based on building materials and deconstruction methods used.
			Landfill diversion rate	% of demolition waste diverted to reuse/recycling	Encourages salvage and recycling, measuring how effectively material is kept out of landfills.	Difficult to establish meaningful comparisons between projects. Depends on regional recycling facilities, labour, and market demand for recovered materials.
			End-of-life GHG emissions	kg CO_2-eq from demolition processes, hauling, disposal	Captures carbon impacts of equipment usage and waste treatment, driving lower-impact deconstruction methods.	May vary based on building type. Scaling up requires sector-level assessments of waste management and emissions policies.
			Reusability / salvage potential	Hybrid rating scale or ratio of recoverable components	Evaluates feasibility of disassembly and reuse of key materials, vital for circular economy strategies.	Heavily dependent on initial design decisions (e.g., modularity, fasteners used). Requires integration

(*continued on next page*)

Table 3 (*continued*)

Stage	Major activities*	Key environmental aspects*	Example indicator	Typical units/ methods	Relevance	Scaling considerations
						with material tracking databases.
			Hazardous materials in demolition	kg or % of total demolition materials deemed hazardous	Ensures safe removal and disposal of toxins (e.g., asbestos, lead paint), critical for worker and environmental protection.	Varies based on historical construction practices and regional regulations. Site-specific hazardous material presence complicates scaling.
			Water usage in deconstruction	m^3 of water per tonne of demolished material	Monitors water for dust suppression and salvage cleaning, highlighting additional resource needs in demolition phase.	Difficult to compare across projects; depends on deconstruction methods and water reuse practices.

*Adapted from Thanu et al. [74].

Data availability

Data will be made available on request.

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