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Indicator-based environmental and social sustainability assessment of hospitals: A literature review

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ABSTRACT

The healthcare sector's direct and indirect GHG emissions account for 4%–5% of global net emissions. Hospitals face the challenge of sustainable transformations and need to measure, monitor, and report on their sustainability performance. While indicator-based assessments of hospital sustainability have received increased attention over the last years, they are heterogenous in their terminologies, categories, and included indicators. This study reviews taxonomies and included indicators in hospital sustainability assessments, laying the foundation for future developments of consistent indicator-based assessments. The objective is to (1) critically review existing assessments of hospitals; (2) identify relevant sustainability topics in a hospital context and derive a best-practice categorization; (3) highlight thematical gaps. Based on the PRISMA method, we identify 88 relevant articles. First, 47 articles (comprehensive hospital sustainability assessments with extensive indicator sets) are reviewed, forming the basis for deriving a best-practice categorization. Second, considering an additional 41 articles (proposing indicators for specific hospital aspects), we collect all indicators and compile a consolidated indicator pool. We find substantial variations in the taxonomies and terminologies of the reviewed articles; most notably, there is a disagreement about what constitutes an indicator. 73% of all consolidated indicators are qualitative, and 78% are site-specific. Thematical gaps relate to sustainability along upstream and downstream value chains (esp. food and pharmaceuticals) and quantitative social indicators in general. The developed best-practice taxonomy and the compiled indicator pool serve as a comprehensive basis for future sustainability assessments of hospitals.

1. Introduction

The purpose of the healthcare sector to contribute to a healthy and sustainable society contrasts with the significant impacts healthcare services and, most notably, hospitals exert on the environment and society – both on-site and along the upstream and downstream value chains (Karliner et al., 2019). Hospitals consume significant amounts of energy, water, and other resources (González et al., 2018; Rohde and Martinez, 2015; Tay and Singh, 2021) and produce considerable quantities of (hazardous) waste (Tsakona et al., 2007; Zamparas et al., 2019). Most notably, the healthcare sector's direct and indirect GHG emissions are estimated to account for about 4.4% of global net emissions in 2014 (Karliner et al., 2019; Pichler et al., 2019). Hospitals in particular are responsible for a large share of the sector's environmental burdens (Keller et al., 2021). At the same time, hospitals are a social hotspot, with issues such as high workloads and stress (Koranne et al., 2022), challenging employment conditions (Aiken et al., 2013), and health risks (Uebel et al., 2007), most notably during the COVID-19 pandemic (Morawa et al., 2021). In contrast to the primary purpose of the healthcare industry, its high environmental and social impacts threaten human and planetary health. Thus, hospitals are arguably unsustainable by definition in that they fulfill current needs by compromising the ability of future generations to meet their own needs. This contradiction explains the increasing interest of academia and policy in reducing the negative impacts of hospitals (Hensher and McGain, 2020; WHO, 2017).

In alignment with corporate social responsibility, sustainability in

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the hospital context is defined by integrating social and environmental concerns into business operations (Costa et al., 2022). On the one hand, this is crucial to ensure a sustainable and equitable future, as current practices are "causing indirect public health damages and increasing healthcare service needs" (Sherman et al., 2020, p. 8). On the other hand, the "advantages of sustainability practices will eventually be translated through improved earnings, higher product [or service] quality […], cost saving that results from sustainable logistics and supply chain, and minimal environmental liability and legislation costs" (Hanaysha et al., 2022, p. 68). To increase hospital sustainability, "minimizing, controlling, and mitigating all the environmental impacts" (Jiménez-Lacarra et al., 2022, p. 2) from, e.g., water and energy consumption, toxic chemicals, health-care waste, or wastewater is necessary (WHO, 2017). Quantitative methods such as environmental and social Life Cycle Assessment (LCA, S-LCA) are, albeit with varying degrees of maturity and data availability (Valdivia et al., 2021), the most advanced and standardized methods for environmental and social impact assessment in the scientific community (Curran, 2013; Ramos Huarachi et al., 2020). However, an Organizational LCA or S-LCA of an entire hospital requires a wealth of foreground data (e.g., data on energy, water, procured goods, and all physical inputs and outputs, additionally site-specific social and socioeconomic data; Cimprich and Young, 2023) and suitable background data (matching items of generic databases with the foreground data). The complexity of both gathering a hospital's comprehensive data and conducting a complete LCA for it leads to the fact that LCAs and S-LCAs of entire hospitals are virtually non-existent; the comprehensive, organizational LCA studies of Cimprich and Young (2023) and Keller et al. (2021) being rare exceptions. In addition, LCA and S-LCA also have limitations when assessing certain sustainability aspects, ranging from microplastics to staff awareness of sustainability. Here, indicators can be a tool to convey information "in a simple and useful manner" (Ramos and Pires, 2013, p. 82) and a viable approach. They classify observations of real objects to evaluate unobservable phenomena and thus reduce complexity (LUSTAT, 2012; Meyer, 2004). In contrast to, e.g., modeling product systems and performing impact assessment in LCA, directly measurable indicators (e.g., *energy consumption per bed* or *employee turnover*) are interpretable without expert knowledge and, due to their ease of application, allow for continuous monitoring over time (Madden et al., 2020; UN, 2009). Furthermore, indicators help to assess the effect of, for instance, policies, decisions, or changes (Faezipour and Ferreira, 2011). They can support managers and policymakers in formulating strategies to address healthcare-specific sustainability challenges (Mehra and Sharma, 2021). Thus, for hospital sustainability assessments that can be carried out regularly by managers and academia, an indicator-based approach is the most suitable option. To ensure that indicators serve their intended purpose, they are often organized in a framework (Ramos and Pires, 2013).

Despite the advantages that indicator frameworks yield for complex systems such as hospitals, application scopes, and assessment processes for indicator selection and structuring vary strongly in the literature (Carnero, 2014; Guo et al., 2015), and so far, a standardized and comprehensive indicator set is not yet available. Multiple recent references identify the development of internationally comparable, validated, and standardized sustainability indicators as a future challenge for consistent and comparable assessments (Hensher and McGain, 2020; Salas et al., 2020; Sherman et al., 2020). However, Ness et al. (2007) also claim that hospital sustainability assessment methods should reflect site characteristics.

Thematically, indicator-based sustainability assessments of hospitals focus on different subject areas. Previous studies find that existing assessments mainly target the built environment or the environmental assessment perspective (Buffoli et al., 2015; Capolongo et al., 2016). Typical research areas in the healthcare sustainability discourse are green building certification systems like *LEED*, *BREEAM*, *CASBEE*, *GreenStar*, or *DGNB*, as well as more integrated assessments from academia, such as *SustHealth* from Italy and *HBSA-PT* from Portugal (Buffoli et al., 2015; Castro et al., 2017b). The differences between them, as well as other norms and standards (e.g., ISO 14001) in terms of thematical coverage, have been the subject of several previous studies (Castro et al., 2017a; Khosravi et al., 2019; Sahamir and Zakaria, 2014).

However, a recent study by Cimprich and Young (2023) finds that the environmental sustainability of hospitals is strongly influenced, if not dominated, by impacts along upstream and downstream value chains. Related studies confirm that environmental impacts associated with purchases exceed those from on-site operations for all impact categories (Karliner et al., 2019; WHO, 2017; Yang et al., 2017). Hence, several studies point out the need to discuss sustainability differentiated between upstream, on-site, and downstream levels (Cimprich et al., 2019; McGain and Naylor, 2014; Sherman et al., 2020) and Seifert et al. (2021) determine issues that hospital management needs to address for improving environmental performance across all value chain stages. Socially, while hospitals are obvious "melting pots" (Capolongo et al., 2016, p. 15) with several social issues (as mentioned before), hospitals' upstream and downstream supply chains may also be linked with social hotspots. However, to our knowledge, comprehensive studies of social impacts along entire value chains of inpatient healthcare services, analogously to environmentally focused ones by Cimprich and Young (2023) or Keller et al. (2021), do not exist yet.

To harmonize future sustainability assessments of hospitals, a comprehensive overview of existing indicators for environmental and social hospital sustainability assessment on upstream, site, and downstream levels is required. Therefore, the study at hand sets out to answer the following research question:

RQ: Which environmental and social hospital sustainability indicators exist in the literature, and how can they be structured to enable comprehensive assessments of hospital sustainability?

To answer the research question, a structured literature search and review is conducted (step A). Section 2.1 describes the methodology applied to identify relevant articles. This includes the definition of the review scope, the conceptualization of keywords, and the literature search process. The relevant literature is then classified (step B) according to their assessment scopes (e.g., the healthcare system as a whole, entire hospitals, hospital divisions, or specific aspects such as waste management). The studies are then analyzed regarding their terminologies and taxonomies, i.e., their approaches to hierarchically structure and categorize indicators. From this analysis, a best-practice taxonomy, i.e., indicator structure and categorization, is derived (step C). Lastly, we gather and consolidate all environmental and social indicators proposed in the identified articles and analyze this compiled indicator pool regarding thematical coverage and gaps (step D).

2. Methodological approach

The following subsections describe the methodological approach (step A–D) for identifying and structuring indicators for environmental and social hospital sustainability assessments.

2.1. Step A: literature search

To identify relevant studies, a systematic literature review is conducted that is based on the framework proposed by vom Brocke et al. (2009) and on the 'Preferred Reporting Items for Systematic Reviews and Meta-Analysis' (PRISMA method; Page et al., 2021). The PRISMA method proposes a reliable and transparent process that ensures replicability and is commonly used for literature reviews (Obucina et al., 2018). Based on a preliminary search, a four-sided set of keywords is conceptualized (see supplemental digital content, SDC1, Table S1). Keywords relate to the questions '*What* is the objective?' (e.g., "sustainability", "green", "assessment", "evaluation", "framework"), '*How* is the objective assessed?' (e.g., "indicator", "measure", "performance", "criteria"), and '*Where* is the assessment applied?' (e.g., "hospital", "healthcare facility", "healthcare building", "healthcare system").

Especially for the terms ‘indicator’ and ‘hospital’, several possible synonyms need to be included, as well as the term ‘healthcare’, due to the observation that some assessments of the healthcare system in general also include assessments of hospitals. Subsequently, suitable search strings are developed for the search databases Web of Science, PubMed, and Google Scholar (Table 1) and adjusted according to the requirements of the different databases. We choose Web of Science as the basis of the search, covering a wide range of journals and offering a good density of relevant articles, PubMed to ensure specifically healthcare-related and medical articles are covered, and Google Scholar to round out the search and identify relevant articles that have possibly been missed hitherto, despite its “inconsistent accuracy” (Falagas et al., 2007, p. 338).

The search was conducted in May and June 2022 and was not limited to specific journals, article types, or time periods. It resulted in a total of 3077 titles screened (see SDC2, sheet A1). First, 140 articles are excluded as duplicates. Then, title, abstract, and keywords are screened for two inclusion criteria: (1) hospitals or their subdivisions are the assessed subject; (2) the sustainability assessment is based on indicators. Subsequently, 158 articles underwent full-text screening, which resulted in the exclusion of 75 more articles. This comprises, inter alia, articles that assess aspects of the healthcare system beyond the hospital context (e.g., macro-economic assessments, assessments of healthcare insurance), articles that do not address environmental or social sustainability (e.g., financial assessments, marketing), articles with a sole focus on further actions without including status-quo assessments, or articles in another language than English. In turn, a backward search yielded five more articles. Finally, **88 relevant articles** are identified (see SDC2, sheet A2).

2.2. Step B: classification of literature

These 88 articles are then classified in terms of their assessment scope. Sherman et al. (2020) propose a six-level hierarchy for healthcare emissions research. Cimprich et al. (2019) categorize literature on healthcare system and hospital level (but foremost differentiate between foreground and background systems). Similarly, after screening the identified studies, we identify four assessment scopes of possibly relevant literature. Fig. 1 summarizes the described literature selection process, based on the flow chart proposed by the PRISMA method, and shows the categorization of the articles and how they are included in this review. As depicted, we distinguish between.

- ➢ Level 0 (4 articles): articles that assess the healthcare system as a whole (including hospitals as subsystems),
- ➢ Level 1 (43 articles): holistic assessments on the level of an entire hospital,
- ➢ Level 2 (4 articles): assessments of a hospital division (such as the OR, the ICU, or the canteen), and
- ➢ Level 3 (37 articles): assessments relating to a specific aspect within a hospital (such as (im)material input or output, e.g., energy, food, or waste; or a specific (non-)medical process, e.g., surgeries or cleaning).

2.3. Step C: categorization

In step C, we derive a comprehensive list of categories that indicator-based assessments of hospitals should include. First, we discuss the terminologies used (used vocabulary, synonyms, and understanding of what an indicator *is*) and how indicator sets are structured in the literature. In SDC1, we provide further information on how indicators are identified & selected (i.e., the reasoning behind incorporating the proposed indicators), prioritized (e.g., determination of relative importance), applied (i.e., whether the proposed indicators have been used for a practical assessment or not), and aggregated (i.e., how indicators are, if applicable and sensible, to be aggregated). Second, the categories (and other categorizing elements) employed in the literature are clustered based on verbal similarities, from which the categories of the study at hand are derived (cf. SDC1, Fig. S3; SDC2, sheet A3). As this is supposed to represent the state of the art of structuring comprehensive hospital sustainability indicator sets, we only include the 47 articles on levels 0 and 1 in this step (cf. Fig. 1), as those articles on levels 2 and 3 are, by definition, characterized by a narrower perspective on specific aspects.

2.4. Step D: compilation of a consolidated indicator pool & analysis of thematical coverage

Lastly, all 88 articles on all levels 0 to 3 are reviewed for their indicators (section 3.2). All indicators are collected and consolidated (e.g., removal of ideational redundancies), resulting in the unified indicator pool (SDC2, sheet A4). Identifying indicators from the literature proved to be the most intricate step due to the heterogeneous understanding of what constitutes an indicator (as shown in section 3.1.1). For example, a ‘criterion’ could be akin to a category in one study (e.g., Bottero et al., 2015), a sustainability dimension in another (e.g., Mehra and Sharma, 2021), and something readily measurable in a third (e.g., Aliakbari Nouri et al., 2019); one study could label something an ‘indicator’ that is used to group subordinate elements (e.g., Nilashi et al., 2015, use i.a. *energy efficiency* to group subordinate ‘parameters’), while others use ‘indicators’ and ‘metrics’ synonymously (e.g., Duque-Uribe et al., 2019). Here, we decided based on the following rule. When an element either implies a **unit** or is to be primarily evaluated as part of an audit checklist with a **Y/N** (yes/no) assessment, it is considered a (quantitative or qualitative) indicator. For instance, *reduction in energy consumption* implies a unit, while *compliance with environmental and social value standards* is considered a qualitatively assessable indicator (Y/N or qualitative ratings; Duque-Uribe et al., 2019).

All identified indicators are then assigned to the categories of the

Table 1
Search string formulation.

Database	Date of search	Search hits – total – screened	Search string
Web of Science	May 22, 2022	2027 2027	TS=((Sustainab* OR green) AND (assess* OR evaluat* OR framework) AND (indicator$ OR measure* OR performance OR criteria) AND (hospital$ OR "healthcare system$" OR "health care system$*" OR "healthcare facilit*" OR "health care facilit*" OR "healthcare building$" OR "health care building"))
PubMed	June 16, 2022	850 850	Sustainab*[tiab] AND (framework[tiab] OR assess*[tiab] OR evaluat*[tiab]) AND (indicator*[tiab] OR measure*[tiab]) AND hospital*[tiab]
Google Scholar	May 14, 2022	>138,000 200	sustainability indicators healthcare hospital

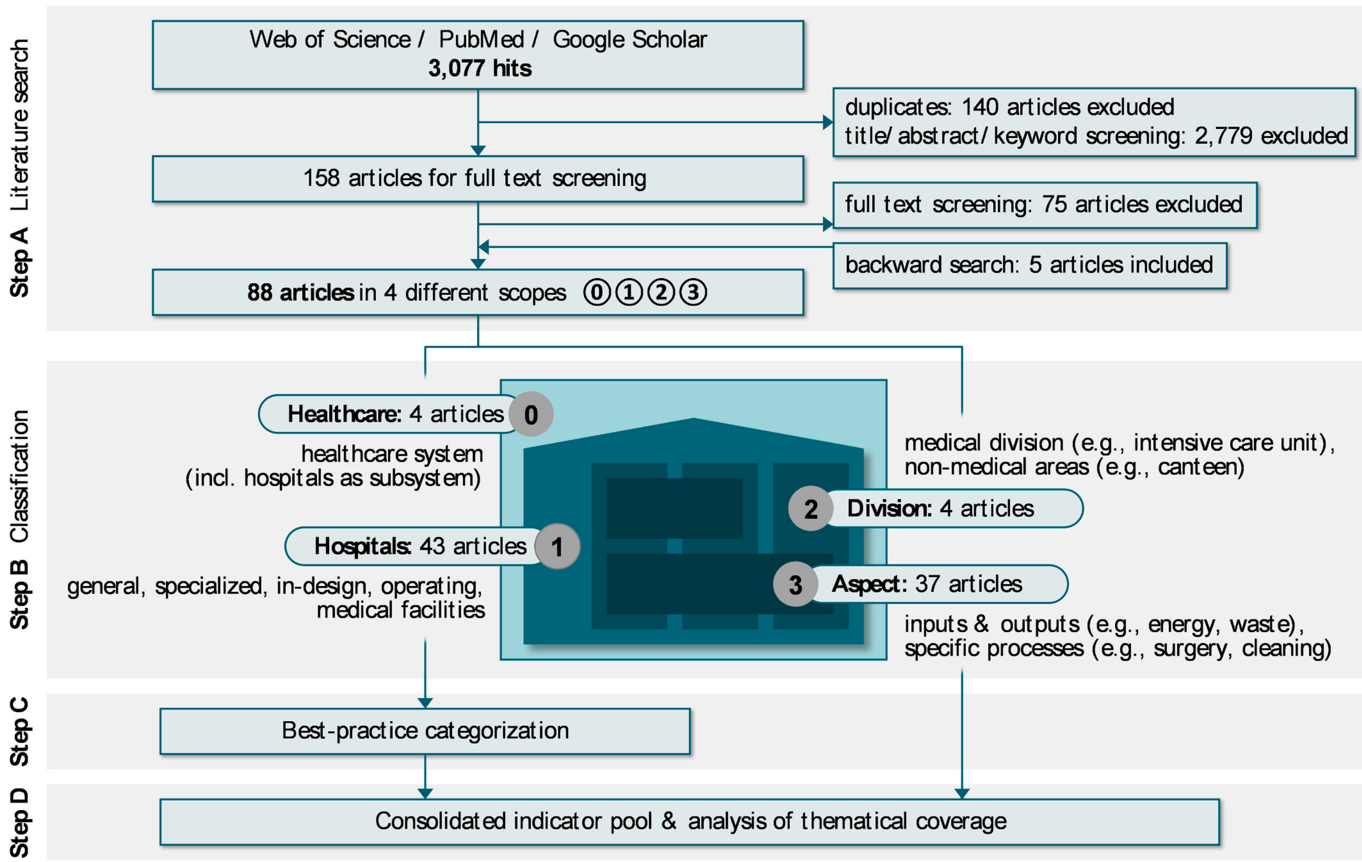

Fig. 1. Flow chart for PRISMA-based literature selection, literature classification, categorization, and thematical coverage of gathered indicators.

best-practice structure derived in step C. Additionally, they are further clustered thematically to allow for an analysis of the thematic coverage, which reveals research gaps in the current state of the art and under-represented hospital areas and aspects.

It bears mentioning that several articles on levels 0 and 1 refer to identical, previously published indicator sets or parts of them. This is shown in SDC1, Table S2. When reviewing indicator set-specific features (e.g., categorization), we cite the most recent, relevant, and/or detailed of the associated studies as reference. For example, both Castro et al. (2015b) and Sahamir and Zakaria (2014) compare assessment elements of healthcare building sustainability assessment (HBSA) tools. The former are selected as reference, as they provide a compilation of the four most cited HBSA tools *LEED*, *BREEAM*, *GreenStar*, and *CASBEE*. A total of five studies contribute to the development of SustHealth (v1), for which the final result is provided by Bottero et al. (2015). Brambilla et al. (2020) present a first study on the development of SustHealth (v2), which was only recently complemented by Brambilla et al. (2022). Lastly, as expected, several studies also refer to impact categories from LCA, which are thus also only included once (with Keller et al., 2021, as reference).

3. Results

Section 3 includes the analysis of taxonomies in the identified literature, the derivation of a best-practice categorization (section 3.1), and a description of thematical coverages and gaps (section 3.2).

3.1. Taxonomy for environmental and social hospital sustainability assessments

Section 3.1 reviews the taxonomies of level 0 and 1 articles. This includes the terminologies used and structures in which indicators are arranged (section 3.1.1), as well as the categorization the reviewed articles employ, leading to a best-practice categorization (section 3.1.2).

3.1.1. Structures and terminologies of indicator sets

Generally, the vast array of structures and indicator definitions renders comparing different indicator-based healthcare assessments intricate (Brambilla and Capolongo, 2019; Castro et al., 2015) – from synonyms for the term indicator to various understandings and interpretations of the term and different hierarchical structures. First, different studies use different terms for what qualifies as an indicator. For example, Nagariya et al. (2022) use the term '(sub)attribute', while Jahani Sayyad Noveiri and Kordrostami (2021) refer to 'input measures' and 'output measures'. Other employed terms are, for instance, '(sub-) criteria', 'factor', or 'measure' (Al Hammadi and Hussain, 2019; Aliakbari Nouri et al., 2019; Chang et al., 2018; Mehra and Sharma, 2021; Wong et al., 2018). Second, the observed studies show different understandings of what indicators should be. Zhan et al. (2022) distinguish between 'first-level' and 'second-level' indicators for a green hospital pre-evaluation. First-level indicators refer to general aspects of green hospital buildings (e.g., indoor comfort) and are determined by several specific second-level indicators (e.g., indoor natural lightning) that are assessed through simulation. Wong et al. (2018) apply a list of key performance indicators from other industries to the healthcare context with varying granularity. Indicators such as the *hospital's age* or *operating costs* imply measurability, while indicators such as *technology*, *service reliability*, and *continuous improvement* are not directly measurable and require further specification by other, subordinate indicators. Similarly, hospital building certifications use a subordinate 'item' level for some indicators (Brambilla and Capolongo, 2019).

Several studies distinguish between individual and composite indicators (OECD, 2008; Rovan, 2011). Individual indicators come with a quantitative or qualitative and ideally unambiguous measurement system comparable over time (Brambilla et al., 2020; Guo et al., 2015; Romero and Carnero, 2019). For example, Romero and Carnero (2019) place individual indicators on the lowest level of a five-level hierarchy and provide indicator-specific qualitative or quantitative evaluation methods. Likewise, Pederneiras et al. (2023) develop a three-level hierarchy and use individual indicators to operationalize the lowest hierarchy level. Khosravi et al. (2019) measure individual indicators in time units within an exponentially distributed stochastic model. They attribute them directly to the Triple Bottom Line (TBL) dimensions. Migdadi and Omari (2019) compile a one-dimensional list of quantitative indicators to assess the environmental sustainability of hospital operations. Here, each indicator is given a unique unit. Ryan-Fogarty et al. (2016) even use the term indicator as a synonym for 'unit'. Composite indicators, on the other hand, combine individual indicators to describe multi-dimensional concepts and to convey aggregate information to policy, management, and the general public (Brambilla et al., 2020; Ramos and Pires, 2013; Rovan, 2011). They thus potentially leave room for interpretation and actual quantification. If poorly constructed or misinterpreted, composite indicators can send misleading messages (OECD, 2008). For instance, Castro et al. (2017a) develop a three-level hierarchy for assessing healthcare building sustainability with composite indicators on the lowest level. Their indicators, e.g., *toxicity of finishing materials*, *waste separation & storage*, or *infection control*, would require individual indicators on a subordinate hierarchy level to be quantifiable. Nilashi et al. (2015) use the term indicator for broader thematical clusters such as *material, waste and pollution* or *occupants' satisfaction*. They define so-called parameters to describe the indicators. Lastly, some studies also refer to LCA impact categories (e.g., *global warming potential*, *human toxicity*, or *land use* as indicators (Keller et al., 2021; Stevanovic et al., 2019). For completeness, we also include those studies in the review at hand, although they usually pertain to different types of assessments with different advantages and disadvantages (cf. section 1).

Some indicators or subordinate elements carry identical names but are allocated to different dimensions by the authors, indicating different assessment goals and multidimensional relevance. For instance, *noise pollution* is used by Romero and Carnero (2019) within the environmental dimension, while Bottero et al. (2015) and Djukic and Marić (2017) assign it to the social dimension. An exemplary environmentally-focused indicator is the *noise level in dB* at specified distances outside the hospital (Carnero, 2020), while indicators for patients' noise perception inside are assigned to the social dimension (Djukic and Marić, 2017). Likewise, energy efficiency aims to reduce environmental impacts while also entailing economic benefits, although authors mostly categorize it in the environmental dimension (e.g., Duque-Uribe et al., 2019; Chang et al., 2018; Bottero et al., 2015). On the one hand, Nilashi et al. (2015) use *energy efficiency* to summarize the subordinate elements *building envelope performance*, *renewable energy*, and *natural lighting*. On the other hand, they use *energy efficiency* on a subordinate level within a *cost and economic* category. Moreover, some studies classify indicators according to their cause, some according to their effect. For instance, Pantzartzis et al. (2017) allocate *space flexibility* to the *built environment & functionality* category, focusing mainly on the cause. At the same time, it is used by Djukic and Marić (2017) for patient and employee satisfaction, focusing exclusively on the effect.

Therefore, to accommodate different hierarchical understandings of the term 'indicator' and to thus allow for a shared understanding and better comparability in this study and beyond, several hierarchical levels are needed in an indicator set. In addition, the different usages of the term indicator likely reflect different perspectives on assessing sustainability practically (e.g., indicator sets such as SustHealth for evaluating hospitals; Bottero et al., 2015) or more theoretically (e.g., Khosravi et al., 2019).

To address the issues mentioned above and to accommodate said differences, we propose a five-level structure. In line with common definitions (Meyer, 2004), we propose to use the term 'indicator' for practical (quantitative or qualitative) evaluations (e.g., *water consumption in m^3*; *electricity consumption in kWh*). For cases where the same indicator can or should further distinguish between divisions of the hospital or other aspects (e.g., *water consumption in m^3 in the canteen* or *in the operating rooms*; *electricity consumption in kWh from rooftop photovoltaics* or *from the local grid mix*), we introduce 'sub-indicators'. For grouping very similar indicators or for cases where a study uses the term indicator more in the sense of a composite indicator (e.g., *energy use*), we propose 'indicator groups'. They are further categorized into 'categories' (e.g., *energy*), which are assigned to a sustainability 'dimension' (e.g., *environmental*). Bottom-up, n:1 relationships are used for simplicity, even though, in reality, one hierarchical element may affect more than one superordinate element (e.g., indicators in the category *food* may have both environmental and social implications). The hierarchy and terminology are presented in Table 2.

3.1.2. Best-practice categorization

For sustainability assessments in general, a plethora of different thematical clusters exist, i.e., how indicators are grouped, how indicator groups are categorized, and how categories are assigned to a sustainability dimension (Fiksel et al., 2013). This is also true for hospital sustainability specifically. The variations observed in the identified literature mainly concern the number, range, and depth of thematical clusters. They indicate the importance of an unambiguous, well-defined, and goal-oriented categorization to support the indicator selection process and to contribute to increased assessment objectivity (Fiksel et al., 2013; Jahani Sayyad Noveiri and Kordrostami, 2021).

On the level of sustainability **dimensions**, 21 of 32 indicator sets are based on the TBL (e.g., Bottero et al., 2015; Chang et al., 2018; Mehra and Sharma, 2021; Pederneiras et al., 2023; Nilashi et al., 2015). Nagariya et al. (2022) add *customer management* and *health and safety risk management* as separate dimensions. Pantzartzis et al. (2017) introduce *built environment* and *technological environment* instead of a single environmental dimension. Castro et al. (2017a) similarly introduce the two dimensions *site* and *technical* but also maintain an environmental dimension. Aliakbari Nouri et al. (2019) propose the four dimensions *financial*, *supply chain*, *stakeholder*, and *learning, growth, and innovation*. Lastly, no overarching dimensions are used in nine cases (e.g., AlJaberi et al., 2020; Moldovan et al., 2022; Pinzone et al., 2012).

Categories have a higher granularity than dimensions, and different goal definitions among the observed literature lead to a broad range of included topics and categorizations (e.g., energy, waste, mobility). For deriving the hereafter proposed best-practice categorization, we group all categorizing elements (e.g., categories, groups, criteria, topics, and similar elements that group or subsume other elements, such as indicators, on a lower hierarchical level) used in articles (levels 0 to 1) according to verbal similarities in their designations, leading to a consolidated categorization that subsumes all topics covered in the literature. For example, the categorizing element 'Materials and resources' (Bottero et al., 2015), respectively is clustered with other

Table 2
Terminology for a five-level indicator-based sustainability assessment structure.

Theoretical	Dimension	Broader thematical areas; here: *environmental & social dimension*	
	Category	Thematical area that can be assigned to a dimension (e.g., *energy*)	
	Indicator group	Groups indicators according to their goal (e.g., *energy use*)	
Practical		**Quantitative**	**Qualitative**
	Indicator	−measurable −has/implies a unit (e.g., *electricity consumption in kWh*)	−rating scales −Y/N
	Sub-indicator	−measurable −fraction of an indicator (e.g., *electricity consumption of the ICU in kWh*)	

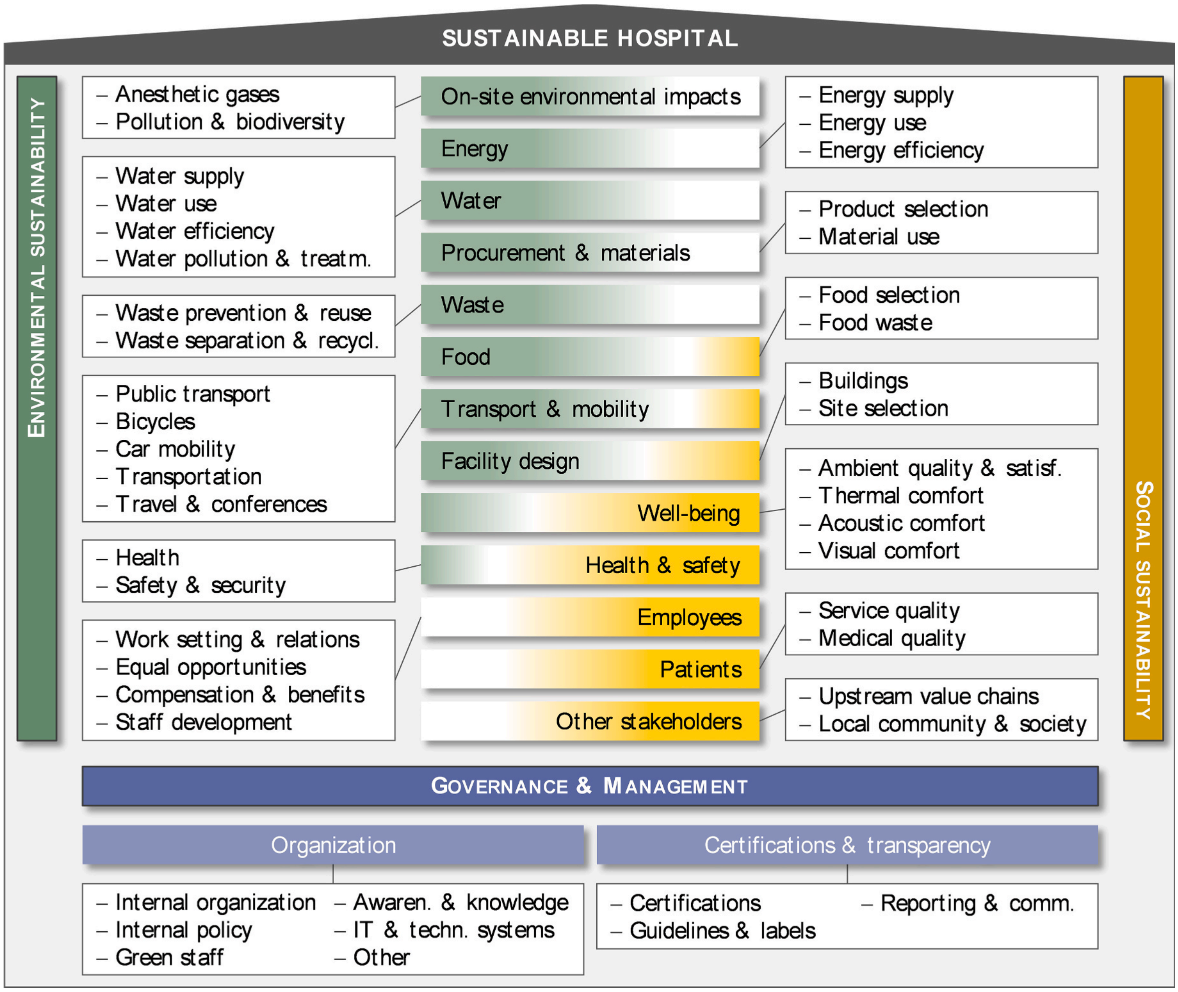

Fig. 2. Overview of the best-practice indicator pool taxonomy on category and indicator group level.

verbally resource- or material-related elements (e.g., ‘resource utilization’, ‘resource conservation’, ‘procurement and consumption of resources’, etc.) of other studies. The entire process is described and visualized in SDC1 (Fig. S3) and presented in full in SDC2 (sheet A3). Categories are further subdivided into **indicator groups** to allow for a thematic analysis of covered topics. While categories are derived from the described approach, indicator groups are derived by grouping the identified indicators (of all articles on levels 0 to 3) in a category based on their goal. Indicator groups are further explained in the subsequent section 3.2.

Summarizing, the hereafter proposed **best-practice categorization** (Fig. 2) comprises an environmental dimension with eight categories and a social dimension with five categories. Additionally, in alignment with principles of corporate social responsibility assessments and the interrelated ESG (environment, social, governance) criteria (Costa et al., 2022), we propose an overarching *Governance & management* dimension (two categories) that includes technical topics, certifications, and managerial and organizational topics such as sustainability education and awareness, governance, or the inclusion of sustainability topics into strategic planning. Economic topics or topics unrelated to sustainability are not included here.

The categories within the ***Environmental dimension*** cover all inputs (e.g., energy or raw materials) and outputs (e.g., waste or emissions) relevant to the hospital operations. The category **On-site impacts** contains indicators referring to direct environmental impacts of the hospital (analogous to what is defined as ‘scope 1’ emissions in the GHG Protocol; except for aspects already covered by other categories, e.g., Energy or Transport & mobility). Next, **Energy** and **Water** cover aspects of supply, (economical) use, efficiency, and, in the case of water, pollution & treatment. The category **Transport & mobility** subsumes mobility aspects of patients and employees as well as internal and external logistics. **Facility design** covers indicators regarding site selection and the design and construction of sustainable buildings and areas. Within **Procurement & materials**, aspects of purchasing and consuming all kinds of materials are covered (except for **Food**, which is a separate category due to its high relevance). Lastly, **Waste** includes all aspects of the waste hierarchy (prevention, reuse, recycling, recovery, and disposal).

The categories in the ***Social dimension*** are partially based on a stakeholder perspective (e.g., as defined by the Guidelines for Social Life Cycle Assessment of Products & Organizations, UNEP et al., 2020: workers, consumers, society, local community, value chain actors, and children). Adapted to the hospital context, the best-practice categorization includes **Employees**, **Patients** (corresponding to consumers), and **Other Stakeholders** (subsuming all stakeholders outside the hospital, e.g., local community, society, children, suppliers, etc.). The stakeholder-based categorization is supplemented by the two cross-stakeholder categories **Health & safety** (addressing issues such as infections, security, and emergencies) and **Well-being** (covering issues such as ambient quality, comfort, and overall satisfaction), due to their apparent importance in the hospital context.

All indicators that cannot be assigned to solely environmental or social sustainability are subsumed under ***Governance & management***. This dimension includes indicators for obtained certifications and labels, adhering to existing guidelines, and transparent sustainability reporting (category **Certifications & transparency**), as well as the overarching organizational structure (category **Organization**) of a hospital (related to sustainability management, e.g., employing sustainability commissioners, existing sustainability policies, green IT, and awareness for sustainability).

Naturally, some environmental topics are also particularly related to social issues and vice versa. For example, *Facility design* and *Ambient quality & well-being* are two inherently related categories, and articles with corresponding categories differ in whether they understand these categories primarily environmentally or socially. For simplification and applicability beyond this study, we apply a 1:n relation, meaning that a category is matched to precisely one dimension, one indicator group to one category, and an indicator to one indicator group.

3.2. Consolidated indicator pool & thematical coverage

Lastly, we present the synthesized pool of existing environmental and social indicators and an analysis of all identified indicators on a thematic level. To allow for a thematical analysis, indicators are assigned to the predefined categories (inner rings in Figs. 4–6; see section 3.1.2) and clustered thematically. This thematical clustering results in the subsequently introduced indicator groups (outer rings).

All articles on all levels 0 to 3 are analyzed for the indicators they use or propose. In total, 46 indicator groups are compiled, and the ~1500 indicators proposed in the literature are, by aggregating ideational duplicates, consolidated into 505 indicators that constitute the final, best-practice indicator pool. Fig. 3a shows the distribution of consolidated indicators over the dimensions: 154 indicators (30.5%) are assigned to the environmental dimension, 244 (48.3%) to the social dimension, and 107 (21.2%) to governance & management. Analogously to the number of indicators, the social dimension has the highest number of references (499 references), followed by the environmental dimension (403 references) and the dimension of governance & management (185 references). Overall, the single most mentioned indicator is 'energy consumption' (29 references), followed by 'perceived satisfaction by occupants, patients, staff, and community' (25 references). Among the environmental indicators, 'material consumption' (17 references) and 'waste generation' (15 references) are the next most referenced indicators. The prevalence of these environmental topics aligns with current research findings (Buffoli et al., 2015; Djukic and Marić, 2017). In the social dimension, 'indoor noise level' (12 references) and 'temperature' (9 references) are referenced second and third most frequently. Lastly, in the dimension Governance & management, the consolidated indicators 'employee training on environmental matters' (14 references) and 'education for service quality implemented' (6 references) underline the importance of sustainability education and awareness as an essential management task.

The indicators are each classified as upstream, site, or downstream, or, if multiple stages are addressed, as overarching (Fig. 3b). Site indicators refer to environmental or social issues for which the hospital is directly responsible and which occur in or near the hospital. They can be viewed analogously to 'scope 1' emissions (as defined in the GHG Protocol), while upstream indicators refer to scopes 2 and 3, and downstream indicators to scope 3. Most indicators (396; 78.4%) relate to the site directly, 27 (5.3%) to the upstream supply chains, 17 (3.4%) to the downstream flows (mostly waste topics), and 65 (12.9%) of the indicators are overarching. Most **upstream indicators** are in the environmental dimension and focus primarily on energy or supply chain topics (e.g., 'environmental criteria for product selection applied'). Exemplary social indicators concern supplier development or the elimination of child labor, while 'supply chain management strategy and transparency' is an example of an upstream managerial indicator. As stated before, the low number of upstream indicators is apparent. In contrast to upstream and downstream indicators, **on-site indicators** predominantly concern social topics. This is expected, as they cover patients, personnel, the hospital's ambient quality, and local stakeholders' general well-being and health & safety. Environmental site indicators refer inter alia to the efficient use of energy, water, and materials, building and mobility sustainability, and direct, on-site impacts (including anesthetic gas emissions). In many cases, site indicators of the Governance & management dimension address the hospital's internal processes (e.g., 'occupant education'). The abundance of site indicators hints at a good thematical coverage; however, the dominance of social over environmental indicators is noticeable. **Downstream indicators** are exclusively environmental indicators and cover mostly waste generation or treatment but also the installation of a sewage treatment plant. Downstream indicators for social issues are nonexistent. Lastly, **overarching indicators** are, expectedly, primarily assigned to Governance & management. Exemplary indicators are 'eco-directed sustainable prescribing' and 'staff travel planning' in the environmental and 'stakeholder communication' in the social dimension. Indicators such as

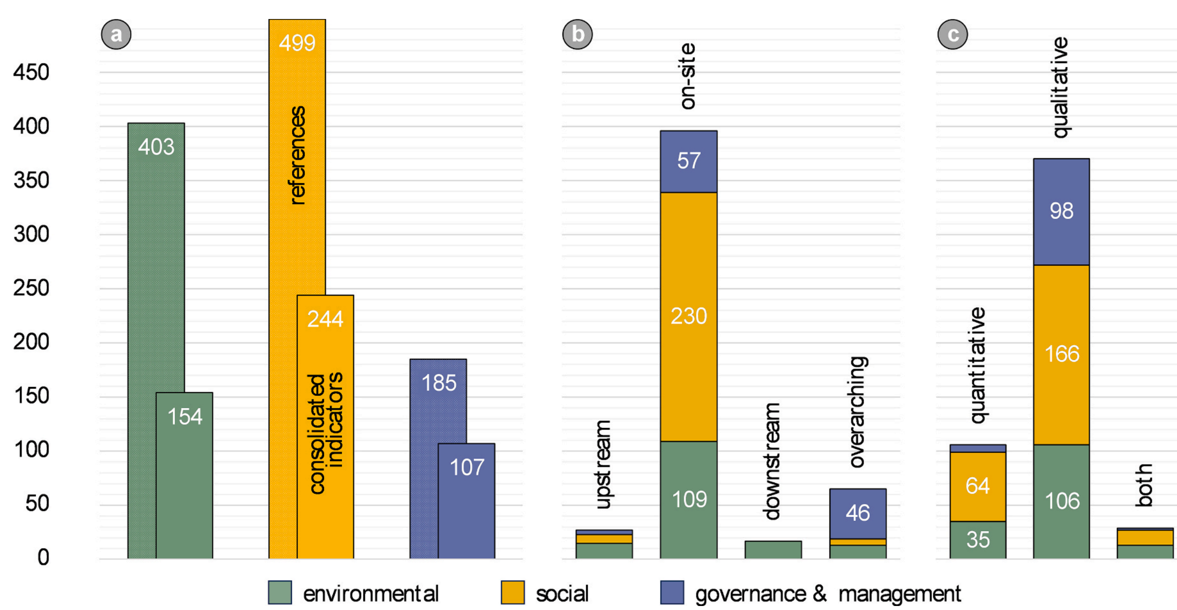

Fig. 3. (a) Number of consolidated indicators and respective references; (b) consolidated upstream, site, downstream, and overarching indicators; (c) distribution of quantitative and qualitative indicators.

'management commitment to sustainable development' and various certifications, guidelines, and labels are examples in the Governance & management category.

Across all dimensions, 135 (26.7%) indicators imply or have a unit assigned and are therefore **quantitative**, whereas 370 (73.3%) indicators are solely assessable by ratings (e.g., interview-based), qualitative scales or Yes/No schemes and are therefore of a **qualitative** nature (Fig. 3c). Many of them could alternatively instead be interpreted as sustainability actions. Indicators for which both options apply (29) are included among the quantitative ones. While indicators in the social and environmental dimensions are distributed relatively equally (32.0% of social indicators are quantitative and 31.2% of environmental ones), quantitative indicators for the dimension Governance & management are rare (8.4%). It is notable, however, that about half of the quantitative indicators in the social dimension refer to the stakeholder group of patients, which implies a lack of quantitative indicators for other aspects and stakeholder groups (such as employees, local community & society or general well-being and health & safety, c.f. section 3.2.2).

3.2.1. Environmental dimension

The categories **Facility design** (36) and **Energy** (28) contain the most indicators in the environmental dimension (Fig. 4). Facility design includes predominantly indicators regarding energy-efficient design (e.g., 'passive' or 'bioclimatic design') of *buildings* and aspects of *site selection* (e.g., 'distance to major water/power/gas supplier'), while the category Energy contains indicators referring to energy consumption or the generated CO_2 from energy use. Castro et al. (2017a) name energy as the most critical environmental category in the environmental dimension, and Keller et al. (2021) identify energy efficiency as a major lever to reduce the carbon footprint of hospitals. We find that energy can be further subdivided into three thematical groups (*energy supply*, *energy use*, and *energy efficiency*). Energy supply contains indicators referring to energy sources (e.g., 'type of primary energy' or 'heating and cooling supply'), whereas energy use includes aspects of energy consumption (e.g., 'energy consumption' as such, 'energy monitoring'). Indicators of the group energy efficiency cover possibilities for energy savings by using more efficient devices or systems (e.g., 'energy-efficient lighting'). The category **Transport & mobility** (21) is divided into five groups. *Transport* covers aspects of internal logistics and patient transportation.

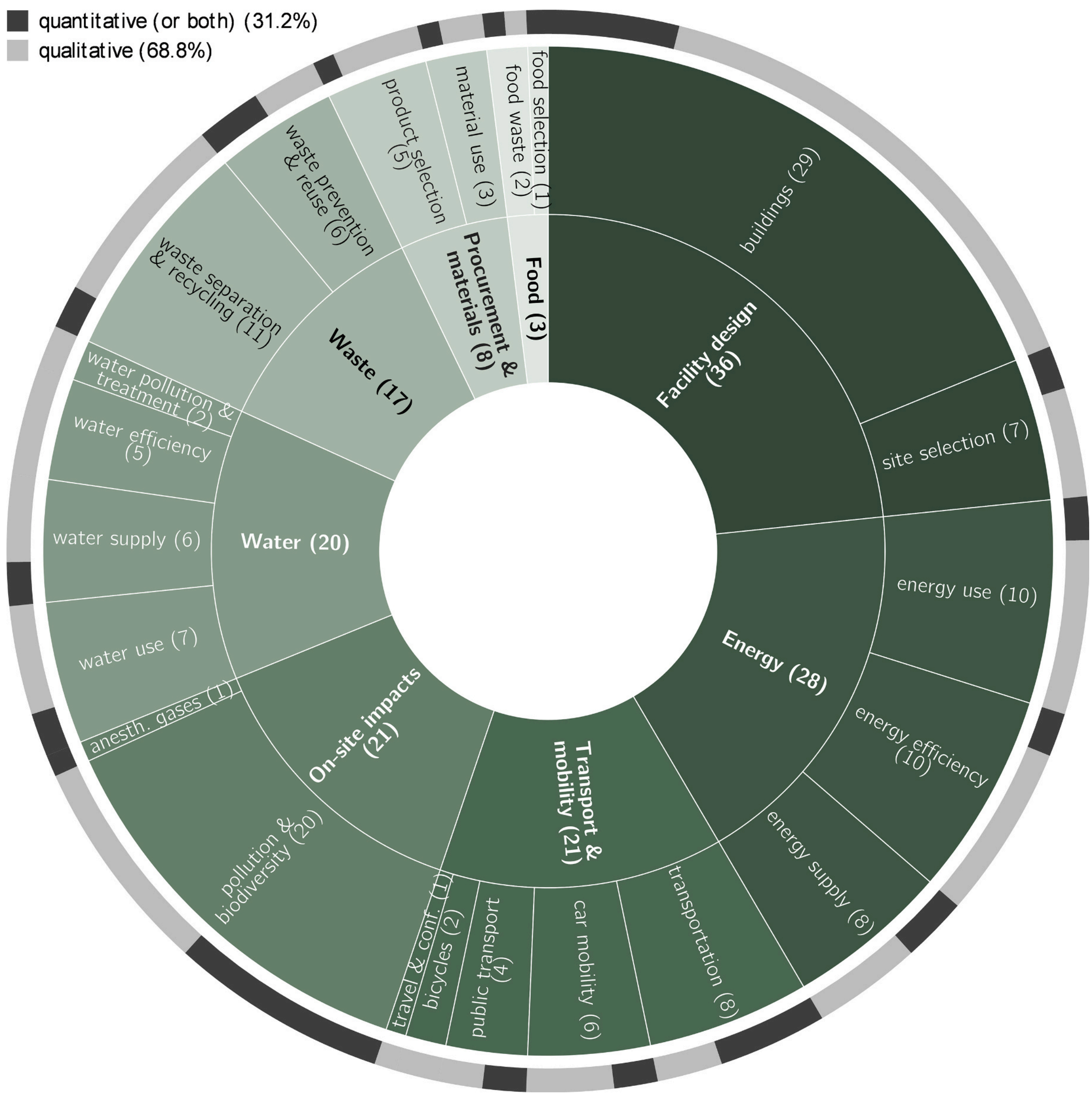

Fig. 4. Number of consolidated indicators in the environmental categories (inner circles) and indicator groups (outer circles), as well as the number of indicators that are quantitative, qualitative, or both.

Three groups distinguish between different means of mobility (*car mobility*, *public transport*, *bicycles*) and refer to inter alia bike accessibility, the use of electric vehicles, or the distance to public transportation. Lastly, indicators referring to sustainable business travel are grouped within *conferences & travel*. Although this category affects stakeholders such as patients, staff, visitors, or suppliers, the environmental aspects of mobility dominate in the reviewed literature (cf. SDC2, sheet A3). Concerning **On-site impacts** (21), particularly important polluters are *anesthetic gases* (Andersen et al., 2012; Van Norman and Jackson, 2020). Other impacts are direct emissions into water, cleaning agents' toxicity, or the hospital's land use. They are grouped with aspects of more 'traditional' nature conservation (e.g., greening of roofs, nesting boxes for swifts, unsealing of surfaces, etc.) in the group *pollution & biodiversity*. Analogous to the category Energy, for **Water** (20), a distinction is made between *water use* (e.g., amount of water consumed), *water supply* (e.g., 'piped water source on premises'), and *water efficiency* (e.g., 'use of automatic faucet sensors'). This category is supplemented by the group *water pollution & treatment* (e.g., 'sewage treatment plant installation'). **Waste** (17) indicators primarily assess waste separation & recycling, e.g., appropriate sorting and separation of waste or recycling quotas. Indicators also cover *waste prevention & reuse* (e.g., 'waste generation'). Indicators referring to the upstream supply chain are allocated to **Procurement & materials** (8), except those in the Food category. Along with energy supply emissions, materials procurement might be the most significant driver of hospitals' GHG emissions (Cimprich and Young, 2023). We differentiate between *product selection* (e.g., 'implementation of sustainable procurement guide') and *material use* (e.g., 'amount of material consumption'). With only two indicators for *food waste* and one for *food selection*, **Food** is the least represented category. This contrasts the fact that food supply chains are a significant driver of hospitals' environmental impacts (Carino et al., 2020; Cimprich and Young, 2023; Keller et al., 2021). The same applies to the procurement and use of pharmaceuticals (Cimprich and Young, 2023; Keller et al., 2021), for which no indicators could be identified.

The low number of indicators for these two, likewise essential and complex, topics allows for one of two conclusions (1) Upstream (i.e., scope 3): impacts are hitherto underexplored in literature and frameworks, which have primarily focused on direct environmental impacts. With the undoubted importance that upstream impacts (hospital

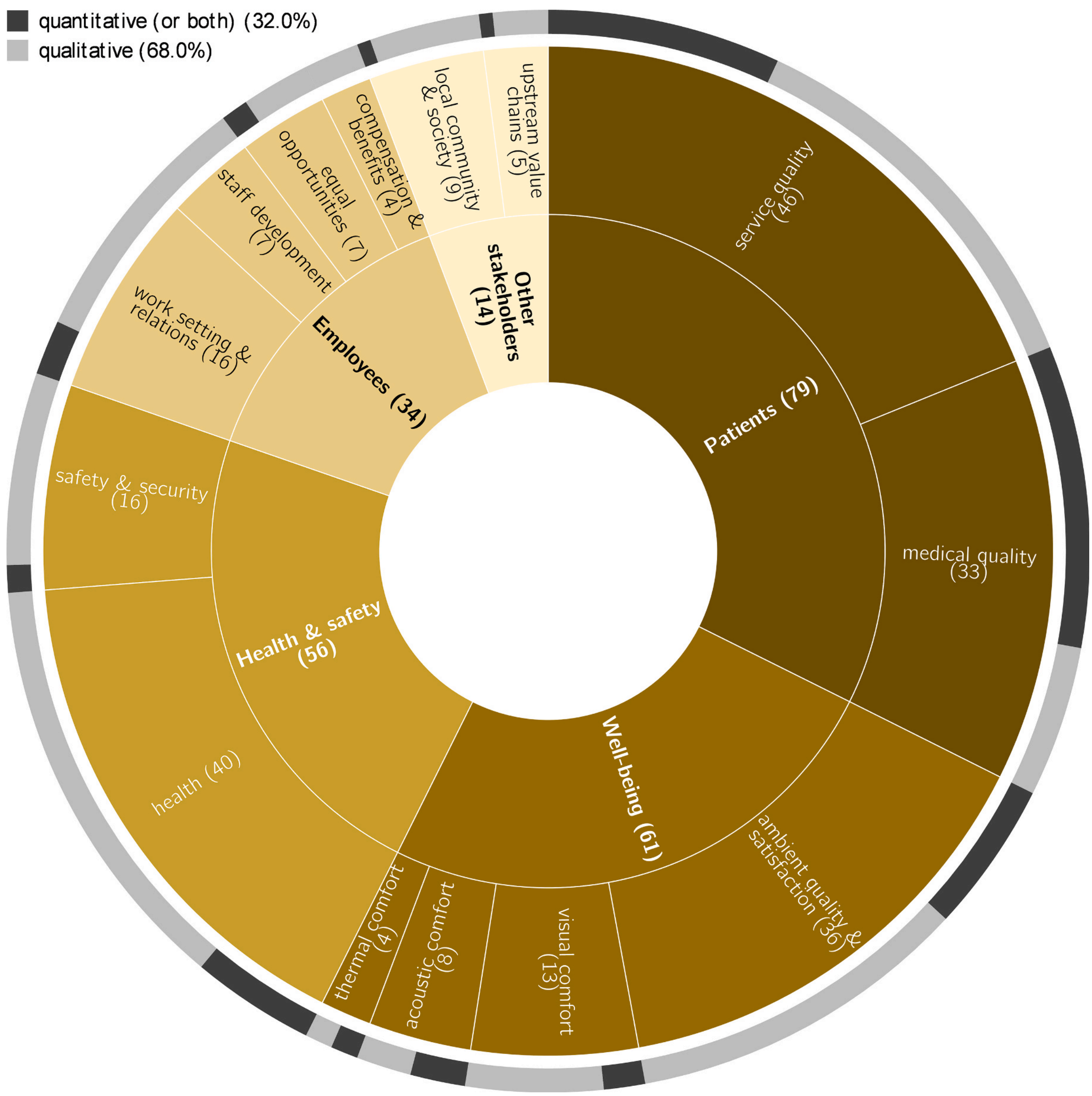

Fig. 5. Number of consolidated indicators in the social categories (inner circles) and indicator groups (outer circles), as well as the number of indicators that are quantitative, qualitative, or both.

materials in general, food in particular) have on hospitals' environmental performance, this means that the lack of indicators for these topics is a clear research gap, which needs to be urgently addressed in future research; or (2) indicators themselves are not suited to evaluate these topics. While indicators promise to readily provide information on a hospital's performance without the need for complex and data-intensive assessments such as LCA, the complexity of supply chains cannot be evaluated accurately enough with 'simple' indicators.

3.2.2. Social dimension

In the social dimension (Fig. 5), the stakeholder category **Patients** includes the largest number of indicators (79). Indicators in this category are subdivided into *service quality*, such as average time for ward rounds or doctor-patient relationships, and *medical quality* (e.g., 'number of wrong releases' or 'average time to take a patient's vital signs'). Although some articles (Chang et al., 2018; Nagariya et al., 2022; Wong et al., 2018) frame patients generically as 'customers', the category Patients is arguably the most significant structural distinction between the social performance of a hospital and that of a generic company. **Well-being** (61) and **Health & safety** (56) are the second and third largest categories, respectively. This is because they cover broad thematical ranges and subsume all indicators relating to all stakeholders' well-being (here subdivided into *ambient quality & satisfaction*, *visual*, *acoustic*, and *thermal comfort* on the one hand, and *health* and *safety & security* on the other). Examples of indicators of the former category are, e.g., 'perceived satisfaction', 'outside view quality', or 'indoor noise level'. The latter comprises, e.g., 'presence of disinfectant' or 'rate of workplace accidents'. Despite the often adverse working conditions (Aiken et al., 2013) and employees spending more time in a hospital than patients, the category **Employees** comprises significantly fewer indicators (34) than Patients. Indicators in this category are subdivided into *work setting & relations*, *staff development*, *equal opportunities*, and *compensation & benefits* and contain indicators such as 'work-life quality', 'job security', or 'career development opportunities'. Analogously to the gap identified regarding procurement and the environmental impacts of upstream supply chains, the category **Other stakeholders** (14) is the smallest of the social categories. It aims at stakeholders along *upstream value chains* and outside the hospital (*local communities & society*). In the latter, indicators are, e.g., 'community satisfaction', 'community complaints', or 'regional priority in procurement'.

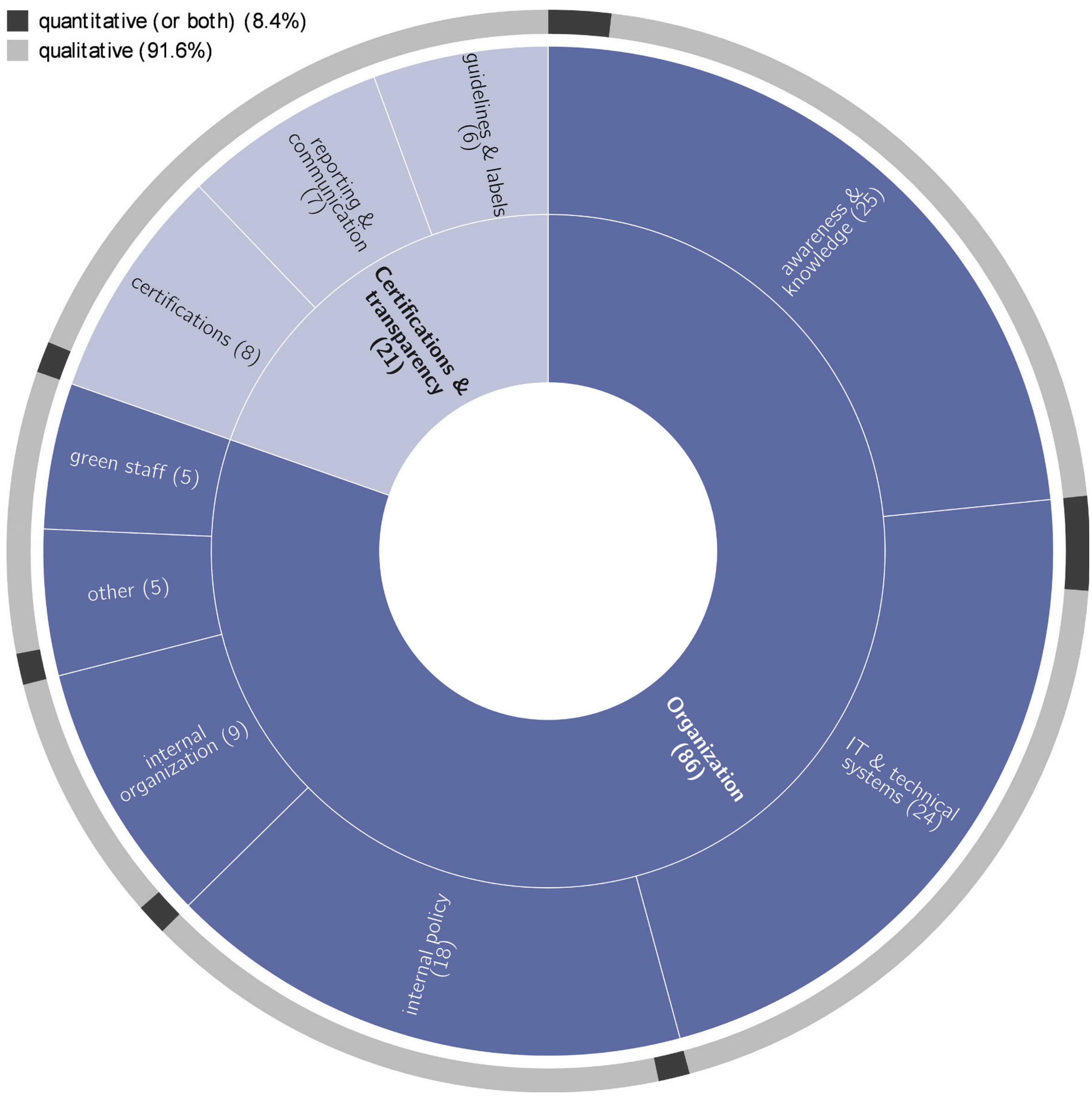

Fig. 6. Number of consolidated indicators in the categories (inner circles) and indicator groups (outer circles) of Governance and management, as well as the number of indicators that are quantitative, qualitative, or both.

Notably, the shares of quantitative or qualitative indicators are very similar between the social and the environmental dimensions. On the one hand, this might be unexpected since many social aspects (e.g., those regarding overall satisfaction) are based on subjective and individual perceptions, while environmental issues are often based on measurable, physical flows and many impacts based on scientific evidence. However, the large number of quantitative social indicators can, to a large degree, be explained by the disproportionally high number of indicators for *service* or *medical quality* in the Patients category, which are primarily time-based indicators (e.g., 'average time for admission and discharge'). In turn, the other social categories contain relatively fewer quantitative indicators than most environmental categories.

3.2.3. Governance & management

The dimension Governance & management (Fig. 6) includes indicators regarding the general organizational structure (**Organization,** 86 indicators) of a hospital, such as *awareness & knowledge* of sustainability issues, green *IT & technical systems*, *internal policy* and *internal organization* aligned with sustainability, hiring of *green staff* (e.g., energy, waste, or climate managers), and *other* issues (such as, e.g., 'provisions for assessment of environmental footprint'). The second category targets **Certifications & transparency** (21), which refer to sustainability *reporting & communication* (e.g., 'environmental targets communicated to all workforce'), *certifications* (e.g., ISO 14001 or EMAS), and *guidelines & labels* (e.g., 'compliance with related environmental policies'). Within this dimension, the indicator employee training on environmental matters is cited most often (14 references), followed by reputation and image and education for service quality (six references each). Notably, *EMAS* (environmental management system) accreditation is only referenced twice, despite being the most prominent certification, together with ISO 14001 (Seifert and Guenther, 2019). Most indicators that are part of the indicator group *IT & technical systems* are only referenced once, which could be attributed to technical topics like data management or CRM systems only partially overlapping with sustainability topics. *Guidelines & labels* includes six indicators, rendering the group the smallest within the *Certifications & transparency* category. Indicators within this group concern voluntary compliance with sustainability guidelines.

4. Discussion

Beyond the mere differentiation between qualitative and quantitative indicators, it bears mentioning that not all indicators are equally suited to measure what they claim to measure – in this case, the somewhat fuzzy concepts of environmental and social 'sustainability'. According to the OECD (2002, 25), an indicator is a "quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect the changes connected to an intervention", and the UN (2009) requires indicators to be 'SMART' – specific, measurable, attainable, relevant, and trackable, with Liu et al. (2020) adding comparable, hierarchical, and systematic. Likewise, Meyer (2004) defines requirements that a good indicator needs to meet.

- ➢ Theoretical requirements: the indicator needs to be scientifically valid, precise, and able to sufficiently capture the non-measurable construct (here: environmental and social sustainability).
- ➢ Methodological requirements: the indicator needs to be valid (i.e., measure what it claims to measure) and reliable (i.e., it needs to be consistently measurable over time and in the same way by different observers).
- ➢ Practical requirements: the indicator needs to be measurable (i.e., quantifiable using available tools and methods), timely (i.e., providing a measurement at relevant and appropriate time intervals), and programmatically important (i.e., relevant for achieving the objectives).

The number of indicators in the compiled pool indicates the need to review them against these requirements. For example, the indicator 'local food' can (assuming a clear definition of 'local') be objectively quantified, corresponding positively to requirements (2) and (3). However, despite a certain tendency, local food entails not *necessarily* fewer environmental impacts than other food (depending on agricultural yields, production practices, packaging, etc.; Michalke et al., 2023).

The main contributions of this work are twofold: Methodologically, we shed light on how the term 'indicator' is understood across different studies (section 3.1.1), on the heterogeneous structures and terminologies used in existing indicator sets (ibid.), and on how indicators are collected, selected, prioritized, aggregated, and applied differently in different studies (see SDC1). Thematically, the proposed best-practice categorization (comprising an environmental dimension with eight categories, a social dimension with five categories, and an overarching governance & management dimension with two categories) constitutes the hitherto most comprehensive basis for future sustainability assessments of hospitals. Hospitals planning to implement an indicator-based sustainability monitoring tool or facing non-financial reporting requirements can interpret the here proposed best-practice categorization as a literature-based materiality assessment. Furthermore, the consolidated pool of 505 indicators provides a wide selection of indicators to be utilized in future sustainability evaluations of hospitals. Given the climate crisis and the ongoing political debate on stricter regulatory requirements to achieve net zero goals, continuously monitoring and identifying impacts is becoming increasingly relevant also in the healthcare sector. Indicators help to assess the effect of, for instance, policies, decisions, or changes and can support managers and policymakers in formulating strategies to address healthcare-specific sustainability challenges. However, the quality criteria mentioned above and data availability limitations must be considered.

5. Conclusion

In this study, we present the state of the art of taxonomies (general structure, terminology, categorization) and included indicators of indicator-based sustainability assessments of hospitals. In detail, we (1) identify and review 88 relevant articles, (2) identify relevant topics for sustainability in a hospital context and derive a best-practice categorization, and (3) unveil thematical coverage and gaps of the pool of collected indicators. In addition, we summarize the methodological approaches of the reviewed articles (regarding identification, selection, prioritization, application, and aggregation of indicators; see SDC1). We find strong variations in the taxonomies and terminologies of the reviewed articles, from diverging understandings of what constitutes an indicator to heterogeneous topics and categories. Most (73%) indicators are qualitative, raising the question of measurability and comparability. Major thematical gaps relate to (1) sustainability along upstream and downstream value chains (especially food and pharmaceuticals) and (2) quantitative indicators for social sustainability (especially for stakeholders other than patients) and governance. These thematical gaps provide pathways for future research, laying the foundation for future developments of consistent indicator-based assessments of hospitals. Beyond this, future research should build upon the presented indicator pool and identify indicators best suited to evaluate sustainability in a hospital context using the quality and aptness criteria mentioned above.

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CRediT authorship contribution statement

Lukas Messmann: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Sandra Köhler:** Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. **Katerina Antimisaris:** Conceptualization, Investigation, Writing – original draft. **Ricarda Fieber:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Andrea Thorenz:** Funding acquisition, Supervision, Writing – review & editing. **Axel Tuma:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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References

Aiken, L.H., Sloane, D.M., Bruyneel, L., Van Den Heede, K., Sermeus, W., 2013. Nurses' reports of working conditions and hospital quality of care in 12 countries in Europe. Int. J. Nurs. Stud. 50 (2), 143–153. https://doi.org/10.1016/j.ijnurstu.2012.11.009.

Al Hammadi, F., Hussain, M., 2019. Sustainable organizational performance: a study of health-care organizations in the United Arab Emirates. Int. J. Organ. Anal. 27 (1), 169–186. https://doi.org/10.1108/IJOA-10-2017-1263.

Aliakbari Nouri, F., Shafiei Nikabadi, M., Olfat, L., 2019. Developing the framework of sustainable service supply chain balanced scorecard (SSSC BSC). Int. J. Prod. Perform. Manag. 68 (1), 148–170. https://doi.org/10.1108/IJPPM-04-2018-0149.

AlJaberi, O.A., Hussain, M., Drake, P.R., 2020. A framework for measuring sustainability in healthcare systems. Int. J. Healthc. Manag. 13 (4), 276–285. https://doi.org/10.1080/20479700.2017.1404710.

Andersen, M.P.S., Nielsen, O.J., Wallington, T.J., Karpichev, B., Sander, S.P., 2012. Assessing the impact on global climate from general anesthetic gases. Anesth. Analg. 114 (5), 1081–1085. https://doi.org/10.1213/ANE.0b013e31824d6150.

Bottero, M.C., Buffoli, M., Capolongo, S., Cavagliato, E., Di Noia, M., Gola, M., et al., 2015. A multidisciplinary sustainability evaluation system for operative and in-design hospitals. In: Capolongo, S., Bottero, M.C., Buffoli, M., Lettieri, E. (Eds.), Improving Sustainability during Hospital Design and Operation. Springer International Publishing, Cham, pp. 31–114. https://doi.org/10.1007/978-3-319-14036-0_4.

Brambilla, A., Apel, J.M., Schmidt-Ross, I., Buffoli, M., Capolongo, S., 2022. Testing of a multiple criteria assessment tool for healthcare facilities quality and sustainability: the case of German hospitals. Sustainability 14 (24), 16742. https://doi.org/10.3390/su142416742.

Brambilla, A., Capolongo, S., 2019. Healthy and sustainable hospital evaluation—a review of POE tools for hospital assessment in an evidence-based design framework. Buildings 9 (4), 76. https://doi.org/10.3390/buildings9040076.

Brambilla, A., Lindahl, G., Dell'Ovo, M., Capolongo, S., 2020. Validation of a multiple criteria tool for healthcare facilities quality evaluation. Facilities 39 (5/6), 434–447. https://doi.org/10.1108/F-06-2020-0070.

Buffoli, M., Capolongo, S., Di Noia, M., Gherardi, G., Gola, M., 2015. Healthcare sustainability evaluation systems. In: Capolongo, S., Bottero, M.C., Buffoli, M., Lettieri, E. (Eds.), Improving Sustainability during Hospital Design and Operation. Springer International Publishing, Cham, pp. 23–29. https://doi.org/10.1007/978-3-319-14036-0_3.

Capolongo, S., Gola, M., Noia, M., Nickolova, M., Nachiero, D., Rebecchi, A., et al., 2016. Social sustainability in healthcare facilities: a rating tool for analyzing and improving social aspects in environments of care. Annali Dell'Istituto Superiore Di Sanita 52. https://doi.org/10.4415/ANN_16_01_06.

Carino, S., Porter, J., Malekpour, S., Collins, J., 2020. Environmental sustainability of hospital foodservices across the food supply chain: a systematic review. J. Acad. Nutr. Diet. 120 (5), 825–873. https://doi.org/10.1016/j.jand.2020.01.001.

Carnero, M.C., 2014. Model for sustainability in healthcare organizations. In: Wang, J. (Ed.), Encyclopedia of Business Analytics and Optimization, pp. 1550–1568.

Carnero, M.C., 2020. Fuzzy topsis model for assessment of environmental sustainability: a case study with patient judgements. Mathematics 8 (11), 1985. https://doi.org/10.3390/math8111985.

Castro, M.D.F., Mateus, R., Bragança, L., 2015. A critical analysis of building sustainability assessment methods for healthcare buildings. Environ. Dev. Sustain. 17 (6), 1381–1412. https://doi.org/10.1007/s10668-014-9611-0.

Castro, M.D.F., Mateus, R., Bragança, L., 2017a. Development of a healthcare building sustainability assessment method – proposed structure and system of weights for the Portuguese context. J. Clean. Prod. 148, 555–570. https://doi.org/10.1016/j.jclepro.2017.02.005.

Castro, M.D.F., Mateus, R., Bragança, L., 2017b. Healthcare building sustainability assessment tool—sustainable effective design criteria in the Portuguese context. Environ. Impact Assess. Rev. 67, 49–60. https://doi.org/10.1016/j.eiar.2017.08.005.

Chang, D.-S., Wang, W.-S., Wang, R., 2018. Identifying critical factors of sustainable healthcare institutions' indicators under taiwan's national health insurance system. Soc. Indicat. Res. 140 (1), 287–307. https://doi.org/10.1007/s11205-017-1761-7.

Cimprich, A., Santillán-Saldivar, J., Thiel, C.L., Sonnemann, G., Young, S.B., 2019. Potential for industrial ecology to support healthcare sustainability: scoping review of a fragmented literature and conceptual framework for future research. J. Ind. Ecol. 23 (6), 1344–1352. https://doi.org/10.1111/jiec.12921.

Cimprich, A., Young, S.B., 2023. Environmental footprinting of hospitals: organizational life cycle assessment of a Canadian hospital. J. Ind. Ecol., 13425 https://doi.org/10.1111/jiec.13425 jiec.

Costa, A.J., Curi, D., Bandeira, A.M., Ferreira, A., Tomé, B., Joaquim, C., et al., 2022. Literature review and theoretical framework of the evolution and interconnectedness of corporate sustainability constructs. Sustainability 14 (8), 4413. https://doi.org/10.3390/su14084413.

Curran, M.A., 2013. Life Cycle Assessment: a review of the methodology and its application to sustainability. Current Opinion in Chemical Engineering 2 (3), 273–277. https://doi.org/10.1016/j.coche.2013.02.002.

Djukic, A., Marić, J., 2017. Towards socially sustainable healthcare facilities – the role of evidence-based design in regeneration of existing hospitals in Serbia. Procedia Environmental Sciences 38, 256–263. https://doi.org/10.1016/j.proenv.2017.03.070.

Duque-Uribe, V., Sarache, W., Gutiérrez, E.V., 2019. Sustainable supply chain management practices and sustainable performance in hospitals: a systematic review and integrative framework. Sustainability 11 (21), 5949. https://doi.org/10.3390/su11215949.

Falagas, M.E., Pitsouni, E.I., Malietzis, G.A., Pappas, G., 2007. Comparison of PubMed, scopus, Web of science, and Google scholar: strengths and weaknesses. Faseb. J. 22 (2), 338–342. https://doi.org/10.1096/fj.07-9492LSF.

Faezipour, M., Ferreira, S., 2011. Applying systems thinking to assess sustainability in healthcare system of systems. Int. J. Syst. Syst. Eng. 2 (4), 290. https://doi.org/10.1504/IJSSE.2011.043861.

Fiksel, J., Eason, T., Frederickson, H., 2013. A Framework for Sustainability Indicators at EPA. U.S. Environmental Protection Agency. Retrieved. https://www.epa.gov/sites/default/files/2014-10/documents/framework-for-sustainability-indicators-at-epa.pdf. (Accessed 26 July 2023).

González, A., García-Sanz-Calcedo, J., Salgado, D., 2018. Quantitative determination of potable cold water consumption in German hospitals. Sustainability 10 (4), 932. https://doi.org/10.3390/su10040932.

Guo, D., DeFrancia, K., Chen, M., Filiatraut, B., Zhang, C., 2015. Assessing sustainability: frameworks and indices. Sustainability Metrics White Paper Series (3). https://doi.org/10.7916/D8BG2N4C.

Hanaysha, J.R., Al-Shaikh, M.E., Joghee, S., Alzoubi, H.M., 2022. Impact of innovation capabilities on business sustainability in small and medium enterprises. FIIB Business Review 11 (1), 67–78. https://doi.org/10.1177/23197145211042232.

Hensher, M., McGain, F., 2020. Health care sustainability metrics: building A safer, low-carbon health system: commentary examines how to build a safer, low-carbon health system. Health Aff. 39 (12), 2080–2087. https://doi.org/10.1377/hlthaff.2020.01103.

Jahani Sayyad Noveiri, M., Kordrostami, S., 2021. Sustainability assessment using a fuzzy DEA aggregation approach: a healthcare application. Soft Comput. 25 (16), 10829–10849. https://doi.org/10.1007/s00500-021-05992-y.

Jiménez-Lacarra, V., Martinez-Cámara, E., Santamaría-Peña, J., Jiménez-Macías, E., Bruzzone, A., Blanco-Fernández, J., 2022. Environmental efficiency indices in the public hospital sector: a proposal. Appl. Sci. 12, 8120. https://doi.org/10.3390/app12168120.

Karliner, J., Slotterback, S., Boyd, R., Ashby, B., Steele, K., 2019. Health Care's Climate Footprint: How the Health Sector Contributes to the Climate Crisis and Opportunities for Action. Retrieved July 27, 2023, from. https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_092319.pdf.

Keller, R.L., Muir, K., Roth, F., Jattke, M., Stucki, M., 2021. From bandages to buildings: identifying the environmental hotspots of hospitals. J. Clean. Prod. 319, 128479 https://doi.org/10.1016/j.jclepro.2021.128479.

Khosravi, F., Izbirak, G., Adewale Adesina, K., 2019. An exponentially distributed stochastic model for sustainability measurement of a healthcare system. Sustainability 11 (5), 1285. https://doi.org/10.3390/su11051285.

Koranne, R., Williams, E.S., Poplau, S., Banks, K.M., Sonneborn, M., Britt, H.R., Linzer, M., 2022. Reducing burnout and enhancing work engagement among clinicians: the Minnesota experience. Health Care Manag. Rev. 47 (1), 49–57. https://doi.org/10.1097/HMR.0000000000000298.
Liu, A., Miller, W., Crompton, G., Ma, Y., 2020. Principles to define energy key performance indicators for the healthcare sector. 2020 International Conference on Smart Grids and Energy Systems (SGES). IEEE, Perth, Australia, pp. 898–903. https://doi.org/10.1109/SGES51519.2020.00165.
LUSTAT, 2012. Methodische Grundsätze beim Aufbau von Indikatorenprojekten. LUSTAT Statistik Luzern from. https://www.lustat.ch/monitoring/grundlagen?file=files/lustat/indikatoren/downloads/indikatoren_grundlagendokument_20121115.pdf&cid=1280. (Accessed 26 July 2023).
Madden, D.L., McLean, M., Brennan, M., Moore, A., 2020. Why use indicators to measure and monitor the inclusion of climate change and environmental sustainability in health professions' education? Med. Teach. 42 (10), 1119–1122. https://doi.org/10.1080/0142159X.2020.1795106.
McGain, F., Naylor, C., 2014. Environmental sustainability in hospitals – a systematic review and research agenda. J. Health Serv. Res. Policy 19 (4), 245–252. https://doi.org/10.1177/1355819614534836.
Mehra, R., Sharma, M.K., 2021. Measures of sustainability in healthcare. Sustainability Analytics and Modeling 1. https://doi.org/10.1016/j.samod.2021.100001.
Meyer, W., 2004. Indikatorenentwicklung: eine praxisorientierte einführung. Saarbrücken. Retrieved July 26, 2023, from. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-111245.
Michalke, A., Köhler, S., Messmann, L., Thorenz, A., Tuma, A., Gaugler, T., 2023. True cost accounting of organic and conventional food production. J. Clean. Prod. 408, 137134 https://doi.org/10.1016/j.jclepro.2023.137134.
Migdadi, Y.K.A.-A., Omari, A.A., 2019. Identifying the best practices in green operations strategy of hospitals. Benchmark Int. J. 26 (4), 1106–1131. https://doi.org/10.1108/BIJ-09-2017-0242.
Moldovan, F., Blaga, P., Moldovan, L., Bataga, T., 2022. An innovative framework for sustainable development in healthcare: the human rights assessment. Int. J. Environ. Res. Publ. Health 19 (4), 2222. https://doi.org/10.3390/ijerph19042222.
Morawa, E., Schug, C., Geiser, F., Beschoner, P., Jerg-Bretzke, L., Albus, C., et al., 2021. Psychosocial burden and working conditions during the COVID-19 pandemic in Germany: the VOICE survey among 3678 health care workers in hospitals. J. Psychosom. Res. 144, 110415 https://doi.org/10.1016/j.jpsychores.2021.110415.
Nagariya, R., Kumar, D., Kumar, I., 2022. Sustainability evaluation of service supply chains: a case study of an Indian hospital. Int. J. Prod. Perform. Manag. 71 (7), 2865–2892. https://doi.org/10.1108/IJPPM-05-2020-0237.
Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60 (3), 498–508. https://doi.org/10.1016/j.ecolecon.2006.07.023.
Nilashi, M., Zakaria, R., Ibrahim, O., Majid, M. Z. Abd, Mohamad Zin, R., Chugtai, M.W., et al., 2015. A knowledge-based expert system for assessing the performance level of green buildings. Knowl. Base Syst. 86, 194–209. https://doi.org/10.1016/j.knosys.2015.06.009.
Obucina, M., Harris, N., Fitzgerald, J.A., Chai, A., Radford, K., Ross, A., et al., 2018. The application of triple aim framework in the context of primary healthcare: a systematic literature review. Health Pol. 122 (8), 900–907. https://doi.org/10.1016/j.healthpol.2018.06.006.
OECD, 2002. Glossary of key terms in evaluation and results based management. Retrieved July 26, 2023, from. https://www.oecd.org/development/peer-reviews/2754804.pdf.
OECD, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD, Paris. Retrieved July 27, 2023, from. https://unstats.un.org/unsd/EconStatKB/KnowledgebaseArticle10366.aspx.
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ n71. https://doi.org/10.1136/bmj.n71.
Pantzartzis, E., Edum-Fotwe, F.T., Price, A.D.F., 2017. Sustainable healthcare facilities: reconciling bed capacity and local needs. International Journal of Sustainable Built Environment 6 (1), 54–68. https://doi.org/10.1016/j.ijsbe.2017.01.003.
Pederneiras, Y.M., Pereira, M.A., Figueira, J.R., 2023. Are the Portuguese public hospitals sustainable? A triple bottom line hybrid data envelopment analysis approach. Int. Trans. Oper. Res. 30 (1), 453–475. https://doi.org/10.1111/itor.12966.
Pichler, P.-P., Jaccard, I.S., Weisz, U., Weisz, H., 2019. International comparison of health care carbon footprints. Environ. Res. Lett. 14, 064004 https://doi.org/10.1088/1748-9326/ab19e1.
Pinzone, M., Lettieri, E., Masella, C., 2012. Sustainability in healthcare: combining organizational and architectural levers. Int. J. Eng. Bus. Manag. 4, 38. https://doi.org/10.5772/54841.
Ramos Huarachi, D.A., Piekarski, C.M., Puglieri, F.N., De Francisco, A.C., 2020. Past and future of social life cycle assessment: historical evolution and research trends. J. Clean. Prod. 264, 121506 https://doi.org/10.1016/j.jclepro.2020.121506.
Ramos, T., Pires, S.M., 2013. Sustainability assessment: the role of indicators. In: Caeiro, S., Filho, W.L., Jabbour, C., Azeiteiro, U.M. (Eds.), Sustainability Assessment Tools in Higher Education Institutions. Springer International Publishing, Cham, pp. 81–99. https://doi.org/10.1007/978-3-319-02375-5_5.
Rohde, T., Martinez, R., 2015. Equipment and energy usage in a large teaching hospital in Norway. Journal of Healthcare Engineering 6 (3), 419–434. https://doi.org/10.1260/2040-2295.6.3.419.
Romero, I., Carnero, M.C., 2019. Environmental assessment in health care organizations. Environ. Sci. Pollut. Control Ser. 26 (4), 3196–3207. https://doi.org/10.1007/s11356-017-1016-9.
Rovan, J., 2011. Composite indicators. In: Lovric, M. (Ed.), International Encyclopedia of Statistical Science. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 275–276. https://doi.org/10.1007/978-3-642-04898-2_15.
Ryan-Fogarty, Y., O'Regan, B., Moles, R., 2016. Greening healthcare: systematic implementation of environmental programmes in a university teaching hospital. J. Clean. Prod. 126, 248–259. https://doi.org/10.1016/j.jclepro.2016.03.079.
Sahamir, S.R., Zakaria, R., 2014. Green assessment criteria for public hospital building development in Malaysia. Procedia Environmental Sciences 20, 106–115. https://doi.org/10.1016/j.proenv.2014.03.015.
Salas, R.N., Maibach, E., Pencheon, D., Watts, N., Frumkin, H., 2020. A pathway to net zero emissions for healthcare. BMJ m3785. https://doi.org/10.1136/bmj.m3785.
Seifert, C., Guenther, E., 2019. Prevention is better than cure-Environmental management measures in hospitals. Corp. Soc. Responsib. Environ. Manag. 26 (4), 781–790. https://doi.org/10.1002/csr.1720.
Seifert, C., Koep, L., Wolf, P., Guenther, E., 2021. Life cycle assessment as decision support tool for environmental management in hospitals: a literature review. Health Care Manag. Rev. 46 (1), 12–24. https://doi.org/10.1097/HMR.0000000000000248.
Sherman, J.D., Thiel, C., MacNeill, A., Eckelman, M.J., Dubrow, R., Hopf, H., et al., 2020. The green print: advancement of environmental sustainability in healthcare. Resour. Conserv. Recycl. 161, 104882 https://doi.org/10.1016/j.resconrec.2020.104882.
Stevanovic, M., Allacker, K., Vermeulen, S., 2019. Development of an approach to assess the life cycle environmental impacts and costs of general hospitals through the analysis of a Belgian case. Sustainability 11 (3), 856. https://doi.org/10.3390/su11030856.
Tay, H.L., Singh, P.J., 2021. Revisiting redundancy in hospitals—a case-based research study. Health Care Manag. Rev. 46 (3), 185–195. https://doi.org/10.1097/HMR.0000000000000257.
Tsakona, M., Anagnostopoulou, E., Gidarakos, E., 2007. Hospital waste management and toxicity evaluation: a case study. Waste Manag. 27 (7), 912–920. https://doi.org/10.1016/j.wasman.2006.04.019.
Uebel, K.E., Nash, J., Avalos, A., 2007. Caring for the caregivers: models of HIV/AIDS care and treatment provision for health care workers in Southern Africa. J. Infect. Dis. 196 (s3), S500–S504. https://doi.org/10.1086/521113.
UN, 2009. Performance Indicators to Monitor and Evaluate the Effectiveness of the Implementation of the Technology Transfer Framework. United Nations from. https://unfccc.int/resource/docs/2009/sb/eng/04.pdf. (Accessed 26 July 2023).
UNEP, 2020. In: Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (Eds.), Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. United Nations Environment Programme (UNEP) from. https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020/. (Accessed 26 July 2023).
Valdivia, S., Backes, J.G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J.B., et al., 2021. Principles for the application of life cycle sustainability assessment. Int. J. Life Cycle Assess. 26 (9), 1900–1905. https://doi.org/10.1007/s11367-021-01958-2.
Van Norman, G.A., Jackson, S., 2020. The anesthesiologist and global climate change: an ethical obligation to act. Curr. Opin. Anaesthesiol. 33 (4), 577–583. https://doi.org/10.1097/ACO.0000000000000887.
vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., Cleven, A., 2009. Reconstructing the giant: on the importance of rigour in documenting the literature search process. Proceedings of the European Conference on Information Systems.
WHO, 2017. Environmentally sustainable health systems: a strategic document. Copenhagen. Retrieved July 26, 2023, from. https://apps.who.int/iris/handle/10665/340375.
Wong, K., Chong, K., Chew, B.C., Tay, C., Mohamed, S., 2018. Key performance indicators for measuring sustainability in health care industry in Malaysia. J. Fund. Appl. Sci. 10, 646–657. https://doi.org/10.4314/jfas.v10i1s.46.
Yang, Y., Ingwersen, W.W., Hawkins, T.R., Srocka, M., Meyer, D.E., 2017. USEEIO: a new and transparent United States environmentally-extended input-output model. J. Clean. Prod. 158, 308–318. https://doi.org/10.1016/j.jclepro.2017.04.150.
Zamparas, M., Kapsalis, V.C., Kyriakopoulos, G.L., Aravossis, K.G., Kanteraki, A.E., Vantarakis, A., Kalavrouziotis, I.K., 2019. Medical waste management and environmental assessment in the rio university hospital, Western Greece. Sustainable Chemistry and Pharmacy 13, 100163. https://doi.org/10.1016/j.scp.2019.100163.
Zhan, Z., Xu, W., Xu, L., Qi, X., Song, W., Wang, C., Huang, Z., 2022. BIM-based green hospital building performance pre-evaluation: a case study. Sustainability 14 (4), 2066. https://doi.org/10.3390/su14042066.