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RESEARCH

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A next-generation holistic building design framework: a focus on integrating sustainable and vernacular design principles

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Abstract

The proliferation of sustainable design approaches and assessment methods has resulted in a vast array of indicators. However, this abundance often leads to confusion during interpretation and application. Additionally, rapid urbanization and environmental concerns sometimes overshadow social and economic considerations, emphasizing environmental impact reduction. This study addresses these challenges through an integrated approach that combines a Systematic Literature Review (SLR) with a Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis to provide a holistic model for sustainable building design. The SLR was carried out individually through a relative Structural Query Language (SQL) regarding sustainable building design and vernacular principle. The output of SLR was subjected to DEMATEL model to recognize the holistic indicators interconnection and validate the proposed model. The research identified 23 global indicators for building sustainability worldwide, with five—Energy, Materials & Resources, Sites & Ecology, Indoor Environmental Quality, and Water—emerging as the most prevalent. Additionally, 22 consistently applied indicators in vernacular design practices exhibited significant overlap with those in sustainable design. This model integrated two novel indicators—Vernacular Principles and Social—Culture—with common sustainable building indicators. These primary indicators complement the common and applicable sustainable building indicators, ensuring a balanced approach that considers global contexts. DEMATEL analysis confirmed the validity and interconnection of these indicators, emphasizing the critical role of vernacular principles in achieving true sustainability.

Keywords Sustainable building, Vernacular principles, Design indicators, Systematic literature review, DEMATEL

1 Introduction

The building sector is a major consumer of energy and an emitter of greenhouse gases, accounting for 40% of global resource use, 30% of total energy consumption, and 30% of global carbon emissions [1–6]. With nearly half of the world's population residing in urban areas [7], human activities like deforestation, land-use changes, urbanization, and construction development have made the building sector a critical concern for contemporary societies [8]. These activities contribute to various environmental issues within the building sector, including waste generation, high energy consumption, internal and external pollution, CO_2 emissions, environmental degradation, and reliance on non-renewable resources [9]. In response to these challenges, the sustainability movement has emerged as a promising approach to address the ecological crisis by integrating environmental, cultural, and economic considerations. Consequently, sustainable development principles have been comprehensively integrated into building design [10], solidifying sustainable

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architecture as a key trend in the early twenty-first century [11]. Numerous sustainable design approaches, standards, and assessment tools have been established globally to promote sustainable building design at all scales. These include the United Nations Sustainable Development Goals (UN-SDGs), European Performance of Buildings Directive (EPBD), ASHRAE Standard 189, International Energy Agency (IEA) initiatives, Chartered Institution of Building Services Engineers (CIBSE) programs (UK), U.S. Environmental Protection Agency (EPA) guidelines, U.S. Department of Energy (DOE) standards, Building Energy Modeling (BEM) tools, Nearly Zero-Energy Buildings (nZEBs) initiatives, green building design principles, eco-design practices, and smart building technologies [12–14]. Since 1990, numerous building rating systems have been developed to evaluate a building's sustainability performance [15]. The most recognized systems, forming the basis for many others worldwide, are the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and the Sustainable Building Tool (SBTool), established by the International Initiative for a Sustainable Built Environment (iiSBE) [16]. Additionally, various individual studies have explored sustainable building design indicators and their evaluation through Multi-Criteria Decision Making (MCDM) analysis [1, 17–21].

The proliferation of sustainable design approaches and assessment methods has led to a vast number of sustainability indicators worldwide. This has confused interpretation and application, making sustainable building design a complex challenge for architects [22]. Furthermore, rapid urbanization and environmental concerns may lead to an overemphasis on environmental impact reduction, neglecting economic and social-cultural aspects [17, 23]. This highlights a potential shortcoming in existing approaches and the need for comprehensive models that encompass all three pillars of sustainability: environmental, social, and economic. Additionally, many current design approaches, rating systems, and standards originate in developed nations, reflecting their specific contexts and often requiring significant technological advancements, resources, and infrastructure for implementation. This can limit their applicability in diverse settings. However, to understand the goals and practices of sustainable architecture, examining its core principles and methodologies remains crucial. Sustainability is a core tenet of vernacular architecture, which has evolved through the utilization of local resources and technologies, fostering a harmonious relationship between buildings and their surrounding environments [24]. The three pillars of sustainability (environmental, social, and economic) are embedded in vernacular architecture, highlighting its holistic approach and the interconnected nature of these spheres [25, 26]. Through an analysis of vernacular architecture and its inherent sustainability principles, valuable insights can be extracted and applied to contemporary sustainable design practices [27]. Vernacular architecture prioritizes resource efficiency, minimizing energy and material consumption while embodying cultural and social values [28]. Compared to modern buildings, which account for more than 40% of worldwide energy usage and 30% of yearly greenhouse gas emissions, vernacular design has demonstrably more ecologically adaptive principles developed over many generations [29]. Integrating vernacular principles into sustainable architecture serves as an effective tool to promote sustainability and address modern global challenges, while simultaneously preserving the inherent sustainability of vernacular design within its specific context [30]. Vernacular design principles and strategies act as a complementary model for achieving sustainable building design.

Vernacular architecture, a rich repository of time-tested design principles, offers invaluable lessons for contemporary sustainable building practices [31]. Recognized by numerous scholars as a cornerstone of sustainable design, vernacular architecture has demonstrated its effectiveness through diverse methodologies [32–34]. Examples of sustainable architecture abound globally, inspiring architects to draw inspiration from the past [26]. Initiatives like the VerSus research project aim to extract knowledge from vernacular architecture and apply its principles to modern sustainable design, fostering a conceptual framework for sustainable architectural practice [35]. Projects such as Earthship Buildings, The Earth House Estate Lättenstrasse, and Hassan Fathy's New Gourna Village exemplify the application of vernacular principles in contemporary sustainable architecture [36–38]. Moreover, innovative examples like Startup Lions' Campus, China Bamboo Hostels, Pearl Academy of Fashion, 72, Screen Office Building and Arab World Institute showcase the potential of vernacular architecture to inform cutting-edge design solutions [39–41]. In the contemporary era, the study of vernacular architecture seeks to identify practical solutions within its features and adapt them to modern construction [30]. This renewed interest has led to a growing recognition of the importance of preserving vernacular architecture [42]. Despite the growing interest in sustainable architecture and the potential contributions of vernacular principles, a significant gap persists between acknowledging their merits and fully integrating them into contemporary design. Furthermore, a comprehensive design model that

integrates vernacular indicators into a holistic framework for sustainable building is currently lacking.

Building upon the limitations of current sustainable design approaches and the absence of a holistic model, this study investigates the interconnected relationship between sustainable architecture and vernacular principles. We demonstrated that this synergy can be harnessed to develop a comprehensive set of sustainability indicators. The primary objective is to establish a holistic and robust sustainable design model by integrating the most prevalent sustainable design indicators and leveraging the strengths of vernacular design. This novel system has the potential to significantly improve the effectiveness of evaluating sustainability across all environmental, social, and economic dimensions. Furthermore, it aims to address the shortcomings identified in existing sustainable design and assessment methodologies. To achieve this, the study will initially focus on identifying and characterizing the most widely used sustainable building design and vernacular design indicators. Subsequently, it will determine the relative interconnections among these proposed indicators and elucidate their cause-and-effect relationships. This approach directly contributes to the crucial task of defining a comprehensive set of indicators and their interconnection within a holistic design model. By establishing such a framework, this study empowers architects and policymakers to develop robust sustainable design models and rating systems that can be applied holistically, encompassing all dimensions of sustainability. Moreover, it offers stakeholders an opportunity to consider local capabilities and conditions, informed by vernacular principles, when integrating sustainability into their projects.

2 Methodology

This study utilized a two-pronged methodological approach to achieve its objectives. The first component involves a comprehensive Systematic Literature Review (SLR) to identify the most prevalent and applicable sustainable and vernacular design indicators. This review explored potential relationships between these indicators and vernacular design principles. Additionally, a deep review and evaluation of existing sustainability rating system indicators from around the globe was conducted to complement and potentially validate the findings from the SLR. The second component employed Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis to integrate Vernacular Principles as a key indicator within the proposed sustainable design model. This analysis helped strengthen the validity and robustness of the model. By combining these methodologies, the study sought to effectively integrate vernacular design principles into a holistic sustainable design model. The specific framework for this integration is presented in detail in Fig. 1.

This study employed a two-part SLR following the rigorous four-stage SALSA framework [43] to comprehensively analyze existing research. This framework, alongside adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [44], ensures a systematic, transparent, and reproducible approach [44]. The SLR involved defining a research question and establishing a search protocol with relevant databases, keywords, and inclusion/exclusion criteria. Then, a comprehensive literature search and rigorous screening process was conducted. Extracted data on methodologies, research gaps, sustainable design indicators, and the link between vernacular principles and sustainability were critically appraised. Finally, a synthesis of this data identified key themes and insights to inform the development of a holistic sustainable design model incorporating vernacular principles.

In accordance with the SLR framework, a rigorous search strategy was implemented, utilizing the Scopus and Google Scholar databases. The search strategy was carefully designed to identify studies relevant to sustainable and vernacular design principles. As illustrated in Fig. 1, the SLR comprised two distinct phases. The first phase focused on identifying research related to sustainable design approaches. A Structural Query Language (SQL) was developed using keywords such as 'sustainable,' 'indicators,' 'parameters,' 'buildings,' 'architecture design,' and 'life cycle.' This query was designed to retrieve studies that significantly addressed indicators of sustainable building design. The second phase shifted the focus to research related to vernacular design principles. A SQL query was constructed using keywords like 'vernacular,' 'passive,' 'building,' 'design,' 'architecture,' 'principle,' and 'indicators.' This query aimed to identify studies specifically exploring the sustainable dimensions of vernacular principles. An initial search identified a substantial dataset encompassing approximately 690 articles on sustainable building design and 481 on vernacular principles. To ensure the quality and relevance of these studies on sustainable building indicators and vernacular principles, a rigorous selection process was employed (Fig. 1). In the first screening phase, articles were evaluated based on their titles, abstracts, and keywords. This resulted in the exclusion of 495 articles from the sustainable building design dataset and 314 from the vernacular principles dataset. Subsequently, a more in-depth analysis of the remaining articles' content and introductions led to the elimination of 195 articles on sustainable building design and 167 on vernacular principles. Through this meticulous evaluation, a final selection of 30 articles on sustainable buildings and 25 on vernacular principles was made

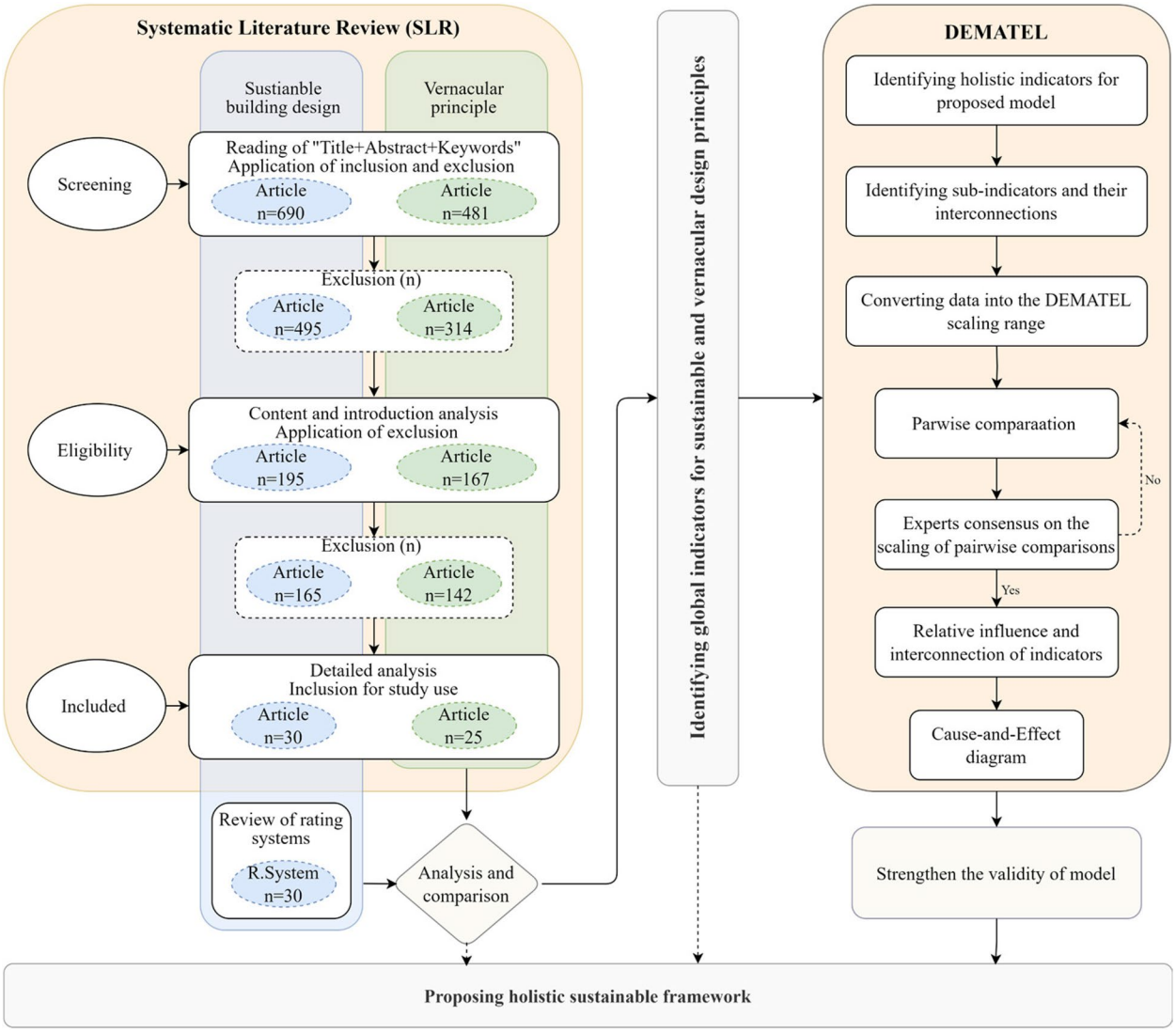

Fig. 1 Methodology flowchart of the study

for inclusion in the study. These articles were selected as the most relevant and qualified based on systematic literature reviews (SLR) that assessed indicators of sustainable building and vernacular principles.

In addition, along with the SLR to improve and complement the collected data from SLR a deep evaluation of existing 30 rating systems around the world regarding their considered indicators was conducted. As a result, data extraction provided valuable insights into existing research gaps, research methodologies, the use of sustainable design indicators, and the potential connection between vernacular principles and sustainable building design. Following the study objective, after the collection of most related studies and rating systems around the globe, a comprehensive evaluation of each study regarding sustainable design and vernacular principal indicators was conducted. The selection of sustainable building indicators was based on a comprehensive analysis of the most related 30 studies collected through SLR and in-depth evaluation of 30 global rating systems. For vernacular principles, which are not directly considered indicators, the identification process involved a detailed analysis and interpretation of data from 25 pertinent related articles obtained via SLR. This approach aimed to align these indicators with sustainable indicators. The same method was applied to select and identify sub-indicators and determine their correlation. Consequently, the study is expected to provide valuable information on sustainable and vernacular design indicators with their alignment for identifying

holistic sustainable design indicators that address the existing shortcomings of sustainable approaches and confirm the novelty of this study.

2.1 Decision-Making Trial and Evaluation Laboratory (DEMATEL)

This research integrated two novel indicators into the established framework of sustainable design. Vernacular design principles and social-cultural considerations are incorporated alongside the most used and applicable sustainable design indicators. To assess the complex interplay and influence between these indicators and validate the claim, a DEMATEL analysis was employed. DEMATEL offers a powerful MCDM approach specifically designed to analyze intricate and interconnected problems [45]. Developed in the 1970s by the Geneva Research Centre of the Battelle Memorial Institute, this method excels at untangling cause-and-effect relationships within complex systems. The key strength of DEMATEL lies in its ability to reveal not only the factors driving change (causative factors) but also the level of interdependence among these factors. This allows us to extract the intricate web of mutual relationships between all the sustainability indicators under consideration [46]. DEMATEL achieves this by visually representing these relationships using digraphs, creating a clear and organized structural model of the system. Furthermore, similar to the Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) methods [47], DEMATEL allows for criteria weighting, making it particularly well-suited for prioritizing the various sustainability indicators within our proposed design model. The specific procedures involved in implementing the DEMATEL method will be outlined in detail in the following section [48].

Step 1: In the initial phase of the analysis, the average weightings of the experts' direct-influence matrix, denoted by 'a', are computed. This matrix captures the inter-factor relationships established through existing literature or expert judgment. The experts quantify these relationships between factors, denoted as 'a_{ij}', by assigning scores on a 0-to-4 Likert scale. The scale reflects the degree of influence, with 0 indicating no influence, 1 signifying minimal influence, 2 representing moderate influence, 3 denoting strong influence, and 4 signifying very strong influence. The experts were instructed to specifically evaluate the extent to which factor 'i' influences factor 'j'. It is noteworthy that the influence of a factor on itself is inherently zero. The mean scores provided by the experts regarding the influence of factor 'i' on factor 'j' are represented by 'a_{21}', 'a_{1n}', 'a_{21}', 'a_{2n}', and so forth.

$$a_{ij} = \begin{matrix} 1 \\ 2 \\ n \end{matrix} \begin{bmatrix} 1 & 2 & n \\ 0 & a_{12} & a_{1n} \\ a_{21} & 0_{\ldots} & a_{2n} \\ a_{n1} & a_{n2\ldots} & 0 \end{bmatrix} \tag{1}$$

Step 2: Following the acquisition of the direct-influence matrix 'a' in Step 1, a normalization procedure is undertaken to arrive at the normalized matrix 'B' (represented as $(B = a_{ij}/k)$. This normalization step facilitates the interpretation and comparison of influence scores within the matrix. The normalization equation is as follows:

$$k = max\left(max\sum_{j=1}^{n} a_{ij}, max\sum_{j=1}^{n} a_{ij}\right), ij \in \{1, 2, \ldots, n\} \tag{2}$$

Within this equation, (maxi $\sum a_{ij}$) signifies the maximum sum of the average scores in each row, and (maxi $\sum a_{ij}$) denotes the maximum sum of the average scores in each column. The normalization process entails dividing each element (a_{ij}) of the original matrix 'a' by the corresponding row sum and column sum. Subsequently, the resulting values are multiplied by the maximum row sum (maxi $\sum a_{ij}$) and the maximum column sum ($max_j \sum a_{ij}$) to obtain the normalized influence scores within matrix 'B'.

Step 3: Focuses on determining the total influence matrix 'T'. This matrix captures both direct and indirect influences between factors. The following equation is employed to achieve this:

$$T = B + B^2 + \cdots + B^k = B(I - B)^{-1} \tag{3}$$

In this equation, 'B' signifies the normalized direct-influence matrix obtained in Step 2. 'I' represents the identity matrix with the same dimensions as 'B', and '1' denotes a matrix of the same size filled with ones. The equation involves a series of matrix operations. First, the identity matrix 'I' is subtracted from the normalized matrix 'B'. Subsequently, the inverse of the resulting difference matrix is calculated. Finally, this inverse is multiplied by the matrix of ones ('1') to yield the total influence matrix 'T'. This process accounts for the cumulative effect of both direct and indirect influences between factors within the system.

Step 4: Delves into the analysis of the total influence matrix 'T' obtained in Step 3. This matrix encapsulates the complete picture of both direct and indirect influences amongst the factors. To extract meaningful insights from 'T', two key vectors are derived:

- Vector R_i: This vector represents the total influence (direct and indirect) exerted by factor 'i' on all other factors within the system. It is obtained by summing up the elements in each row of the total influence matrix 'T'.

- Vector C_j: This vector signifies the total influence (direct and indirect) received by factor 'j' from all other factors within the system. It is calculated by summing up the elements in each column of the total influence matrix 'T'.

$$R_i = [R_i]_{nx1} = \left[\sum_{j-1}^{n} t_{ij}\right]_{nx1} \tag{4}$$

$$C_j = \left[C_j\right]_{nx1} = \left[\sum_{j-1}^{n} t_{ij}\right]_{nx1} \tag{5}$$

By analyzing these vectors, researchers can identify factors with high total influence (R_i) or high susceptibility to influence (C_j), aiding in understanding the overall dynamics and interdependencies within the system under investigation.

Step 5: Continuing the analysis from Step 4, Step 5 delves deeper into the causal relationships between factors represented within the total influence matrix 'T'. Here, two new vectors are derived:

- $R_i + C_j$: This vector is obtained by summing the corresponding elements ($R_i + C_j$) for each factor (i = j) in the total influence matrix. It reflects the overall interconnectedness of each factor with others within the system.
- $R_i — C_j$: This vector is calculated by subtracting the corresponding elements ($R_i — C_j$) for each factor (i = j) in the total influence matrix. A positive value in $R_i — C_j$ signifies that factor 'i' exerts a greater influence on other factors compared to the influence it receives from them. Conversely, a negative value indicates a higher susceptibility of factor 'i' to influences from other factors compared to its own influence on others. The magnitude of $R_i — C_j$ reflects the strength of this causal influence.

By analyzing these vectors, researchers can identify key factors based on their overall interconnectedness ($R_i + C_j$) and their propensity to influence or be influenced ($R_i — C_j$). This allows for a more nuanced understanding of the causal dynamics within the system.

Step 6: To further refine the analysis and focus on the most impactful relationships, Step 6 introduces a threshold value denoted by α. This threshold is established as the average value of all elements within the total influence matrix 'T'. Essentially, elements in 'T' with values significantly lower than the average influence (α) are considered to have a minimal impact and are disregarded. This filtering process allows researchers to concentrate on the most significant direct and indirect influences amongst the factors, providing a clearer picture of the core interdependencies within the system.

$$A = \frac{\sum_{i-1}^{n}\sum_{j=1}^{n}\left[t_{ij}\right]}{N} \tag{6}$$

Step 7: Culminates in the visualization of a causal relationship network. This network portrays the intricate interdependencies between the factors within the system. It is constructed by plotting only those elements (tij) from the total influence matrix 'T' that exceed the established threshold value (α) determined in Step 6. These significant influences are mapped onto a coordinate plane using the corresponding values from the $R_i + C_j$ and $R_i — C_j$ vectors. By analyzing this visual representation, researchers can readily identify:

- Critical Factors: Factors with prominent positions within the network, indicated by high $R_i + C_j$ values, signify their extensive interconnection with other factors.
- Influence Dynamics: The positioning of factors along the x-axis (positive $R_i — C_j$) and y-axis (negative $R_i — C_j$) reveals their propensity to influence or be influenced. Factors with high positive $R_i — C_j$ values are prominent influencers, while those with high negative $R_i — C_j$ values are more susceptible to external influences.

This causal relationship network serves as a powerful tool for comprehending the overall influence structure and interdependencies within the system under investigation.

3 Results

The SLR on sustainable building design identified a total of 18 indicators employed and considered across the reviewed studies. Among these, the six most prevalent indicators—Energy, Materials & Resources, Site & Ecology, Waste Management, Indoor Environmental Quality, and Water—exceed 50% usage frequency in the studies. However, the remaining eleven indicators received lower consideration in various studies. Table 1 presents a selection of the 30 most relevant studies from the SLR, highlighting various sustainable design strategies, frameworks, design indicators, and emphasizing the importance of the sustainable indicators evaluated in these studies.

Additionally, to enhance and complement the result of the SLR on sustainable building design, and to achieve a comprehensive understanding of sustainable building design indicators, a thorough evaluation of the most prevalent rating systems was undertaken. This analysis

Table 1 Summary of sustainable building design indicators obtained from reviewed studies via SLR highlighting the importance and consideration of each indicator

No	Subjects and Focus of the Studies	Year	Considered Indicators								
			Materials & Resources	Site & Ecology	Waste Management	Indoor environmental quality	Water	Energy	Passive Strategy	Innovative Design	Managment
1	BIM for Green Buildings	2024	✓	✓		✓	✓	✓			
2	Green Building Ratings	2024	✓	✓		✓	✓	✓			
3	BIM Tool for Sustainability	2023	✓	✓	✓	✓	✓	✓		✓	
4	Auditing and Rating Sustainability	2023		✓		✓		✓			
5	Assessing Building Sustainability	2023	✓	✓		✓	✓	✓		✓	✓
6	Sustainable campus indicators	2022			✓		✓				✓
7	Green Rating Framework	2021	✓	✓		✓	✓	✓			
8	High-Performance Green Design	2021	✓	✓		✓	✓	✓			
9	Applicability of Rating Criteria	2020	✓	✓	✓	✓	✓	✓		✓	✓
10	Green Building indicator—MCDM	2020	✓	✓		✓	✓	✓		✓	
11	MCDM in Building Sustainability	2020	✓	✓	✓	✓	✓	✓	✓		
12	Built Environment Audits	2019	✓			✓		✓			
13	Certification boosts sustainability	2019	✓	✓		✓	✓	✓		✓	
14	Sustainability Parameters via LCA	2019	✓	✓			✓	✓			
15	Regenerative Building Criteria	2018	✓	✓	✓		✓	✓	✓	✓	
16	Fuzzy AHP for Sustainable Tools	2018	✓	✓	✓	✓	✓	✓		✓	
17	Sustainable Operations Hierarchy	2017	✓	✓	✓	✓	✓	✓			
18	Environmental Rating System	2017	✓	✓	✓	✓	✓	✓		✓	
19	Sustainable Indicators Framework	2017	✓		✓	✓	✓	✓			
20	Sustainability Assessment Method	2017	✓	✓	✓		✓	✓	✓		
21	Sustainability Performance Criteria	2017	✓	✓	✓		✓	✓			
22	Sustainable Property Expert tool	2016	✓	✓	✓		✓	✓			
23	Sustainable Building Assessment	2016	✓	✓		✓	✓	✓			
24	Sustainability Rating Systems	2015	✓	✓		✓	✓	✓			
25	Building Sustainability Indicators	2015	✓	✓	✓	✓	✓	✓			
26	Green Building Performance	2014	✓	✓	✓		✓	✓			
27	Sustainable building life cycle	2012	✓	✓		✓	✓	✓			
28	Sustainable Parameter Weights	2012	✓	✓		✓	✓	✓			
29	Sustainability Tool Development	2011	✓	✓	✓		✓	✓			
30	Key performance indicators	2010	✓		✓	✓		✓		✓	
Frequency of Sustainable Design Indicators Used in 30 Articles (Percentage)			93	86	53	73	90	97	10	30	10

Table 1 (continued)

No	Subjects and Focus of the Studies	Year	Considered Indicators									References
			Transportation & Pedestrians	Cost & Economic	Health & Well-being	Outdoor Environmental Quality	Equipment & Services	Social—Culture	Accessibility & Satisfaction	Adaptability & Integrationsss	Awareness & Education	
1	BIM for Green Buildings	2024			✓	✓	✓		✓			[49]
2	Green Building Ratings	2024			✓			✓		✓		[50]
3	BIM Tool for Sustainability	2023										[51]
4	Auditing and Rating Sustainability	2023		✓		✓	✓	✓		✓		[52]
5	Assessing Building Sustainability	2023				✓						[53]
6	Sustainable campus indicators	2022	✓	✓					✓		✓	[54]
7	Green Rating Framework	2021	✓	✓								[55]
8	High-Performance Green Design	2021										[1]
9	Applicability of Rating Criteria	2020	✓	✓	✓	✓	✓	✓			✓	[56]
10	Green Building indicator—MCDM	2020										[57]
11	MCDM in Building Sustainability	2020		✓								[15]
12	Built Environment Audits	2019		✓		✓	✓	✓				[58]
13	Certification boosts sustainability	2019						✓				[38]
14	Sustainability Parameters via LCA	2019			✓			✓	✓	✓	✓	[59]
15	Regenerative Building Criteria	2018			✓			✓	✓	✓	✓	[17]
16	Fuzzy AHP for Sustainable Tools	2018		✓			✓	✓				[60]
17	Sustainable Operations Hierarchy	2017		✓	✓			✓	✓	✓	✓	[61]
18	Environmental Rating System	2017						✓			✓	[62]
19	Sustainable Indicators Framework	2017		✓				✓			✓	[63]
20	Sustainability Assessment Method	2017		✓	✓		✓	✓		✓	✓	[64]
21	Sustainability Performance Criteria	2017		✓	✓			✓	✓	✓		[65]
22	Sustainable Property Expert tool	2016		✓	✓				✓			[7]
23	Sustainable Building Assessment	2016		✓		✓	✓	✓				[10]
24	Sustainability Rating Systems	2015										[66]
25	Building Sustainability Indicators	2015										[67]
26	Green Building Performance	2014	✓									[68]
27	Sustainable building life cycle	2012	✓									[69]
28	Sustainable Parameter Weights	2012		✓		✓	✓	✓				[70]
29	Sustainability Tool Development	2011		✓	✓	✓			✓		✓	[71]
30	Key performance indicators	2010		✓						✓		[72]
Frequency of Sustainable Design Indicators Used in 30 Articles (Percentage)			17	53	33	27	27	50	27	27	30	

revealed a broader range of 21 indicators employed and considered across various rating systems around the globe. Five of these indicators exhibited exceptional prominence, with frequency of usage rates exceeding 50%. These highly important and widely applicable indicators included Site & Ecology, Water, Energy, Materials & Resources, Indoor Environmental Quality. Conversely, the remaining indicators were utilized to a significantly lesser extent, with usage rates falling below 30%. Table 2 provides an overview of the most widely recognized sustainable building rating systems employed internationally. It introduces a list and importance of sustainable indicators that consider evaluated rating systems, and it is noteworthy that many of these systems share and adopt indicators for assessing the sustainability of buildings.

Moreover, to explore the potential correlation between vernacular design principles and sustainability, a comprehensive analysis of global literature was conducted using the SLR methodology. This analysis focused on vernacular design principles and their connection to established sustainable indicators. The results revealed that a total of 22 indicators were consistently identified across the reviewed global studies. Significantly, these indicators exhibited a high degree of overlap with those employed in sustainable architectural design and rating systems. Among this set of indicators, six emerged as particularly prominent, each exceeding a 50% usage rate and accompanied by their own sub-indicators. These key indicators included Site & Ecology, Energy, Materials & Resources, Indoor Environmental Quality, Social – Culture and Cost & Economic. Table 3 summarizes the findings from the 25 most relevant articles that were identified through the SLR, which explore the sustainability dimension of vernacular principles and their associated indicators.

This alignment between vernacular design indicators and frequently used sustainable design indicators highlights a strong inherent connection between the two approaches. Furthermore, vernacular design extends beyond typical sustainable design practices by also integrating economic and social aspects. This focus strengthens the two sustainability dimensions that are often underrepresented in contemporary design – a significant distinction of the vernacular approach.

3.1 Indicators for a holistic sustainable design model

This study identified a total of 23 indicators consistently employed across various sustainable building design studies and assessment methods worldwide, as supported by [74]. Five of these indicators emerged as particularly prominent, each with its sub-indicators: Sites & Ecology, Energy, Materials & Resources, Water, and Indoor Environmental Quality. The analysis of vernacular design practices revealed a similar pattern. A total of 22 indicators were found to be consistently considered in vernacular design studies across the globe. Interestingly, all but three of these indicators Wildlife Habitat, Regional Priority and Local Builder & Techniques, were found to be intersected. This convergence between commonly used sustainable design indicators and the most frequently employed vernacular design indicators highlights a significant underlying connection between these two design approaches. Furthermore, vernacular design demonstrates a clear distinction by also integrating social-cultural considerations – a dimension often overlooked in contemporary sustainable design practices. Therefore, the integration of Vernacular Principles as a primary indicator with five common sustainable indicators and social—Culture in a holistic model proposes a list of seven sustainable indicators that bridge the existing gap and contribute to the development of holistic design models that cover all dimensions of sustainability. These holistic indicators are seven including Sites & Ecology, Energy, Materials & Resources, Indoor Environmental Quality, Water, Vernacular Principles, and Social—Culture. This integration of these indicators, particularly Vernacular Principles in addition to the improvement of all indicators identified in this study, have a significant correlation with each other and contribute to their achievement significantly. Table 4 presents the correlations between the seven proposed holistic indicators, analyzed through their sub-indicators. Data for this analysis was derived from the SLR and rating system evaluations presented in Tables 1, 2, and 3. The sub-indicators for the established sustainable indicators were chosen based on existing studies and rating systems that employed similar sub-indicators for their main indicators. However, for the vernacular design principle, whose main indicators stemmed from the analysis and interpretation of relevant studies, the sub-indicators were identified using the same method. Notably, some sub-indicators across different main indicators may not share the same name, but they capture similar meanings.

This study identified seven key sustainability indicators (Table 4) that exhibit a synergistic relationship. These indicators, when considered together, demonstrate a mutually reinforcing effect, not only in pairwise comparisons but also within the broader context of sustainable building design. Encompassing a range of environmental, social, and cultural aspects, the brief definitions of each indicator can be summarized as follows:

- Sites & Ecology: This indicator focuses on minimizing the building's environmental impact while protecting and enhancing biodiversity within existing ecosystems.

- Energy: This indicator prioritizes minimizing energy consumption during building operation, ultimately leading to reduced carbon emissions.
- Materials & Resources: This indicator emphasizes resource conservation, minimizing waste generation throughout a building's life cycle, and using eco-friendly materials with a lower environmental footprint.
- Water: This indicator promoting efficient water use is crucial to reduce strain on freshwater resources. This can involve implementing drought-resistant landscaping and water-saving fixtures.
- Indoor Environmental Quality: This indicator prioritizes the health, well-being, and comfort of building occupants and requires strategies that address factors like thermal comfort, air quality, and access to natural light.
- Vernacular Principles: This indicator bridges cultural and environmental aspects. It encourages drawing inspiration from local architectural traditions that have historically adapted to the specific environment, materials, and cultural context. By incorporating these principles, buildings can achieve a better harmony with their surroundings.
- Social—Culture: This indicator emphasizes community engagement throughout the design process. It ensures accessibility for all users and fosters social interaction through well-designed spaces that promote a sense of community.

The integration of these indicators within a holistic design model has the potential to significantly address the identified gaps in contemporary sustainable building design practices. By adopting this comprehensive approach, we can contribute to a marked improvement in the overall sustainability of modern buildings.

3.2 Interconnection and relative mutual influence of the indicators

This study rigorously followed the multi-stage DEMATEL process outlined in the Methodology (Sect. 2.1) to assess the complex interplay and influence between the indicators within the established framework. The initial analysis focuses on the Average Direct-Influence Matrix (denoted as 'a'). Traditionally, this matrix is constructed using region-specific data, such as questionnaires or literature. However, to develop a globally applicable design model, this study adopted a novel approach. Data from a comprehensive SLR and an evaluation of global rating systems (Tables 1, 2, and 3) were used to identify sub-indicators for each main indicator (Table 4). The interconnections among these sub-indicators within the holistic design model were then evaluated. To ensure compatibility with the DEMATEL method, a meticulous pair-wise comparison process was applied. This process transformed the data in Table 4 into a scale ranging from 0 to 4, representing the degree of influence. The resulting Average Direct-Influence Matrix, presented in Table 5, quantifies the interrelationships and the degree of influence between the identified indicators. To ensure the reliability of the DEMATEL pairwise comparisons obtained from the literature review, a panel of 15 university scholars with PhD degrees and specific expertise in the field was consulted. After achieving expert consensus on the scaling of pairwise comparisons, the DEMATEL analysis was conducted, confirming the validity and transparency of the model.

After the normalization of the Average Direct-Influence Matrix, a Total Influence Matrix denoted as 'T' is derived. This matrix captures both the direct and indirect influences between the factors. To further analyze these interdependencies, the elements in each row (R_i) and each column (C_j) of matrix 'T' are summed separately. These vector representations (R_i and C_j) provide valuable insights into the cause-and-effect relationships within the system. Additionally, a pre-defined threshold value is employed to identify critical indicators in Table 6. In this study, a threshold of 0.30677389 was utilized.

Based on the DEMATEL analysis, indicators exceeding the threshold value in Table 6 exert a more pronounced influence on other indicators within the sustainable building design system. The graphical representation in Fig. 2 visually depicts these interconnections and influences, emphasizing the significance of each indicator based on its threshold value. Site & Ecology and Vernacular Principles, with their higher threshold values and connections to five other indicators, emerge as pivotal elements. These indicators significantly influence other factors, contributing to their achievement and importance. Indoor Environmental Quality, with four interconnected indicators, demonstrates a moderately high level of significance. Energy and Material & Resources follow with moderate significance, each having three interconnected indicators. Social—Culture exhibits a low-moderate significance due to its connections to two indicators. Lastly, Water, with fewer interconnections, has a lower significance within the architectural context of sustainable building design. This analysis underscores the significance of prioritizing influential indicators within the research framework.

By calculating $R_i + C_j$ and $R_i — C_j$ (presented in Table 7), the study delves into the interrelationships among indicators. Notably, Site & Ecology and Vernacular Principles demonstrated a positive $R_i — C_j$ value, indicating their substantial influence on other indicators. Conversely, the remaining indicators with a negative $R_i — C_j$ value were

found to be less influential, suggesting they are more significantly impacted by Site & Ecology and Vernacular Principles. These findings underscore the critical role of Site & Ecology and Vernacular principles in the overall assessment of sustainable building design indicators.

Expanding upon the insights from Table 7, the cause-and-effect diagram in Fig. 3 visually illustrated how indicators exerted varying degrees of influence on one another. The R_i-C_j metric quantified this influence, while $R_i + C_j$ reflected the interrelationships between indicators. Site & Ecology, displaying the highest positive R_i-C_j value, emerged as a dominant force, significantly influencing other indicators. Vernacular Principles, with slightly lower positive R_i-C_j values, exhibited a secondary influence. Conversely, Energy, Material & Resources, Indoor Environmental Quality, Social—Culture, and Water exhibited negative R_i-C_j values, suggesting they were primarily influenced by Site & Ecology and Vernacular Principles and exerted minimal or no influence on indicators with positive R_i-C_j values.

Moreover, Vernacular Principles demonstrated a stronger overall interconnectedness with other indicators, as evidenced by its higher $R_i + C_j$ value. In contrast, Water exhibited the weakest overall connection, reflected in its lowest $R_i + C_j$ value. The remaining indicators displayed varying degrees of interconnectedness with other indicators through their respective $R_i + C_j$ values. Consequently, Fig. 2 and Fig. 3 effectively conveys the relative strengths and weaknesses of these indicators, their influence on one another, and their interconnectedness, offering valuable insights into the study context.

4 Discussion

The past two decades have seen a surge in sustainable building design practices, resulting in a plethora of design strategies, standards, and assessment methods. Each approach offers a unique set of design indicators that guide architects and engineers toward achieving a building's sustainability objectives. These indicators serve as crucial benchmarks for informed decision-making throughout the design and construction phases. However, the proliferation of indicators has introduced challenges in interpretation. While some indicators may appear superficially similar, their significance and weighting vary considerably based on project-specific criteria and the surrounding context. Furthermore, the rapid pace of urbanization and environmental crises have skewed a significant portion of global sustainable building design research and methodologies. This focus has prioritized addressing environmental challenges, often overshadowing the economic and social aspects of sustainability.

Several studies have employed similar methods to evaluate building sustainability using various sustainable design models and assessment approaches. A commonality observed across these approaches is their focus on specific indicators, with the current study identifying the five most prevalent ones: Sites & Ecology, Energy, Materials & Resources, Indoor Environmental Quality, and Water. For instance, the DEMATEL method was used to introduce Energy Efficiency, Indoor Environmental Quality, Sustainable Site Planning & Management, Materials & Resources, Water Efficiency, and Innovation for assessing green building manufacturing in Malaysia. [57]. Similarly, a framework for building sustainability assessment in Kazakhstan was developed using the SWARA method, incorporating indicators such as Site Selection, Energy Efficiency, Water Efficiency, Materials, Indoor Environmental Quality, Waste Management, Building Architectural Quality, and Economics [15]. In Iran, Fuzzy-AHP was employed to introduce and customize indicators for sustainable building assessment, including Energy Efficiency, Water Efficiency, Sustainable Site, Materials and Resources, and Indoor Environmental Quality [60]. An AHP-based model for Indian sustainable building assessment was also established, encompassing indicators like Sustainable Site, Water Efficiency, Energy Efficiency, Materials and Resources, Indoor Environment Quality, Environmental Loading, Social-Economic Aspects, Cultural Aspects, and Service Quality [10, 70]. These findings are further supported by established rating systems like LEED and BREEAM, which utilize similar methods and indicators to assess building sustainability. LEED employs seven indicators: Sustainable Sites, Indoor Environmental Quality, Energy and Atmosphere, Water Efficiency, Materials and Resources, Innovation in Design, and Regional Priority [96]. BREEAM incorporates ten indicators: Management, Health and Wellbeing, Energy, Transport, Water, Materials, Waste, Land Use and Ecology, Pollution, and Innovation [97]. A notable trend observed is the emphasis on environmental issues within most sustainable design approaches and rating systems [66]. These frameworks are often developed based on local conditions and specific project objectives. This emphasis can potentially diminish the focus on the social dimensions of sustainability, resulting in incomplete frameworks with limited applicability in a holistic sense. Furthermore, a comprehensive study on the relationship and contribution of vernacular principles, which serve as a foundational basis for sustainability, is lacking, except for the VerSus project supported by the European Research Program [35]. However, this project primarily provides theoretical information about vernacular knowledge for sustainable architecture, which may not be sufficient for the development of vernacular principles indicators and a holistic design model.

Table 2 Summary of sustainable building design indicators derived from global rating systems, emphasizing the significance and consideration of each indicator, modified from [73, 74]

NO	Region	Country	Rating Systems	Year	Considered Indicators						
					Site & Ecology	Water	Energy	Materials & Resources	Indoor Environmental Quality	Transportation & Pedestrians	Awareness & Education
1	America	US	LEED	1998	✓	✓	✓	✓	✓	✓	✓
2		Canada	Green Globes	2000	✓	✓	✓	✓	✓		
3		Brazil	LEED-Br	2007	✓	✓	✓	✓	✓	✓	
4		Mexico	NMX	2013	✓	✓	✓	✓	✓		
5		Cascadia	LBC	2006	✓	✓	✓	✓			
6	Europe	UK	BREEAM	1990	✓	✓	✓	✓		✓	
7		Germany	DGNB	2008	✓						
8		Italia	GBC	2006	✓	✓	✓	✓	✓		
9		France	HQE	1997	✓		✓		✓		
10		Finland	Promis E	2006	✓						
11		Spain	GBCe	2006	✓	✓	✓	✓	✓		
12		Switzerland	Minergie	1998	✓	✓	✓	✓	✓		
13		Norway	NGBC	2008	✓	✓	✓	✓		✓	
14		Czech	SBTool	2010	✓		✓	✓	✓	✓	
15	Asia	China	GB/T	2006	✓	✓	✓	✓	✓		
16		India	GRIHA	2007	✓	✓	✓	✓			
17		Japan	CASBEE	2004	✓		✓	✓	✓		
18		Singapore	BCA	2005	✓	✓	✓		✓		
19		Hon-Kong	HK-BEAM	1996	✓	✓	✓	✓	✓		
20		Taiwan	EEWH	1999	✓	✓	✓	✓	✓		
21		Korea	KGBC	1997	✓	✓	✓	✓	✓	✓	
22		Malaysia	GBI	2008	✓	✓	✓	✓	✓		
23		Vietnam	LOTUS	2007	✓	✓	✓	✓			
24		Singapore	Green Mark	2005	✓	✓	✓		✓		
25		Qatar	GSAS	2013	✓	✓	✓	✓	✓	✓	
26		UAE	Estidama	2010	✓	✓	✓	✓	✓		
27		US & Aus	SITES	2009	✓	✓	✓	✓	✓		✓
28		Australia	Green Star	2003	✓	✓	✓	✓	✓	✓	
29		South Africa	Green Star SA	2008	✓	✓	✓	✓	✓	✓	
30		Global	EDGE	2013		✓	✓	✓	✓		
Frequency of Sustainable Indicators Used in 30 Rating Systems (Percentage)					96	86	93	83	77	30	7

Table 2 (continued)

NO	Region	Country	Rating Systems	Year	Considered Indicators													
					Innovative Design	Waste Management	Health & Well-being	Pollution & Emissions	Management	Equity	Beauty & Aesthetics	Wildlife Habitat	Outdoor Environmental Quality	Adaptability & Integration	Social—Culture	Technical Quality	Equipment & Services	Cost & Economic
1	America	US	LEED	1998	✓			✓							✓			
2		Canada	Green Globes	2000				✓	✓									
3		Brazil	LEED-Br	2007	✓										✓			
4		Mexico	NMX	2013	✓	✓												
5		Cascadia	LBC	2006			✓			✓	✓							
6	Europe	UK	BREEAM	1990	✓	✓	✓	✓	✓									
7		Germany	DGNB	2008											✓	✓	✓	✓
8		Italia	GBC	2006														
9		France	HQE	1997			✓											
10		Finland	Promis E	2006			✓	✓										
11		Spain	GBCe	2006											✓	✓		
12		Switzerland	Minergie	1998		✓	✓											
13		Norway	NGBC	2008	✓			✓	✓									
14		Czech	SBTool	2010		✓							✓		✓		✓	✓
15	Asia	China	GB/T	2006	✓													
16		India	GRIHA	2007	✓	✓	✓		✓								✓	✓
17		Japan	CASBEE	2004														
18		Singapore	BCA	2005	✓													
19		Hon-Kong	HK-BEAM	1996	✓													
20		Taiwan	EEWH	1999		✓												
21		Korea	KGBC	1997				✓	✓									
22		Malaysia	GBI	2008	✓				✓									
23		Vietnam	LOTUS	2007	✓		✓		✓									
24		Singapore	Green Mark	2005									✓					
25		Qatar	GSAS	2013					✓						✓			
26		UAE	Estidama	2010	✓									✓	✓			
27		US & Aus	SITES	2009	✓		✓					✓	✓					
28		Australia	Green Star	2003				✓										
29		South Africa	Green Star SA	2008	✓			✓	✓									
30		Global	EDGE	2013														
Frequency of Sustainable Indicators Used in 30 Rating Systems (Percentage)					46	20	27	27	30	3	3	3	7	3	23	7	10	10

Table 3 Summary of vernacular principles indicators obtained from reviewed studies via SLR highlighting the importance and consideration of each indicator

NO	Subjects and Focus of thes Studies	Year	Considered Indicators								
			Site & Ecology	Water	Energy	Materials & Resources	Indoor Environmental Quality	Locations & Transport	Innovative Design	Regional Priority	Waste Management
1	Vernacular Sustainability	2024	✓			✓			✓	✓	
2	Vernacular Sustainability Vision	2024				✓	✓				
3	Sustainable Vernacular Design	2023	✓	✓	✓	✓	✓				
4	Eco Vernacular Design	2021	✓		✓	✓		✓		✓	
5	Vernacular Architecture Indicators	2020	✓	✓	✓	✓					
6	Vernacular Social Sustainability	2020			✓	✓					✓
7	Climate-responsive Design	2020	✓		✓	✓					
8	Vernacular Design Perception	2020	✓			✓	✓				
9	Natural Materials Efficiency	2020	✓		✓	✓					
10	Sustainable Vernacular	2019	✓		✓	✓	✓				
11	Vernacular Urban Sustainability	2019	✓						✓		
12	Sustainable Ventilation	2019			✓		✓				
13	Traditional Sustainability	2019	✓		✓	✓		✓			
14	Traditional vs. Modern Housing	2019	✓		✓	✓	✓			✓	
15	Sustainable Vernacular Housing	2017	✓			✓					
16	Traditional and Modern Design	2017	✓		✓			✓			
17	Vernacular Sustainability Practices	2016	✓		✓	✓	✓				
18	Vernacular Sustainability	2016	✓		✓		✓				
19	Vernacular Design Potential	2014	✓		✓		✓				✓
20	Vernacular Sustainable Design	2014	✓		✓	✓	✓		✓		✓
21	Traditional Design Lessons	2013	✓	✓	✓	✓	✓		✓		
22	Low-Energy Architecture	2011	✓			✓					
23	Green Vernacular Architecture	2011	✓	✓	✓	✓	✓				
24	Climate Responsive Design	2011	✓		✓	✓					
25	Bioclimatic Vernacular	1998	✓			✓	✓				
Frequency of vernacular principles Indicators Used in 25 Articles (Percentage)			88	16	72	88	52	12	16	12	12

Table 3 (continued)

NO	Subjects and Focus of thes Studies	Year	Considered Indicators													References
			Health & Well-being	Pollution & Emissions	Equity	Beauty & Aesthetics	Outdoor Environmental Quality	Social—Culture	Technical Quality	Equipment & Services	Cost & Economic	Passive Strategy	Accessibility & Satisfaction	Adaptability & Integration	Local Builder & Techniques	
1	Vernacular Sustainability	2024	✓	✓		✓		✓					✓		✓	[75]
2	Vernacular Sustainability Vision	2024	✓	✓			✓	✓			✓					[76]
3	Sustainable Vernacular Design	2023														[77]
4	Eco Vernacular Design	2021					✓	✓	✓			✓				[78]
5	Vernacular Architecture Indicators	2020						✓			✓					[79]
6	Vernacular Social Sustainability	2020	✓	✓				✓					✓			[80]
7	Climate-responsive Design	2020					✓	✓			✓				✓	[81]
8	Vernacular Design Perception	2020						✓		✓	✓	✓				[34]
9	Natural Materials Efficiency	2020								✓	✓					[82]
10	Sustainable Vernacular	2019			✓		✓	✓			✓	✓		✓		[83]
11	Vernacular Urban Sustainability	2019						✓								[84]
12	Sustainable Ventilation	2019										✓				[85]
13	Traditional Sustainability	2019		✓				✓						✓	✓	[86]
14	Traditional vs. Modern Housing	2019	✓					✓				✓		✓		[87]
15	Sustainable Vernacular Housing	2017						✓			✓					[88]
16	Traditional and Modern Design	2017										✓				[89]
17	Vernacular Sustainability Practices	2016					✓	✓			✓			✓	✓	[90]
18	Vernacular Sustainability	2016	✓			✓	✓	✓			✓			✓	✓	[27]
19	Vernacular Design Potential	2014				✓		✓			✓	✓			✓	[91]
20	Vernacular Sustainable Design	2014	✓					✓			✓					[35]
21	Traditional Design Lessons	2013	✓					✓			✓	✓		✓	✓	[22]
22	Low-Energy Architecture	2011						✓			✓				✓	[92]
23	Green Vernacular Architecture	2011		✓						✓		✓				[93]
24	Climate Responsive Design	2011										✓				[94]
25	Bioclimatic Vernacular	1998				✓		✓			✓		✓		✓	[95]
Frequency of vernacular principles Indicators Used in 25 Articles (Percentage)			28	20	4	16	24	76	4	12	56	40	12	24	36	

Table 4 Interconnection and practical application strategies of the proposed holistic indicators: A breakdown by sub-indicators (data collected from references cited in Tables 1, 2, and 3)

Main indicators	Sub Indicators		Interconnection of Main Indicators						
			Energy	Material & Resources	Site & Ecology	Indoor Environment Quality	Social - Culture	Water	Vernacular Principles
Energy	1	Renewable energy & resources	-	✓	-	-	-	✓	✓
	2	Passive Strategies	-	-	✓	✓	-	-	✓
	3	Low-energy building design	-	✓	✓	✓	-	-	✓
	4	Benefit of natural and climatic resources	-	✓	✓	✓	-	-	✓
	5	Respect environmental context and landscape	-	-	✓	✓	✓	-	✓
	6	Optimization of energy performance	-	-	-	-	-	-	-
	7	Energy demand reduction	-	-	-	-	-	-	✓
	8	Adaptation to climate characteristics and geography	-	-	✓	-	-	-	✓
	9	Efficient use of resources	-	-	-	-	-	✓	✓
	10	Use of energy-efficient equipment	-	✓	-	✓	-	-	-
	11	Climate responsive design	-	-	✓	-	-	-	✓
	12	Providing excellent energy-efficiency	-	-	-	✓	-	-	✓
	13	Reduction of energy use and emissions	-	✓	-	✓	-	-	✓
	14	Harmonization between the buildings and environment	-	-	✓	-	✓	-	✓
	15	Use of natural resources, without high technology	-	✓	-	-	-	-	✓
	16	Developing energy-efficient technological process	-	-	-	-	-	-	-
Material & Resources	1	Reduce pollution and waste materials	✓	-	✓	-	✓	-	✓
	2	Consuming local/regional available materials	-	-	✓	-	-	-	✓
	3	Material with low environmental impact	-	-	✓	✓	-	-	✓
	4	Use of low-emission materials	-	-	✓	✓	-	-	-
	5	Use of renewable and natural resources	✓	-	-	-	-	✓	✓
	6	Use of recycled and reused materials	-	-	-	-	-	-	-
	7	Lifecycle impacts/ Durability	-	-	-	✓	-	-	-
	8	Quantity reduction and flexibility	✓	-	✓	✓	-	✓	-
	9	Use of low energy content of building material	✓	-	-	-	-	-	✓
	10	Using native and natural materials	✓	-	✓	✓	-	-	✓

Table 4 (continued)

Main indicators	Sub Indicators		Interconnection of Main Indicators						
			Energy	Material & Resources	Site & Ecology	Indoor Environment Quality	Social - Culture	Water	Vernacular Principles
Site & Ecology	1	Respect environmental context and landscape	✓	✓	-	✓	✓	-	✓
	2	Adaptive reuse of existing building	-	✓	-	-	-	-	✓
	3	Understanding the features of the site	✓	-	-	✓	✓	✓	✓
	4	Considering ecology and environmental quality	✓	-	-	✓	✓	-	✓
	5	Accessibility	-	-	-	-	✓	-	✓
	6	Community connectivity	-	-	-	-	✓	-	✓
	7	Adapting to local conditions	✓	-	-	-	✓	-	✓
	8	Ecology or environment enhancement	✓	✓	-	✓	✓	✓	✓
	9	Compactness of buildings	-	✓	-	-	-	-	✓
	10	Social, domestic, and economic facilities	-	-	-	✓	✓	-	-
	11	Minimizing the impact of interventions	✓	✓	-	✓	-	-	-
	12	Distance from services & public transport	-	✓	-	-	✓	-	✓
	13	Site protection	-	-	-	-	-	-	-
	14	Safe walkability and friendly transport	-	-	-	-	✓	-	✓
	15	Microclimate comfort	-	-	-	✓	-	-	-
	16	Infrastructure efficiency	-	-	-	-	-	-	-
	17	Biodiversity protection	-	-	-	-	✓	-	-
	18	Site management	-	-	-	-	-	-	-
	19	Infrastructure efficiency	-	-	-	-	-	-	-
	20	Aesthetics and respect for nature.	-	-	-	✓	✓	-	✓
	21	Adapting local forms, texture, and settlement	✓	-	-	-	✓	-	✓
Indoor Environment Quality	1	Thermal comfort	✓	✓	✓	-	✓	-	✓
	2	Acoustic comfort	-	✓	✓	-	✓	-	✓
	3	Natural ventilation	✓	-	✓	-	✓	-	✓
	4	Health and comfort	-	✓	✓	-	✓	-	✓
	5	Visual Comfort	-	-	-	-	-	-	✓
	6	Flexibility of building	-	✓	✓	-	-	✓	✓
	7	Produce satisfactory and low-energy buildings	✓	✓	-	-	-	-	✓
	8	Air pollution monitoring	✓	✓	ü	-	-	-	
	9	Improving natural and passive heating	✓	-	✓	-	-	-	✓
	10	Avoiding toxic materials		✓	-	-	-	-	-
	11	Air quality	✓	✓	✓	-	-	✓	-
	12	Daylighting and illumination	-	-	-	-	✓	-	✓

Table 4 (continued)

Main indicators	Sub Indicators		Interconnection of Main Indicators						
			Energy	Material & Resources	Site & Ecology	Indoor Environment Quality	Social - Culture	Water	Vernacular Principles
Social - Culture	1	Protect the cultural and environmental landscape	✓	-	✓	-	-	-	✓
	2	Encourage social cohesion	-	-	✓	-	-	-	✓
	3	Social justice and equality	-	-	✓	-	-	-	✓
	4	Regional social, cultural, and national identities	-	-	✓	✓	-	-	✓
	5	Recognize intangible values	-	-	✓	-	-	-	✓
	6	Quality of life	✓	✓	✓	✓	-	-	-
	7	Social partnership and cohesion	-	-	-	-	-	-	✓
	8	People design needs	-	-	✓	✓	-	-	✓
	9	Public rights	-	-	-	-	-	-	-
	10	Social interaction	-	-	-	-	-	-	✓
	11	Local community sense	-	✓	✓	-	-	-	✓
	12	Health & safety	-	✓	✓	✓	-	✓	✓
	13	Education	-	-	-	-	-	-	-
	14	Participation &control	-	-	-	-	-	-	-
	15	Community engagement and participation	-	-	✓	-	-	-	✓
	16	Compatibility	-	✓	✓	-	-	✓	✓
	17	Making nature meaningful	-	-	✓	-	-	-	✓
	18	Retrospection (changing bad habits)	-	-	-	-	-	-	-
	19	Diversity	-	-	✓	-	-	-	✓
	20	Democracy and governance	-	-	-	-	-	-	-
Water	1	Rainwater harvesting	-	-	-	-	-	-	✓
	2	Recycle and reuse of water	-	-	-	-	-	-	-
	3	Water-efficient landscaping and garden	✓	-	✓	✓	-	-	✓
	4	Greywater recycling	-	-	-	-	-	-	-
	5	Using water-efficient plumbing fixtures	✓	✓	-	-	-	-	-
	6	Designing low-demand landscaping	-	✓	-	-	-	-	-
	7	Application of water-efficient equipment	-	-	-	-	-	-	-
	8	Leak detection	-	-	-	-	-	-	-
	9	Meeting human efficient water needs	-	-	-	✓	✓	-	-

Achieving genuine sustainability requires a comprehensive approach that addresses environmental, social, and economic dimensions simultaneously. This study introduces an innovative framework for sustainable design that integrates Vernacular Principles and Social—Culture as key indicators alongside the most common and applicable sustainable indicators. Vernacular principles and traditional building practices, honed over centuries, exemplify a sustainable approach. These principles emphasize resource efficiency, energy conservation, and cultural relevance. By aligning with local climate, culture, and economic conditions, vernacular practices inherently support environmental, social, and economic sustainability. Moreover, vernacular principles provide practical, traditional, and passive strategies that contribute to the achievement of sustainable indicators.

Table 5 Average Direct-Influence Matrix (extracted from Table 4)

Indicators	Energy	Material & Resources	Site & Ecology	Water	Indoor Environmental Quality	Social—Culture	Vernacular principles
Energy	0	2.1	1.32	0.8	2	0.4	2
Material & Resources	1.6	0	1.16	0.8	2.6	0.8	2.3
Site & Ecology	1.7	2.4	0	0.8	2.6	2.6	3.1
Water	0.5	0.8	0.4	0	0.6	0.4	1.2
Indoor Environmental Quality	1.7	2	1.5	0.8	0	0.8	2.6
Social—Culture	0.4	0.4	2.4	0.2	1.3	0	2.1
Vernacular Principles	3.1	2.3	2.8	0.8	3	2.5	0

Consequently, they are applicable across diverse locations, regardless of technological advancements, economic resources, or infrastructure. By integrating widely recognized sustainable indicators with Vernacular Principles and Social-Culture considerations, this study bridges the gap in existing sustainable approaches and offers a comprehensive and adaptable framework for achieving building sustainability. The DEMATEL analysis validates the importance of these holistic indicators, strengthening the study's credibility. Additionally, it underscores the transparency and significance of the framework's indicators, including Vernacular Principles, as key components. Therefore, the model acknowledges the interconnected nature of economic, environmental, and social sustainability through its holistic indicators. Successful implementation of the model can significantly contribute to achieving sustainability goals through vernacular and sustainable strategies.

However, a primary limitation of this study was the relatively limited existing research specifically exploring vernacular principles as a sustainable design method. This hindered the comprehensive identification and categorization of vernacular principles indicators and sub-indicators in Tables 3 and 4. To mitigate this, a conceptual analysis approach through the interpretation of indicator meaning regarding their similarity with sustainable building indicators was adopted to find the alignment of existing vernacular principles indicators with sustainable building indicators. Furthermore, the applicability of the model across diverse climatic, economic, and cultural contexts necessitates careful consideration of indicator significance. While the MCDM tool aids in this process, effective adaptation and customization require substantial local community engagement. However, insufficient knowledge of sustainable building design principles and indicator characteristics among local communities can pose challenges for architects and policymakers. To facilitate collaboration, additional training and guidance may be necessary. Moreover, differing perspectives on sustainability and a potential bias towards high-tech solutions can create barriers to the implementation and integration of vernacular principles with modern form and contemporary buildings based on comfort, economic, and aesthetic issues. Addressing

Table 6 T (Totla Relation Matrix) = $B(I\text{-}B)^{-1}$

Indicators	Energy	Material & Resources	Site & Ecology	Water	Indoor Environmental Quality	Social—Culture	Vernacular principles	R_i
Energy	0.215141	**0.355294**	0.29351	0.149096	**0.390396**	0.20003	**0.398024**	2.001491
Material & Resources	**0.327749**	0.241225	0.300922	0.154412	**0.438464**	0.234375	**0.43177**	2.128916
Site & Ecology	**0.412221**	**0.466851**	0.316761	0.188952	**0.542114**	**0.40914**	**0.584524**	2.920563
Water	0.133332	0.155494	0.12707	0.044582	0.163643	0.107646	0.201603	0.933371
Indoor Environmental Quality	**0.340437**	**0.369628**	**0.326991**	0.157127	0.294428	0.242748	**0.45576**	2.187119
Social—Culture	0.216508	0.227159	**0.337481**	0.09707	**0.316216**	0.16315	**0.371237**	1.72882
Vernacular Principles	**0.506498**	**0.487213**	**0.497604**	0.199733	**0.589059**	**0.415654**	**0.43588**	3.131642
C_j	2.151887	2.302864	2.200338	0.990973	2.73432	1.772742	2.878798	

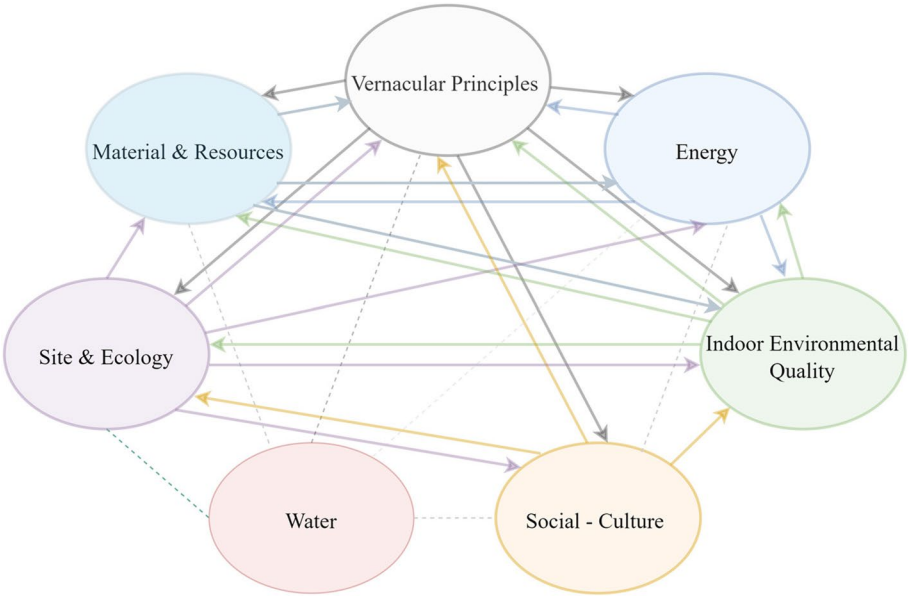

Fig. 2 Illustration of the mutual interconnection and influence of indicators derived from DEMATEL results

these challenges requires a multidisciplinary approach that integrates traditional knowledge with modern technologies, considering the local context. Collaborative efforts characterized by transparent communication and continual improvement are essential to ensure that this model effectively contributes to the creation of well-designed and sustainable built environments in the future.

4.1 Practical applications

This study proposes a comprehensive model that incorporates a wide range of environmental, social, and economic indicators to assess and achieve the sustainability of architectural projects in diverse contexts. However, for effective application in distinct localities, it is crucial to recognize the need for further adjustments through case studies and local community engagement. By incorporating feedback from local communities, the model can be tailored to reflect specific needs and priorities within a particular location. To facilitate implementation, a three-stage approach is recommended for architects and policymakers:

- Project Definition and Contextual Analysis: Clearly define the project's specific goals, requirements, and the surrounding environmental and social landscape, including local capabilities and cultural context.
- Indicator Selection and Customization: Employ Multiple Criteria Decision Making (MCDM) methodologies to adapt the model to the specific project context by selecting and weighting indicators based on local priorities.
- Framework Development: Create a customized sustainability framework by considering the weighted significance of each indicator in relation to the local context.

In a practical application, the initial stage involves a thorough investigation and evaluation of the local context and project requirements, achieved through collaborative efforts among architects, the local community, and policymakers. Once the project's specific environmental, social, and economic needs are identified, the indicators must be adjusted and customized to reflect the unique characteristics of the local context. For applying this model in diverse societies or integrating its indicators into existing sustainable frameworks, a MCDM approach is recommended. Existing studies, such as [7, 60], provide a practical and comprehensive methods for utilizing MCDM to determine the relative weights of each indicator based on specific environmental, cultural, and economic contexts. Moreover, to enhance existing sustainable approaches and rating systems, the model proposes the integration of two novel indicators: "Vernacular Principles" and "Social—Culture." For this purpose, [71] provides comprehensive methods for utilizing MCDM to customize and integrate these novel indicators into existing sustainable approaches. The proposed framework offers a flexible and adaptable approach to sustainable architectural design that can be tailored to a wide range of contexts. By prioritizing key indicators and leveraging

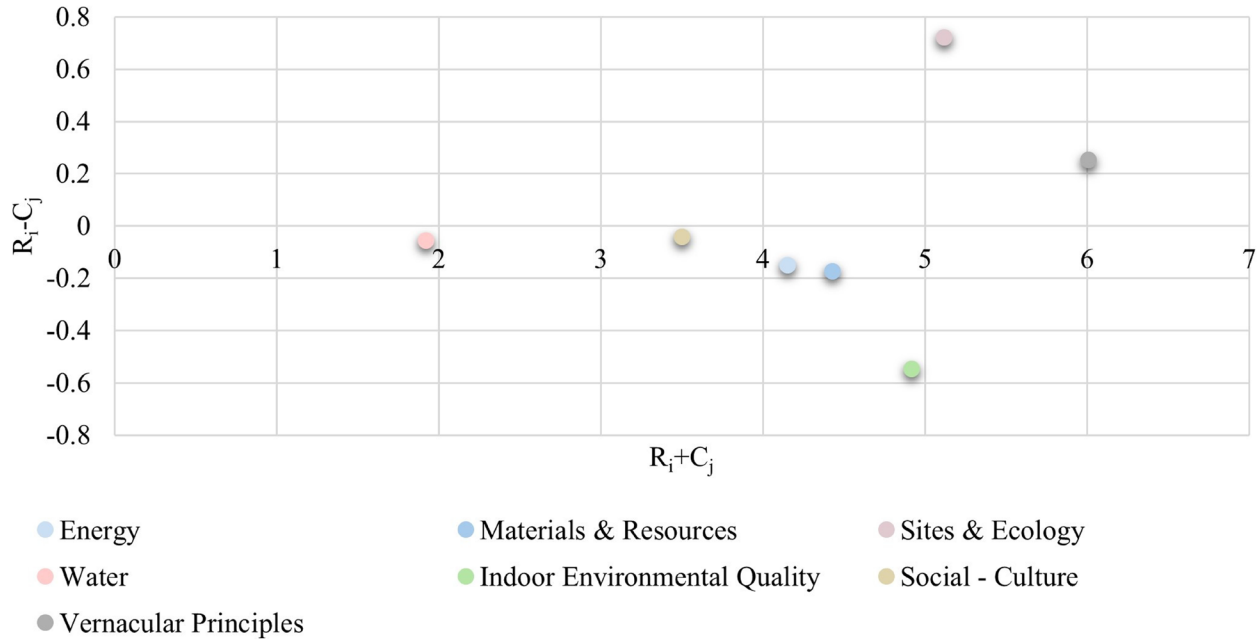

Fig. 3 Interrelationship and influence diagram (Cause and Effect)

local knowledge and resources, architects and policymakers can create buildings that are not only environmentally responsible but also socially and economically sustainable.

5 Conclusions

The proliferation of sustainable design approaches, standards, and assessment methods has led to a plethora of indicators. These indicators serve as vital benchmarks for informed decision-making throughout the design and construction process. However, the abundance of indicators poses challenges for architects and policymakers in terms of selection and interpretation. Moreover, many sustainable approaches primarily focus on environmental considerations and offer theoretical frameworks. This study, through a SLR DEMATEL analysis, proposes a framework that addresses these challenges and provides a holistic sustainable design model encompassing all dimensions of sustainability. Key findings from the study are summarized as follows:

Table 7 Examining interrelationships and influences among indicators through ($R_i \pm C_j$) values

Indicators	$R_i + C_j$	R_i-C_j	Identify
Energy	4.153377	-0.1504	Effect
Material & Resources	4.431779	-0.17395	Effect
Site & Ecology	5.1209	0.720225	**Cause**
Water	1.924344	-0.0576	Effect
Indoor Environmental Quality	4.921439	-0.5472	Effect
Social—Culture	3.501562	-0.04392	Effect
Vernacular Principles	6.010439	0.252844	**Cause**

- A comprehensive SLR and analysis of rating systems identified 23 global indicators for sustainable building design. Among these, five were particularly common and frequently applied: Sites & Ecology, Energy, Materials & Resources, Indoor Environmental Quality, and Water. Notably, these indicators largely overlook the social dimension of sustainability.
- A meticulous SLR of vernacular principles revealed 22 indicators specifically used for vernacular building design globally. Importantly, 19 of these indicators overlap with those used in sustainable design approaches, highlighting a significant convergence between vernacular principles and contemporary sustainable building design. Additionally, indicators incorporating vernacular design principles not only overlap with the most frequently used sustainability indicators but also place a particular emphasis on the social dimension of sustainability.
- The findings demonstrate that vernacular principles can complement existing sustainable design approaches. By integrating Vernacular Principles and Social—Culture as a primary indicator alongside the five most common sustainability indicators, a holistic sustainable framework can be established using two novel indicators. This approach addresses the limita-

tions of existing methods and enhances the applicability and adaptability of sustainable building design.

- The proposed model incorporates seven indicators: Sites & Ecology, Energy, Materials & Resources, Indoor Environmental Quality, Water, Vernacular Principles, and Social-Culture. These indicators are applicable in diverse local contexts and can be readily integrated into various sustainable assessment approaches. By developing a holistic model with seven core indicators, this study streamlines the vast number of sustainable indicators and enhances the applicability of sustainable building design in diverse societies.
- A comparative analysis of these indicators through their sub-indicators and DEMATEL results revealed significant correlations and influences between them, confirming the model's internal coherence and the interconnectedness of sustainability aspects. Sites & Ecology and Vernacular Principles emerged as key indicators with significant influence on others.

This model empowers architects and policymakers to effectively interpret and utilize these indicators in their projects, fostering more sustainable design practices. Furthermore, the study underscores the significant role of Vernacular Principles in achieving sustainability. This insight paves the way for the successful integration of local traditions and strategies into sustainable building design, promoting a more contextually sensitive approach. However, the DEMATEL analysis also highlights the significant influence of local factors on these indicators. Therefore, adjustments using MCDM methods may be necessary for specific applications. To ensure practical applicability and contribute to the field, it is recommended to apply the model in real-world projects based on local context, vernacular resources and community engagement. This approach can promote sustainability that encompasses all dimensions.

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Authors' contributions
Ahmad Walid Ayoobi conceived the overall research design and conducted the conceptualization. The methodology was developed by Ahmad Walid Ayoobi. Mathematical analysis and investigations were carried out by Ahmad Walid Ayoobi, Mehmet Inceoğlu, and Gonca Inceoğlu. Ahmad Walid Ayoobi prepared the original draft. Project supervision was provided by Mehmet Inceoğlu. All authors participated in the final review and approval of the manuscript.

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Data availability
The authors declare that the data supporting the fundings of this study are available upon request.

Declarations

Competing interests
The authors declare no competing interests.

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