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Conceptual framework for sustainable construction

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Abstract
Growing global demand for sustainable development places immense pressure on the construction industry to select and promote sustainable construction practices. The selection of sustainable construction practices is a challenging task, as there are numerous variables and uncertainties involved in the concept of sustainability and a consistent and widely accepted framework for assessment and evaluation seems to be lacking. Based on an extensive literature review on sustainability, sustainable construction was redefined and evaluation frameworks were identified for comparison. Furthermore, a conceptual framework is proposed by identifying specific indicators and criteria relating to the objectives of sustainable construction (sociocultural, economic, technical and environmental) to evaluate the sustainability of construction practices. Recommendations for the application of the proposed framework is also presented.

Keywords Sustainable construction · Conceptual framework · Indicators · Criteria · Sustainability assessment

Introduction

The population explosion followed by an industrial revolution and rapid urbanization in the eighteenth and nineteenth centuries aggravated the exploitation of natural resources and environmental degradation. The United Nations conference on Human Environment, held in Stockholm 1972, explored the links between the environment and development on a global scale [1]. In 1987, the Brundtland Report defined sustainable development and identified the links between social, economic and environmental dimensions [2]. The main concern on sustainable development in the initial stages was conserving natural resources with a perception that the world's natural resources were limited and may be depleted at a rate that could be detrimental to future generations. The Johannesburg Summit of the United Nations proposed the 'three-pillar' concept (People, Planet, and Prosperity/Profit) as the balancing of social and economic development with environmental protection for reflecting the requirement of sustainable development [3]. Various researchers have emphasized the influence of technology on sustainable development along with addressing the other three aspects [4–8]. Beder [5] observed that sustainable development relies on technological changes to achieve its aims by ensuring technology with respect to the specific context and the social, economic and environmental impacts. Similar observations were made by Duran et al. [6], who advocated for the flexibility of interaction between the four fundamental systems (economic, human, environmental and technological) to ensure compatibility between economic and social development and thus contribute to sustainable development. According to Tomislav [8], the development and use of innovative, sophisticated technologies is necessary to reduce the negative impact on the environment and improve human wellbeing.

Construction activities have devastating impacts on the integrity of natural ecosystems and adversely affect sustainable habitats. The role of technology is significant in this context to reduce the environmental impacts of construction. Resource depletion followed by exploitation, solid waste generation, global greenhouse gas emissions, and environmental pollution are common issues associated with this sector with respect to long-term sustainability [9–14]. An estimated quantity of approximately 40 to 50 billion metric tons of sand is extracted from quarries, pits, rivers, coastlines and the marine environment each year. Half of this

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is consumed by the construction industry [15]. Additionally, the building industry is responsible for 35% of total greenhouse gas emissions and 33% of all waste [16]. The growing global demand for sustainable development places immense pressure on the construction industry for selecting and promoting sustainable construction practices and materials. According to Song and Zhang [17], the selection of sustainable materials is a difficult and challenging task, as there are numerous variables and uncertainties involved in the analysis relative to environmental factors. These issues may be related to technological, economic and social aspects. This paper attempts to propose a conceptual framework for sustainable construction to select/evaluate construction practices (materials, methods and techniques employed in construction) to accomplish the objectives of sustainable development. Recommendations for the application of the proposed framework are also included.

Methodology

A semisystematic literature review was adopted considering the broad and diverse disciplines involved to address the following research question:

- What is sustainable construction? What are the specific objectives, indicators and criteria that determine the sustainability of construction practices, and how should their suitability in sustainable construction be determined/assessed?

A basic literature review on sustainable development was initially conducted as a background for the study. Furthermore, the review was extended to identify the views of different researchers on various aspects of sustainability and the frameworks for evaluating sustainability in construction. The four aspects of sustainable development (social, economic, technological and environmental) were also included as a guideline for selecting the literature. Conceptual framework, four aspects of sustainability and related terms were given as the keywords for identifying the research papers. Accordingly, Table 1 was prepared, a definition for sustainable construction was formulated, and the subobjectives were identified. Indicators for each of the subobjectives were identified by reviewing the literature related to the respective definitions of subobjectives, their interrelations and sustainable construction. Definitions of each of the indicators were arrived based on the literature review and assessment strategy (qualitative/quantitative) was decided. Further, criteria for those indicators were identified by reviewing the literature selected on the basis of the keywords related to the respective definitions of each of the indicators and subobjectives. The same process was repeated for the identification of subcriteria.

Sustainability aspects in construction

The concept of sustainability has gained importance in construction since the early nineties. According to Hill et al. [18], the term 'sustainable construction' was originally proposed to describe the responsibility of the construction industry in attaining sustainability. In the early stages, researchers identified it as a tool for minimizing the environmental impacts of construction by giving significance only to environmental sustainability [9, 19–29]. The impact of construction on the environment, optimization of resources and minimization of wastes were the significant criteria for sustainable construction identified in those days [25]. The 'cradle to grave' approach based on the principle of sustainable development was considered the key identity behind this concept [22, 23]. Later, the influence of socioeconomic aspects was identified along with environmental issues [3, 18, 30–59]. Researchers further identified the importance of technology in the sustainability of construction practices with the aim of making it affordable (economic) and suitable to the requirements (social) of stakeholders [60–65]. The feasibility of innovative technological options in terms of economic aspects is significant in making them acceptable. This indicates the importance of technology in sustainable construction and its interconnectedness to economic and social aspects of sustainability.

Table 1 provides a concise review of the different approaches of researchers on sustainability aspects in construction and conceptual frameworks. Selected literature for this review was identified based on the methodology discussed in "Methodology" section. The review shows a uniqueness in the concept of sustainable construction by identifying it as a path towards sustainable development with significance for the four objectives of sustainability: social, economic, technological and environmental. Additionally, recycle/reuse can be observed as an identity of sustainable construction [9, 18–20, 24, 44, 45, 48, 51, 53, 58, 60, 63]. This indicates the need for a transformation from the 'cradle to grave' (linear) concept to the 'cradle to cradle' (circular) approach. Sustainable construction (SC) can thus be defined as an approach/practice based on the 'cradle to cradle' concept, which is socially acceptable, economically affordable, technologically reliable and environmentally friendly, contributing to sustainable development.

The frameworks proposed by Sev [44], Luis et al. [45], Yunus et al. [46], Zalina Shari [48], Zabihi et al. [64], Araújo et al. [51] and Isa et al. [65] focus on the evaluation of the sustainability of buildings rather than the sustainability of construction practices. Similarly, the objectives of the

Table 1 Sustainability aspects in construction and conceptual frameworks

Kibert [19–22] - Sustainable construction is referenced as the construction of a sustainable structure through the application of processes that are environmentally responsible and resource-efficient throughout a building's life cycle. A conceptual model is proposed with 'a cradle to grave' approach giving significance to environmental aspects.
Hill et al. [18, 60] **-** Sustainability in construction is defined as one, based on process-oriented principles encompassing four pillars: social, economic, biophysical, and technical. It includes managing the serviceability of a building during and after the lifetime. A multistage framework for sustainable construction is proposed.
Nair D. G [63] **-** Sustainable construction is considered as a synonym to technological sustainability. A conceptual framework for sustainable construction is proposed by giving equal significance to sociocultural, economic, technological and environmental factors of sustainability.
Ali M et al. [41] **-** Sustainable construction signifies the responsibility of the construction industry for the efficient use of natural resources, minimization of negative impact on the environment, satisfaction of human needs and improvement of the quality of life. A theoretical framework to implement sustainable construction principles in the briefing process of a project is introduced in the context of Saudi Arabia. Significance is given to environment, economic and social sustainability.
Bakhtiar et al. [29] **-** Proposes a list of indicators with significance on environmental factors for examining its effectiveness in different methodologies adopted for promoting sustainable construction. Consideration of cost and time are also mentioned. The proposed framework is a tool for examining the effectiveness of different methodologies (education & training, environmental management system, green building, green design, green procurement, green roof technologies, lean construction, prefabrication, waste management) for promoting sustainable construction.
Sev [44] **-** Sustainable building design and construction is an integrated and holistic process with the aim of creating environmentally conscious and healthy spaces that provides human contact to the natural environment, supporting the local economy and culture. Proposes a framework for implementing sustainability principles and strategies in the construction industry with significance on environment, economic and sociocultural sustainability. This framework acts as a tool for the evaluation of sustainability in the construction industry based on the principles and strategies for resource management, life-cycle design and design for humans.
Luis et al. [45] - Sustainable design, construction, and use of buildings are based on the evaluation of environmental pressure (related to the environmental impacts), social aspects (related to the user's comfort and other social benefits), and the economic aspects (related to the life-cycle costs). This paper discusses different approaches in the building sustainability assessment with respect to the context of Portuguese residential buildings.
Yunus et al. [46] - Sustainable construction is an application of the principles of sustainable development to comprehensive construction cycles from the extraction of raw materials through planning, design and construction of buildings and infrastructure until the final deconstruction and management of resultant waste. A framework is proposed to assess the performance criteria related to sustainability for industrialized building systems in Malaysia with significance on environment, economic, social and institutional sustainability.
Tan et al. [47] - Sustainable construction refers to the integration of environmental, social and economic considerations in construction strategies and practices. A strategic framework for improving the competitiveness of contractors in implementing sustainable construction practices is proposed.
Zalina Shari [48] **-** Sustainable construction involves a balanced and holistic approach to the three dimensions of sustainable development, i.e., social equity, environmental protection and economic development. Proposes a sustainability assessment framework for Malaysian office buildings.
Zabihi et al. [64] **-** Sustainability of building construction can be achieved by enhancing finance and economic savings, reducing the impact on environment and increasing the compatibility with the environment, increasing the social efficiency and usefulness, enhancing the technical quality, and thus optimizing the building. A Building Sustainability Model with significance on social, economic, technological and environmental is proposed.
Araújo et al. [51] - Sustainable buildings are those which allow minimizing the buildings impacts, built and managed with an adequate balance between environment, society and economy. Proposes a list of indicators for evaluating the cost benefit analysis of sustainable construction. Comparison of different building sustainability assessment tools are conducted and indicators are proposed under the sustainability dimensions (environment, society and economy).
Goh et al. [53] - Sustainable construction addresses a comprehensive construction cycle from material extraction, planning, design, implementation, deconstruction and management of resultant waste. Proposes a conceptual maturity model for sustainable construction with significance on environment, economic and social sustainability. This framework can be used for assessing the status of the sustainable development process and current performance level of the construction industry/project.
Alsubeh [54]- Sustainable construction aims at minimizing the use of energy and emissions that are harmful for environment and health, and provides relevant information to customers for use in their decision-making; or as a way of building which aims at reducing (negative) health and environmental impacts caused by the construction process or by buildings or by the built environment. This paper generally describes sustainable construction & architecture, the challenges related to sustainable construction in developing countries, limitations of green construction and the necessity of social sustainability in the context of Jordan.
Isa et al. [65] **-** Formulated a theoretical framework for the life cycle of the buildings with significance on environment, economic, social, and design & innovation. The theoretical framework acts as a guideline for project stakeholders and researchers in formulating sustainability principles for integration into the development of future sustainable building projects **i**n the context of Malaysia
Athapaththu et al. [58] - Proposes a framework to enhance practices of contractor organizations to attain sustainability in construction in Sri Lanka with significance to environment, economic and social sustainability. Suggests eight key areas: legal framework and enforcement, sustainable construction standards, sustainable design, sustainable procurement, technology, processes and innovations, people and organizational structure, education and training, and measurements & reporting.

frameworks of Tan et al. [47] and Athapaththu et al. [58] differ from the objective of this study, as they focus on improving the competitiveness of contractors/organizations in implementing sustainable construction practices. At the same time, the framework proposed by Bakhtiar et al. [29] acts as a tool for examining the effectiveness of different methodologies for promoting sustainable construction. However, Alsubeh [54] presents only a discussion on sustainable construction, challenges and limitations in developing countries in the context of Jordan.

The frameworks proposed by Kibert [19, 20], Hill et al. [18, 60], Ali M et al. [41], Nair, D. G [63] and Goh et al. [53] were selected for comparative evaluation either in view of the comprehensiveness of those frameworks with regard to any one of the sustainability aspects (social, economic, technological and environmental) or the similarity with respect to the objectives of this study. Kibert's framework was selected owing to its comprehensive nature of the significance of environmental sustainability. However, Hill et al. and Nair have given significance to all four aspects of sustainability in their frameworks. Even though the theoretical framework of Ali et al. (implementation of sustainable construction in projects) and the conceptual maturity model of Goh et al. (sustainable development process in construction industry/project) differ from the objective of this research, they were selected for this study considering the significance given to 3P aspects.

Comparative study on selected frameworks

A comparative study was conducted on the selected frameworks to assess their comprehensiveness in addressing the objectives of sustainable construction and the significance given to each of the aspects (social, economic, technological and environmental) and to assess the suitability of this framework in addressing the objective of this research.

Kibert [19, 20] proposed a model for construction projects/industries with the goal of achieving a more environmentally sound built environment. Resource depletion, environmental degradation and healthy environment are considered sustainability criteria for construction instead of traditional criteria (performance, quality and cost). Based on this concept, the issues of sustainable construction are listed under four categories: resources, healthy environment, design and environmental effects. Technical criteria are identified (embodied energy content, greenhouse warming gases and toxins generated/content) in this respect for the selection of materials and products. However, on finding the practical difficulty in applying these criteria in construction, Kibert has put forth seven principles (conserve, reuse, renewable/recyclable, protect nature, nontoxics, life-cycle costing and quality) considering the issues and challenges of sustainable construction, taking into consideration resources (land, energy, water, materials, and landscaping or biota) to create the built environment. He also proposed a model for sustainable construction (Fig. 1) with three axes (principles, resources and phase) considering the interconnectedness of the above principles, resources and different phases of construction (planning development, design, construction, operation, maintenance, modifications and deconstruction). The intersection of these axes is taken as a decision point for accomplishing sustainable construction with regard to minimizing resource consumption and environmental damage. For instance, during the 'planning stage' (Phase axis), material selection (Resource axis) can be performed by applying the seven principles specified under the principle axis. This conceptual model thus provides a guideline for applying the

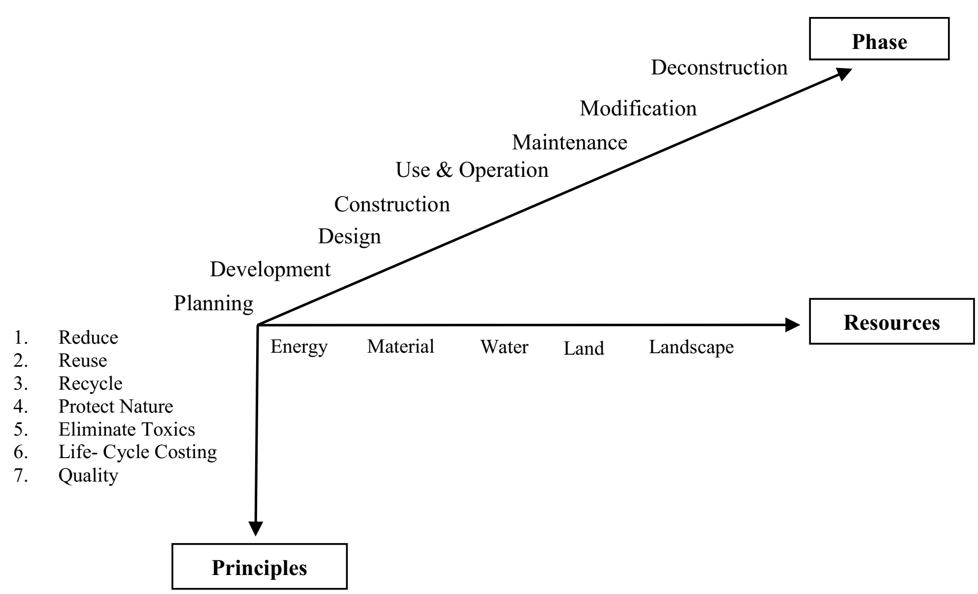

Fig. 1 Framework for sustainable construction (Source: Kibert [20])

principles for different stages of the built environment considering resources.

This model is comprehensive with respect to environmental sustainability, as it provides guidelines for the selection and application of resources for the different phases of a project (cradle to grave) by applying the seven principles. Focus on other aspects of sustainability (social, economic and technological) are found missing. However, considerations of the life cycle cost may contribute to the economic sustainability of a project to a certain extent.

Hill et al. [18, 60] proposed a practical framework that can be applied to a construction project/industry to attain sustainable construction. The application of environmental assessment (EA) for the planning/design stage and the implementation of an environmental management system (EMS) for the construction stage are proposed. EA is considered a synonym for sustainability assessment in this framework, identifies potential impacts, formulates and evaluates alternatives, formulates mitigating measures to reduce impacts and develops compensation plans and monitoring programmes for residual impacts by applying the principles of sustainable construction listed under four pillars of sustainability: social, economic, biophysical, and technical. Under the pillar of social sustainability, ensuring the quality of human life through poverty alleviation, providing social self-determination and cultural diversity through development planning, protecting and promoting human health through a healthy and safe working environment, implementing skill training and capacity enhancement, seeking fair and equitable distribution of social costs and benefits of construction and seeking intergenerational equity are taken as the principles. Ensuring financial affordability for intended beneficiaries, promoting employment creation, using full-cost accounting and real-cost pricing, enhancing competitiveness in the market, selecting environmentally responsible suppliers and contractors, and investing in social and human-made capital are considered the principles under the economic pillar of sustainable construction. However, constructing durable, reliable and functional structures, pursuing the quality of the built environment, using serviceability to promote sustainable construction, humanizing larger buildings, and integrating and revitalizing existing infrastructure are considered technical principles. Under the pillar of environmental sustainability, minimizing the extraction of fossil fuels and minerals, reducing the use of the four generic resources (energy, water, materials and land), maximizing resource reuse/recycling, using renewable resources, minimizing air, land and water pollution, creating a healthy nontoxic environment, maintaining and restoring the earth's vitality and ecological diversity, and minimizing damage to sensitive landscapes are considered. The choice of principles and the decision on the extent (whether to apply weak, strong or very strong), to which each of the chosen principles to be applied depends on the demand of the situation based on sustainability. According to Hill et al., since the optimization of all the listed principles is not always possible based on priorities, compromises are necessary for this framework. Even though some of the principles are not considered immediate priorities in certain cases, they cannot be completely ignored. Overarching principles are proposed as approaches to the evaluation of the applicability and importance of each of the pillars and its associated principles with respect to a particular project with the objective of attaining sustainable construction. For the implementation stage, the framework suggests four key requirements: formulation of an environmental policy, provision of an organizational structure, development of an environmental management programme and undertaking periodic audits under EMS.

Hill et al. claim that the process-oriented principles of sustainable construction of this framework assist stakeholders with a checklist of policy measures under each of the four pillars of sustainability in the planning stage (EA) and suggest practical approaches for implementing the same during the construction stage through four phases of a project, as listed above. As the objective of this framework differs from the objective of this study, a detailed evaluation of EMS is not performed. At the same time, the approaches listed under the process-oriented principles (EA) can be used as a guideline for identifying the indicators and criteria for this study. Systematic grouping of sustainability principles can be highlighted as a positive feature of EA. However, the considerations on life cycle cost and time are missing.

Ali M et al. [41] proposed a framework of sustainable construction for implementing it in the context of Saudi Arabia at the early stages of a project by applying soft value management (SVM) techniques and sustainability principles. Soft value management is used as a technical tool in this framework for addressing the varied functional requirements of sustainable construction principles and formulating policies at the strategic level by filtering different objectives. This framework consists of six interconnected stages: planning (to construct the team and define the briefing workshop), identification (to define the objective of the project), analysis (to integrate sustainable construction principles), creativity (to stimulate the brain storming session), evaluation (to select feasible proposals) and development (to decide on the best alternatives in terms of objectives). The analysis stage, proposed under this framework, is considered for this review, as it is based on the 3P concepts and closely related to the objective of this study. Principles and functions listed under this stage can be considered as a guideline for identifying the indicators and criteria for this study. Ali M et al. adopted a function analysis system technique (FAST) in this stage to integrate sustainable construction principles into functions and thus obtain an understanding of the project.

This includes three steps. Step 1 addresses the identification and definition of functions (the primary functions describe the project objectives with regard to the client's expectations from the project). In step 2, the functions are classified into two categories: basic and secondary. The basic function in a FAST diagram for a project/building is the primary aim for which that project/building is designed and must be accomplished to satisfy the purpose of the project. Secondary functions are those that support the basic function and can be broken down into sublevel functions to improve the evaluation process. Step three depicts the relationships between functions using FAST models. Thus, the ultimate objective, implementation of sustainable construction, is divided into level one functions as environmental, social and economic principles. This is further divided into level two functions and again broken down into sublevel functions describing the methods to accomplish these functions. The participation of key stakeholders with experience in sustainable construction and value management are the essential requirements for implementing this framework along with the additional cost and time required for efficient implementation. Ali M et al. considered this to be a major limitation. The comprehensiveness of the environmental principles and consensus in the different functions and methods with regard to the ultimate objective of implementing sustainable construction proposed under the FAST diagram can be considered a highlight of this framework. However, the framework cannot be considered comprehensive because it fails to consider the significance of technological aspects. Even though the sustainability principles incorporate technological considerations such as durability and constructability (economic factors), no direct mention was given on the basic strength/performance characteristics. Similar observations can be made under economic principles with respect to the duration/time span of a project, which directly influences the cost. The sublevel function 'ensure quality' placed under economic consideration is more suitable under social principles, as the perception of quality is subjective. However, adaptability, which is more related to social aspects, and constructability, which is more related to technological aspects, can be considered under economic aspects only if proper guidelines are given.

Nair [63] proposed a conceptual framework for sustainable-affordable construction for the evaluation of sustainability in construction practices with equal significance to sociocultural, economic, technological and environmental factors of sustainability. Under each of these factors, various criteria are identified, indicating the specific demand to be met for achieving sustainability with respect to those aspects. Acceptance, awareness and enabling self-help are identified as the criteria under sociocultural factors. However, infrastructure, unskilled labour, accessibility to material or labour and material efficiency are considered criteria with respect to economic sustainability. Strength, durability and reliability are considered under technological sustainability. Energy efficiency, waste management and reusable/renewable are taken as the criteria under environmental factors. Even though the framework appears to be comprehensive in integrating four aspects of sustainability, further modifications are required to address duplications, missing criteria and misplacement of criteria. For instance, unskilled labour under economic sustainability and enabling self-help under sociocultural factors can result in duplication and hence may be appropriately identified and placed. Life cycle costs and related criteria that directly contribute to economic sustainability are not considered. Reliability criteria placed under technological factors are more suitable under sociocultural factors, as these criteria are subjective. Similarly, material efficiency (economic factors) can be more suitable under environmental factors in consideration of the optimization of resources. Additionally, equal significance proposed for each of the sustainability aspects cannot always be anticipated. Hence, the applicability of this framework can be suggested only by proposing more flexibility in this concept to suit the demands of situations.

Goh et al. [53] proposed a conceptual maturity model for sustainable construction to assess the strengths and weaknesses as well as the external opportunities and threats related to the current performance of a construction industry/project with respect to the sustainable development process. According to Goh et al., the model offers an initial baseline to measure the evolution of sustainable development maturity across the construction industry. Five domains are identified as key metrics in this model: performance (to focus on the sustainability aspects), management capability and capacity (to ensure the effectiveness and efficiency of implementation), culture (to ensure support from the community), long-term framework and development (to continuously assess and ensure the integration of sustainability features) and research and development (to keep pace with current trends). In each of the domains, subfactors are assigned a measurement scale of 5 points under each domain, and an accumulated scoring basis is used in assessing the maturity level of sustainability in construction. A predefined maturity level ranging from 1 to 5 is suggested as initial, repeatable, defined, managed and optimal (level 1 to 5) to indicate the maturity index of sustainable construction applied in practice with level 5 as the highest level of maturity status. Among the five domains, the performance domain relates to the objective of this review. The other four domains relate to the implementation part of sustainable construction. Hence, detailed evaluation of the performance domain is only conducted with regard to the objective of this paper. According to Goh et al., performances are evaluated based on the nine main principles of sustainable construction, such as resources and materials consumption, environmental impact, quality of comfort (occupational health and safety, indoor environment quality, indoor chemical and pollutant source control, controllability of systems, occupants and owner's satisfaction), energy efficiency, design process (daylight, thermal comfort, ventilation, spaces flexibility and adaptability, ecological innovation), life cycle costing (economic aspects), functional applicability, lifespan (service life, durability and maintenance), heritage and cultural preservation. Subfactors are identified in each principle to measure and determine sustainable competitiveness. Although these principles of sustainable construction appear to be comprehensive, systematic grouping under the principles of sustainable development could have been better in avoiding duplication and eliminating the chances of missing criteria, as observed. The subfactors listed under the principles resources and materials consumption, environmental impact and energy efficiency refer to environmental sustainability. However, the factors listed under the principles quality of comfort and design process are a mixture of social and environmental aspects. Duplication of subfactors is also noticed in resource and material consumption, environmental impact, quality of comfort, energy efficiency and design process. Even though life cycle costing (economic) and durability (technological) are listed, proper consideration is not given to other factors that determine sustainability with respect to economic and technological aspects. However, the other domains of the maturity model that address the implementation of sustainability in the construction industry include the factors related to social (attitude, awareness) and economic (financial capability) sustainability.

The review shows a similarity in the selected frameworks with respect to the identification of indicators under different objectives of sustainability in line with the principles of sustainable development. Duplication/misplacement of criteria was observed as a drawback in most of the frameworks. Although all the presented frameworks claim to be comprehensive in their focus, this review was able to identify these drawbacks and limitations specifically with regard to all objectives of sustainability other than environmental aspects. Additionally, varied levels of significance were found in each of the frameworks with regard to these objectives, with the more recent frameworks becoming more integrative and gaining more attention to the nontechnical and nonenvironmental aspects of sustainability in construction practices. Frameworks proposed by Kibert [19, 20] and Ali et al. [41] have given major significance only to environmental factors. Even though the frameworks of Hill et al. [18, 60], Nair D. G [63] and Goh et al. [53] are similar in considering the basic objectives of sustainability, none of these frameworks can be considered comprehensive and need further modifications. At the same time, systematic grouping of objectives can be seen in Hill et al. [60] and Nair [63]. However, the objective of Hill et al. differs from the objective of this research.

This study proposes a comprehensive conceptual framework with systematic grouping of indicators and criteria (in the form of a checklist) without duplication under each of the basic objectives of sustainable construction.

Proposed framework for sustainable construction

The objectives of sustainable construction can be achieved by addressing the subobjectives of sociocultural sustainability, economic sustainability, technological sustainability and environmental sustainability (Fig. 2).

Infrastructure development for healthy living and social wellbeing clearly indicates the importance of sociocultural sustainability (SCS) in construction, as identified by many researchers [59, 66–74]. Since the affordability of infrastructure and quality of life are closely associated with resource efficiency and environmental quality, the significance of economic sustainability (ECS) and environmental sustainability (ENVS) are explicit in this concept. The affordability of reliable technological options is influential in deciding the selection of alternatives that are environmentally friendly.

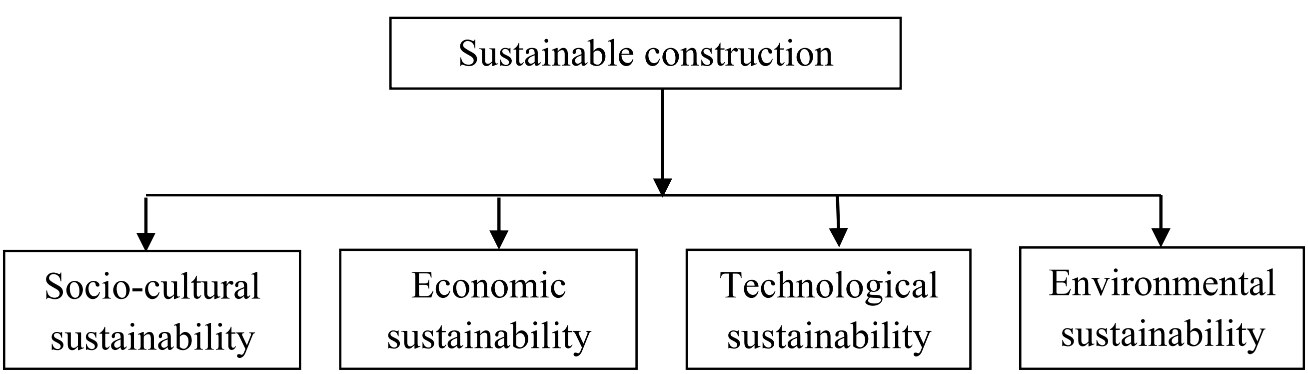

Fig. 2 Sustainable construction – Sub objectives

This indicates the significance of technological sustainability (TCS) in sustainable construction. To generate a logical structured framework and prevent overlap in criteria and indicators, this research follows Keeney [75, 76] and Van der Lei et al. [77] in creating an objective hierarchy model for sustainable construction. Subobjectives, indicators and criteria are proposed in line with the same.

Sociocultural sustainability

According to Chiu, R. L [78], an activity or development concerned with improving the wellbeing of people needs to maintain specific social relations, customs, structure and value to consider it socially sustainable. Additionally, the cultural and social dimensions of a society are often considered together, as they have a strong influence on the development of the community. Social acceptance of construction throughout its lifecycle is an influential factor affecting the sustainability of the process. Hence, community participation together with awareness, adaptability, satisfaction and social benefit, which add to the acceptance level of technology, is considered the basic indicator for evaluating sociocultural sustainability. Sociocultural sustainability in construction can thus be defined as the popularity of technological options and their flexibility to suit the requirements of stakeholders with respect to resource availability and limitations. According to Valdes-Vasquez et al. [79], sociocultural sustainability has a crucial role right from the planning stage of construction.

Indicators of Sociocultural sustainability

- *Community participation* **-** Community participation helps improve the sociocultural sustainability of construction practices, as it creates jobs in communities and enhances the confidence of the community. Hence, this indicator can be measured in terms of the potential of a technological option in utilizing local resources. Technological innovations that demand the participation of unskilled labourers and local infrastructure can ensure community participation.
- *Awareness* - According to Serpell et al. [80], awareness is considered one of the main drivers that promotes the implementation of sustainable construction practices. It can only be measured qualitatively, as it depends on the popularity of technological options and varies from person to person. Practical awareness and knowledge-based awareness can be considered the basic criteria for measuring this indicator.
- *Adaptability/Flexibility* - This indicator can be measured qualitatively, as it implies the flexibility of technological options with regard to the changing needs of the users. According to Loftness et al. [81], the pursuit of sustainability requires a shift from 'tight-fit design to generous design'. Adaptability to the varied requirements of topographical conditions (site conditions), architectural style and compatibility of the technology to traditional/conventional practices in the locality is considered as the criteria for this indicator.
- *Satisfaction* **-** Satisfaction with a technological option is determined by the satisfaction of all stakeholders, including beneficiaries and the workforce [82]. Basically, it originates from past experiences. The reliability, safety and attitude of stakeholders towards a particular technological option initially influence the selection. Comfort and safety experienced later add to the satisfaction of the users and ultimately to their quality of life. According to Petrovic [83] and Zuo et al. [14], quality of life is considered a part of social sustainability. The utility/feasibility of a technological option for different age groups influences their physical comfort and hence their quality of life. Proper ventilation and lighting are also essential factors with respect to physical comfort. In addition, thermal comfort, visual comfort and acoustic comfort are the other subcriteria for measuring comfort. Technological options for different functions demand varying levels of privacy. This criterion also adds to the satisfaction of users.
- *Social costs/benefits* - This indicator implies the potential of a technological option in assuring additional benefits rather than intended objectives. For instance, sustainable practices are usually promoted by policy initiatives by providing monetary benefits/incentives. As we are not able to ensure the equitable distribution of the resources and social cost of construction, this criterion is significant in promoting sustainable construction practices.

Economic sustainability

Economic sustainability of construction implies the affordability of technological options suiting the specified requirements without compromising other aspects of sustainability. Innovative technologies are usually proposed with the objective of cost reduction. Life cycle cost is considered an influential indicator with respect to sustainable construction [21, 45, 84]. The selection of technological options is also judged by the demands of specific situations. The feasibility of resources and speed of construction play vital roles in this context. Thus, lifecycle cost, feasibility of resources and process duration are taken as the basic indicators for the assessment of economic sustainability in construction.

Indicators of economic sustainability

- *Life cycle cost* **-** Life cycle cost implies the total cost of the entire process from cradle to grave. It can be measured by evaluating criteria such as initial cost *(*total cost incurred in the collection of raw materials, transportation and processing), cost in use (the operational cost including the maintenance cost), environmental cost (the cost of safe disposal including all emissions and solid wastes associated at the end of the lifecycle of a technological option) and residual value (reuse/recycling potential of a technological option). Optimization of lifecycle cost needs prime concern in economic sustainability.

- *Feasibility of resources* **-** This indicator can be measured in terms of the potential of a technological option in accessing the resources. The feasibility of resources adds to the affordability of technological options and thus to economic sustainability. According to Nair, D. G [63] technological options that demand minimum infrastructure, basic resources and unskilled labour requirements improve the affordability of sustainable construction only if there is enough accessibility to these resources. Hence, the feasibility of resources such as infrastructure, materials and labour are considered as the criteria for evaluating this indicator.
- *Process duration* - As time and cost performance are interlinked, the duration of technological options is a significant indicator in the evaluation of economic sustainability. Process duration is the total time required for completing all the steps and processes for a technology to become functional.

Technological sustainability

Environmentally friendly and economically feasible technological options can only be said to be sustainable in meeting the minimum mandatory requirements for technological sustainability. Technological sustainability of construction practice/material is defined as its ability to perform in accordance with the functional requirements for the designed strength and durability characteristics specified by standards. Hence, strength and durability are identified as the basic indicators for evaluating technological sustainability.

Indicators of technological sustainability

- *Strength*- This indicator can be measured in terms of the potential of a technological option to meet the basic strength parameters appropriate to the specific needs suiting local circumstances as specified by the standards.
- *Durability*- Durability of a material/technological option as a component of a building or any other civil engineering structure can be measured as its ability to resist deterioration due to weathering action, chemical attack or any other processes exposed to the environment during the functional lifetime of the structure efficiently as specified by the codes without unforeseen maintenance or repair.

Environmental sustainability

Environmental sustainability in construction can be achieved by adopting a cyclical building process (cradle-to-cradle approach) ensuring resource efficiency and environmental quality. Hence, environmental quality and resource efficiency are considered the basic indicators for measuring the environmental sustainability of construction.

Indicators of environmental sustainability

- *Environmental quality* - This indicator can be measured in terms of the quality of air, water, noise and the quantity of quality residual waste generated by the adoption of a specific technological practice.
- *Resource efficiency* – Reducing the use of four generic resources, energy, water, materials, and land, is emphasized by many researchers to ensure resource efficiency in construction [26, 41, 60]. Resource efficiency thus implies the efficient use of resources in sustainable construction with minimal environmental impact.

Energy efficiency can be measured in terms of the total energy requirement with respect to embodied energy and operational energy.

However, material efficiency can be evaluated in terms of material adequacy and quantity of local materials utilized. Among them, material adequacy refers to limiting the quantity of materials for a specified requirement (with respect to strength and durability) as demanded by the situation. However, the criteria for local materials can be measured in terms of the potential of a technological option to utilize (or replace conventional materials) locally available (renewable/reusable/recyclable/waste) materials. Physical destruction of land caused by extraction of raw materials and minerals leads to the destruction of the natural topography, lowering of the water table and ultimately to climate change. Land adequacy can be measured in terms of the extent of physical land destruction directly related to a particular technological option/building process. Figure 3 shows the conceptual framework for sustainable construction.

Recommendations for the application of the proposed framework

The conceptual framework for sustainable construction proposed in this research for evaluating the sustainability of construction practices takes into account different indicators and criteria of multidimensional characteristics in accordance with the objectives of sustainable construction. A combination of qualitative and quantitative indicators are suggested considering these aspects with respect to their contribution towards sustainable development. Based

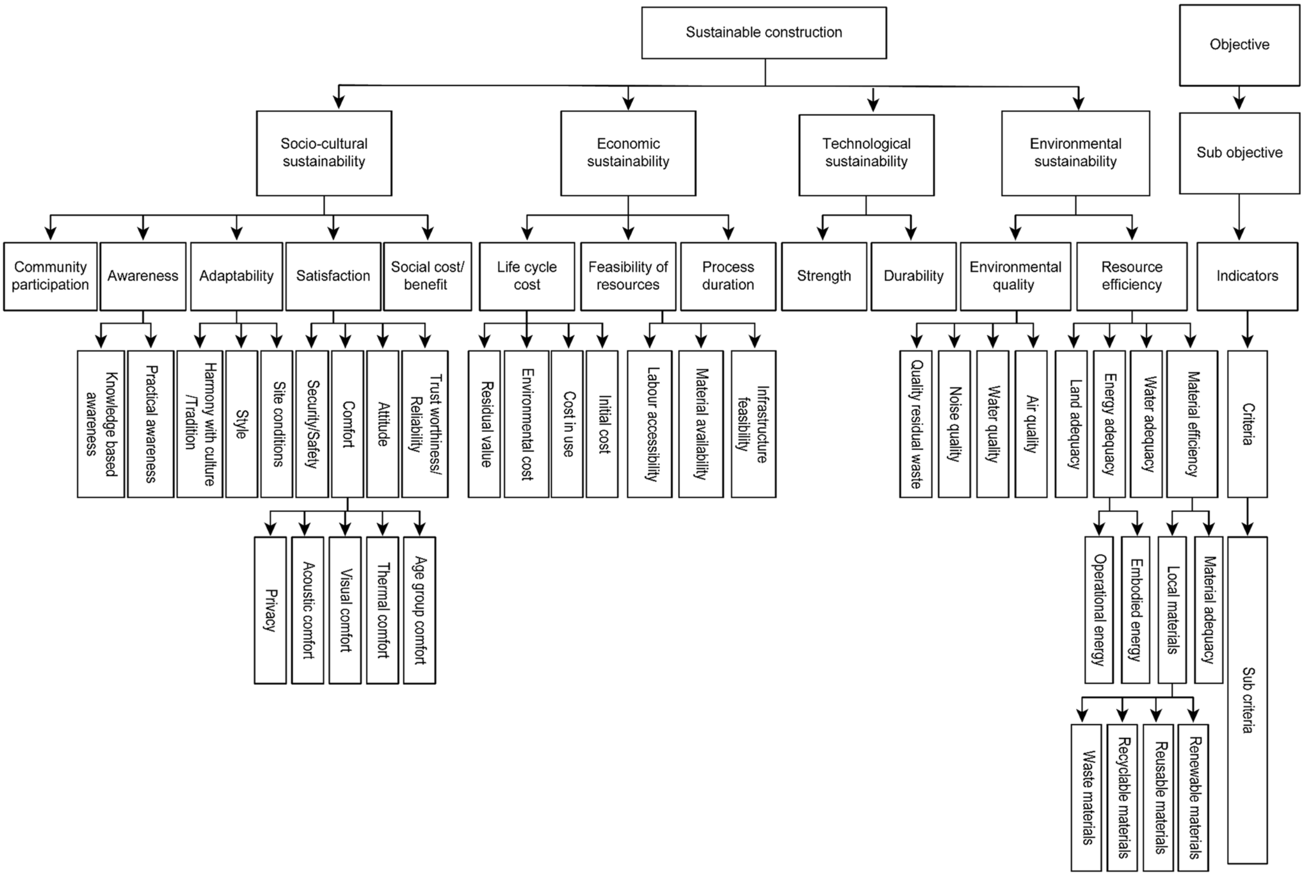

Fig. 3 Conceptual framework for sustainable construction

on the immediate demand of situations, some of the above indicators/criteria may not be considered priorities in certain cases, but they also cannot be completely ignored.

Among the four aspects of sustainability, sociocultural sustainability is highly dependent on the variations in the preferences of concerned individuals; hence, qualitative evaluation is appropriate with respect to this objective. However, the indicators under technological sustainability can be measured quantitatively. The assessment of economic and environmental sustainability needs a mixed approach. Process duration and all criteria except residual value related to life cycle cost can be evaluated quantitatively. All other indicators and criteria under economic sustainability can be measured only qualitatively, as they are very much dependent on the location, skills and efficiency of the workforce employed. Similarly, for quality residual waste, the criterion under the indicator of environmental quality also depends on the efficiency of the workforce and the type of construction practices (e.g. prefabricated building components).

Grading of various criteria in qualitative analysis can be done in accordance with the preferences of the stakeholders and evaluated on the basis of structured questionnaire surveys. However, in quantitative analysis, suitable grading can be adopted based on the quantitative values. Normalization of the values can be performed based on the specified standards. For instance, the value of an indicator/criteria that is higher than the specified requirement for the desired function can be considered equivalent to the standard value. However, the values of indicators/criteria that are lower than the standards may be normalized as usual. A simple additive weighting system can be adopted in quantitative and qualitative cases, and a final sustainability index can be obtained. The weightage of indicators under each sustainability aspect can be assigned based on the number of indicators considered under each objective (for instance, the weightage of each indicator under sociocultural sustainability is 1/5, as there are 5 indicators). The same principle can be adopted for criteria and sub criteria in assigning the weightage. However, stakeholders have flexibility in deciding the weightage for each criterion and subcriteria in line with the objective of sustainable construction to suit the demand of the situation. Thus, the sustainability index (SI) of each of the objectives of sustainable construction can be calculated as follows:

$$\mathrm{SI} = \sum_{i=1}^{N} \sum_{i=1}^{n} \mathrm{xij} \times wj,\ j = 1, \ldots \ldots n$$

where 'N' is the number of indicators, 'n' is the number of criteria, w_j is the weight of each criterion, and x_{ij} is the normalized score of the criterion.

After arriving at the sustainability indices for each of the objectives, the stakeholder can decide on the selection/assessment of construction practices suitable for sustainable construction.

Conclusion

This paper identifies the significance of cradle-to-cradle appraisal, interactions/interconnectedness and fulfillment of the four objectives of sustainable construction as its uniqueness. The proposed conceptual framework for sustainable construction can be considered a comprehensive list of specifications with indicators, criteria and subcriteria (without duplication) under each pillar of sustainability, contributing to the objectives of sustainable construction. This conceptual framework can assist stakeholders in the selection and (ex-ante) evaluation of prevailing construction practices suitable for sustainable construction. As this framework offers ample flexibility to suit the demands of situations within the limits of sustainability, this conceptual framework can be universally adopted.

As the presented framework is currently in a conceptual stage, it needs to be applied and tested in practice. Its strength is that it distinguishes and separates its indicators into four categories: sociocultural, economic, technical, and environmental, thus reducing the overlap and interconnectedness of the various criteria as encountered in most other frameworks. Operationalizing, validating and applying the proposed framework to assess the sustainability of construction practices may be the next stage of this research.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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