Review Article

A Review of the Environmental Impact of Buildings with an Emphasis on Performance Assessment Tools and Their Incorporation of LCA

Vidhyalakshmi Chandrasekaran ⬥ and Jolanta Dvarionienė

Kaunas University of Technology (KTU), Institute of Environmental Engineering, Kaunas, Lithuania

Correspondence should be addressed to Vidhyalakshmi Chandrasekaran; vidhyalakshmi.chandrasekaran@ktu.edu

Background. The environmental performance of buildings has been a focus of interest over the years in the building sector. Numerous building environmental assessment tools (BEA) have evolved to follow the lead of sustainability by updating categories and criteria from a lifecycle perspective. Therefore, it is timely to review the existing methods that already integrated LCA in their processes. The purpose of this study unfolds in three ways: (1) to review the existing BEA methods and LCA studies in residential buildings, (2) to compare the most adopted BEA methods, and (3) to study the integration of LCA and sustainability aspects applied within each selected BEA method. *Methods.* Scopus and Web of Science databases were searched for articles published between August 2010 and August 2021 in English. To identify studies and to conduct this review, four keywords, namely "Building Assessment Tools," "Residential Building," "LCA," and "Sustainability" (and their derivatives), were used. The articles were searched so that all four keywords or at least a derivative of each keyword would appear. Furthermore, the outcomes of the database search were categorized as LCA and BEA for the review. Moreover, the seven most adopted rating systems were selected for review and comparison based on (1) the scope of buildings assessed, (2) lifecycle phases assessed, (3) assessment criteria, and (4) the user of tools. *Findings.* Of the 42 articles that met the enclosure criteria, 20 articles covered the environmental impact and 22 articles covered LCA. The review reveals that most of the analyzed systems focus more on the operational stage than on the other stages. Each BEA method is diverse in terms of its users, criteria, and regions and creates a niche among assessment methods. *Conclusions.* The main conclusion of this study is that a great deal of work is required to achieve the goal of making the existing "environmental" building assessment tools more sustainable. At the same time, a focus on the better implementation of LCA functionalities at each stage and a complement by integrating socioeconomic-based LCA models were also required.

1. Introduction

The building sector has a substantial proportion of the world's energy and resources, both directly and indirectly [1]. The importance of reducing energy in buildings and their potential for cost-effective energy savings have been a target of development over the years. With the shifting focus on a climate-neutral society, making buildings more energy-efficient, less carbon-intensive over their entire lifecycle, and more sustainable has become critical [2]. Several new elements and strategies have been introduced to modernize the building sector [3], and efforts have been made to develop tools that help to investigate the environmental impacts. Most of these tools were developed to establish a comprehensive methodology aiming to evaluate and verify the characteristics of the present buildings with the use of selective criteria, guidelines, factors, or verifiable standards [4]. Typically, two techniques have been taken when developing environmental assessment schemes: life cycle assessment (LCA) and building environmental assessments (BEA). In many instances, both approaches have been combined to investigate the environmental impacts [5]. While building

performance assessment is used as a qualitative tool with a set of criteria and checklists, LCA urges analysis based on numerical evidence to facilitate decision making.

LCA is a widely used approach and state-of-the-art technology for assessing the potential environmental implications of all input and output flows throughout a product's lifecycle, from raw material extraction to end-of-life [6, 7]. The International Organization of Standardization (ISO) adopted environmental management in 1990, with standard series 14040 and 14044, exclusively on LCA methodologies. The LCA comprises four main components: (i) goal and scope with the functional unit and system boundary definition, (ii) life cycle inventory (LCI), where all necessary data are collected, (iii) life cycle impact assessment (LCIA) evaluates the significant potential environmental impacts, and (iv) interpretation phase, where findings are evaluated [8, 9]. The LCA of buildings has been extensively researched because of the high environmental impacts of this sector and its integrated approach to impact assessment and data quality [10]. Many studies related to the energy performance and embodied energy of buildings are exclusively performed using the LCA method with multifaceted goals [11–15]. LCA is evolving daily among various stakeholders, extending its scope to various aspects, such as sustainability, materials management, environmental product declarations (EPD), and design alternatives [16–18].

Environmental assessment methods were first motivated by green building councils (GBCs) across the world to communicate with the market to extend the commitment to sustainable development in buildings. These assessment methods were developed by many countries, such as Australia, Canada, France, Germany, the United Kingdom (UK), and the United States of America (USA) to evaluate the different parameters during various stages of a building. These methods are also termed building environmental assessment (BEA) methods. Currently, there are several building assessment methods present worldwide. However, the building research establishment environmental assessment method (BREEAM) [19] was the first tool developed that has been widely used for performance assessment to date. The tool was developed focusing on the energy use and environmental impact of the building alone. Similar assessment tools, such as leadership in energy and environmental design (LEED) [20], comprehensive assessment system for built environment efficiency (CASBEE) [21], Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) [22], and Haute Qualite Environnementale (HQE) [23], are primarily used for building performance across the world. These methods are categorized based on different criteria, such as management, ecology, water, energy, transport, global warming, waste, and pollution. Several other methods were developed in later years, adopted from the existing ones, with indicators that fit regionally [24] that extend to economic, sociocultural, functional, and technical aspects as well [25]. Most of these methods measure the built environment performance exclusively. However, it involves quite a complex process and parameters. There are several tools introduced to develop green buildings, and each of the tools has different procedures and methods. Therefore, there

is a possibility that the same evaluation could derive different results when analyzed with different assessment methods [26, 27].

BEAs are discussed, e.g., Poveda and Lipsett, Giama and Papadopoulos, Alyami and Rezgui, Markelj et al., Boarin et al., Suzer et al., Gobbi et al., Tang et al., and a few tools are compared in several studies, e.g., Kajikawa et al., [28] Bannani et al. [29], Bernardi et al., [5] among international communities [4, 30–38]. Few studies, such as Rezaallah et al., Lee, Chu Ka-waia, and Cheung Yun-hing, Asdrubali et al., focused on exclusive systems to discuss the roles of the existing methods [39–42]. Despite their current accomplishments in the international communities, BEA remains confined by a lack of clarity. According to Doan et al. and Sartori et al., many studies attempted to study the relationship among BEA tools, some confined to a particular BEA, not discussing their limitations and updates adequately [16, 43]. Studies in the past found limitations in the capacity of the BEA tool to address LCA and raised concerns about the current assessment methods. For instance, Schlegl et al. endorsed improvements to the DGNB method related to the LCA procedure and formulated a model to standardize the structure of LCA evaluation methods in the German context [44]. Lee et al. proposed an LCA framework in BEA, focusing on construction materials in the Korean context to achieve the target score for certification [40]. Furthermore, the non-LCA-based credits, such as design and site selection impact categories, were further explained by Ismaeel [45]. Sartori et al. analyzed the relationship of building software tools from an LCA viewpoint but not from a BEA perspective [16]. Although BEA has been a focus among various researchers from the previous decade, a systematic review of BEA and LCA is limited. On the other hand, there is a need for whole lifecycle-based environmental profiling tools that could deliver robust, diverse, and unbiased analyses in the building sector. There are few existing examples related to the application of BEA methods across the building sector. Therefore, it is well-timed to review these existing methods that already use LCA within their processes to acquire a better understanding of the extent to which they are applied and how their outputs are considered.

The scope of this paper is to review the environmental impact on residential buildings with an emphasis on the most widely used existing building performance assessment methods from the widest range of available information from research journals, technical manuals, and official websites or establishments that created these methods. The paper reviews the two main approaches for assessing building performance: LCA and BEA. The main contributions offered by this paper are the review of the existing BEA and LCA studies in residential buildings through literature sources. Also, the paper conducts a comparative study of the seven most adopted environmental assessments for buildings. Moreover, the paper also aims to look for relevance to the LCA concept and sustainability dimension within the selected assessment methods and to draw general conclusions. The paper is divided into five sections. The first describes the concepts underlying the environmental assessment methods and summarizes the two main

approaches: LCA and BEA, for assessing building performance. The material and methods implemented to develop, the establishment of four selection criteria, the analysis of seven assessment methods, and their comparisons are presented in detail in section 2. Section 3 is dedicated to the integration of LCA within the seven selected schemes based on several criteria, such as project type and building type, considering all the aspects involved in environmental performance evaluation. The discussions and conclusions of the primary contributions of this paper are subsequently presented in sections 4 and 5.

2. Materials and Methods

In this review, the methodological approach aims to respond to the research gap and the objective of schematizing the workflow adopted from published studies. In the first stage, a comprehensive literature search was conducted through a scientific database search engine. The literature search was based on the following keywords: building environmental assessment methods, LCA, sustainability, and residential buildings (and their derivatives) and filters, as shown in Figure 1. Simultaneously, the most adopted building environmental assessment systems were considered based on the number of projects (more than 3000) and a minimum of 5 years of service. There are around 600 rating systems available worldwide, out of which seven systems met the criteria, as shown in Table 1. Only building environmental systems have been considered, and no benchmarking or evaluation software has been further analyzed. The considered systems are listed below.

(i) Building research establishment environmental assessment methodology (BREEAM), United Kingdom.

(ii) Comprehensive assessment system for built environment efficiency (CASBEE), Japan.

(iii) Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), Germany

(iv) GREEN STAR, Australia and New Zealand

(v) Haute qualite environnementale (HQE), France.

(vi) Leadership in energy and environmental design (LEED®), USA

(vii) WELL, USA

In the second stage, a comprehensive review of the extracted scientific articles from the database search was conducted. In this review, LCA and BEA systems were analyzed separately, in which seven assessment systems were considered and analysed further based on the review performed, and the remaining methods were eliminated, as shown in Figure 1. Moreover, a comparison of the selected seven systems was conducted, and an overview was provided about the structure and components of these tools. Furthermore, in the next stage, the level of integration of LCA within the selected BEA systems was analyzed based on the scope, LCA credits, and categories provided in the assessment system. It shows the level of importance given to the LCA

components in that individual system. Most of the data in this study arise straight from the official technical manuals. Additional information was gathered from the official websites of certification bodies and previous scientific articles.

2.1. Environmental Assessment-LCA. BEA follows a universally accepted approach to facilitate the evaluation of environmental impacts through LCA. An LCA for the entire building comprises all materials in the building but is not limited to materials found in substantial amounts. The whole LCA process of the building is performed based on the set of standard references and the assumption of modeling related to ISO 21931 and EN 15978. The different stages of the construction life cycle are defined as follows: (A1-A3) product stage, (A4-A5) construction process, (B1–B7) use stage, (C1–C4) end of life, and (D) benefits and loads beyond the system boundary [46]. LCAs can be classified according to their scope, considering different stages of the building–product stage (cradle to gate), the whole life cycle of the building (cradle to grave), or adding impacts beyond the end of life (cradle to cradle) [5, 6, 47].

Various studies (Table 2) have focused on residential buildings [11–15, 27, 53, 64] to identify the overall impact of various products, processes, and stages of the life cycle 34. However, these studies [11, 13, 15, 27, 58, 59] were performed using LCA, focusing on embodied energy or/and operational energy in residential buildings as a parameter for environmental performance. The energy of different types affects the environment in different ways according to the regions. Therefore, it is straightforward to look for the importance of energy impact and environmental performance with respect to different climatic zones. According to Villegas et al., the cold weather in Sweden contributes significantly to the energy effect of multifamily housing renovations. The study concluded that the operational, building materials, and building installation process have the highest impact [14] and can be compensated for with the use of renewable energy as an alternative. A similar study was conducted in an Indian context with five different climatic geographical zones (i.e., hot, dry, warm, humid, composite, cold, and moderate) in a residential building with varying envelopes. Lifecycle energy demand was studied with traditional and alternative materials (envelopes), and it was concluded that alternative wall materials with significant insulation could result in better energy performance [65].

By reviewing these studies, the parameters considered for the existing research vary substantially, however, a common trend is observed in the study. Almost all research is focused on the use phase, particularly energy consumption, heating, and cooling. These studies often analyzed the impact of optimization suggestions on single or multifamily dwellings thus far. It is also evident from the results that the phase of the use of the dwelling is in the range of 60% to 90% of the total environmental burdens, contributing to the potential for global warming [13, 16]. This conclusion appears to be valid, despite the evidence showing comparable outcomes even under completely different climatic conditions. A common conclusion is necessary to reduce energy
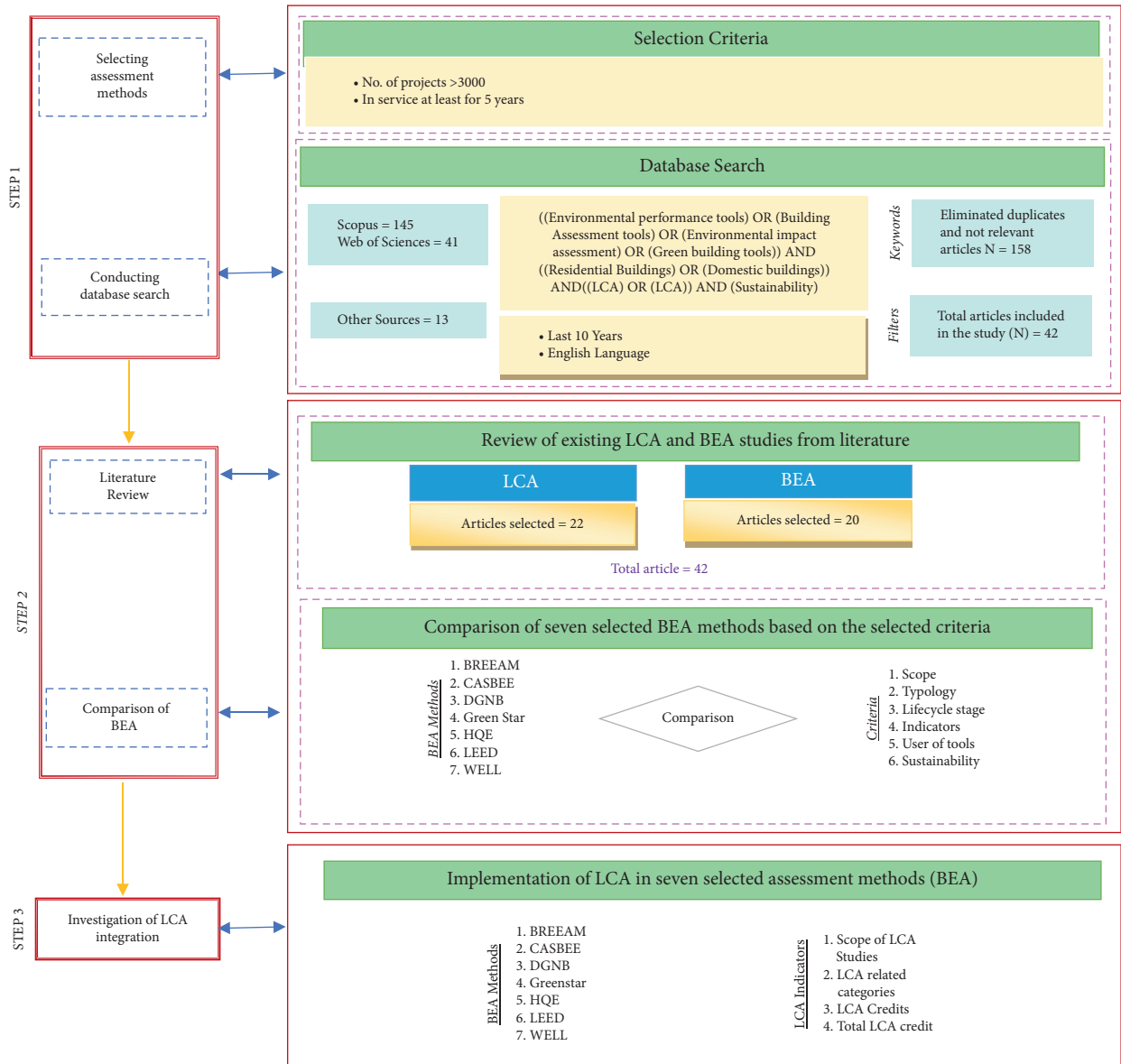
Figure 1: Structure of the study.

Table 1: List of major environmental building assessment methods.

S. No.	Method	Number of countries where projects carried out	Number of projects	Years of service
1	BREEAM	89	16000	31
2	LEED	162	80000	21
3	CASBEE	1	14048	17
4	HQE	26	380000	29
5	Green Star	2	3109	18
6	DGNB	20	5900	12
7	WELL	98	34617	7
8	Living building challenge	70	380	15
9	Green globes	2	1997	16
10	Green Mark	6	100	16
11	VERDE	1	NA	NA
13	Miljöbyggnad	1	1973	12
15	TERI_GRIHA	1	2073	7

TABLE 2: Review of LCA from previous studies.

Reference	Country of study	Type of study	LCA indicators	LC phases	Outcome
[11]	The Netherlands	WPC	GWP, HTP, EP, FDP, AP	O	The study concluded that low-energy residential structures lead all of the environmental impact categories. In addition, it is suggested that the user's electricity demand can be effectively reduced by up to 47% less electricity, leading up to a 9% to 45% reduction in overall environmental impact.
[12]	Norway	WPC	CC, PM, AP, CED	C + O + M + EOL	The author concluded that the passive house building envelope and the air-water heat were 20%. A combined reduction of 27% was achieved.
[13]	Lithuania	WPC/ BMCC	GWP, ODP	P&C, O&M, D&R, T	The operational phase of energy-efficient homes has a reduced environmental impact. The study indicated that considering the materials used to construct the envelope of a building becomes critical for the design of sustainable structures.
[48]	Portugal	WPC	LCE, GHG	C + O + T	According to the report, user transportation accounted for 51 percent to 57 percent of energy and emissions. These findings appear to be applicable to other southern European towns that have grown significantly in terms of car ownership and use.
[49]	Canada	WPC	FDP, GWP, AP, HH, EP, REP, ODP, PCOP	P + C + O + M + EOL	The study examined the environmental implications of two-story residential and building assemblies. Manufacture and operation were the most significant impact categories, with the walls and roof bearing the majority of the environmental loads.
[50]	Greece	BMCC	NA	EOL	The conclusions of the study presented the benefits of the environmental impacts achieved at the end of steel buildings and their positive effects of the steel construction technology applied in terms of environmental sustainability.
[47]	NA	Review	NA	NA	This paper provides an overview of three distinct streams of lifecycle analysis, namely life, lifecycle energy assessment, and lifecycle carbon emissions assessment, all of which have been extensively utilized to assess the effects of decisions.
[51]	Hong Kong	MCM	NA	E + P + T + C + O + M + EOL	The LCSA framework and case study were established to incorporate three lifecycle methodologies: construction environmental modeling, construction cost modeling, and construction social impact modeling.
[52]	Italy	Sensitivity analysis	NA	NA	The research presented the sensitivity analysis to suggest a new criterion for providing a valid assessment approach for evaluating the environmental performance of residential structures.
[53]	Spain	MCM	Energy and GHG	NA	To compare retrofitting options, a multicriteria framework is proposed in this study.
[54]	Spain	WPC	CC, AP, EP, HT, PCOP, PE, ADP, ET	NA	The proper selection of building materials can lead to a significant reduction in the environmental impact of both construction and demolition.

Table 2: Continued.

Reference	Country of study	Type of study	LCA indicators	LC phases	Outcome
[55]	Malaysia	BMCC	GHG, ODP, HT, FDP, ET	NA	The study analyzed the environmental impacts of residential buildings using the MCDM method, showing that PPVC is the most sustainable method. Additionally, sensitivity analyses were conducted to rule out human subjectivity.
[56]	Canada	WPC	NA	All	The article will next discuss the major opportunities, problems, and lessons learned from the LCA/LCC projects' outcomes and the study's conduct.
[57]	Europe	MCM	GWP and TPE	O	LCA was adopted to compare the results and the proposed approach. A preliminary set of benchmarks and values for residential buildings was defined for the global warming of the lifecycle and total primary energy.
[58]	Canada	BMCC	GWP	M + C	According to the research, neither the modular nor the conventional construction method was shown to be the best option for ecologically friendly construction.
[14]	Sweden	WPC	GWP, AP, EP and ADP	NA	The study conducted LCA on residential buildings and revealed that the operational phase has the greatest environmental impact. In the heating season, the renovations had a significant influence on energy demand because of a cold temperature and limited solar irradiation.
[59]	Palestine	WPC	Energy demand and GHG	All	This article presented an LCA study on contemporary houses with energy demand and GHG emissions as indicators. The results indicated that the energy consumption and GWP of contemporary dwellings have a greater influence on the environment than those of traditional houses. It is primarily because of concrete's and steel's tremendous impact.
[60]	NA	MCM	CC, AP, EP, ADP, net present value	NA	Ecoefficiency ratios and alternative design comparisons can be made using this new methodological technique, which combines LCA and LCC with a data envelope analysis methodology. Using this method, an antique residential structure in southern Europe was retrofitted with modern amenities.
[27]	Kazakhstan	WPC	EE, GHG	O	The findings of the study show that there is a correlation between the level of comfort in a structure and its influence. When it comes to CO_2 emissions, higher comfort levels have a greater impact.
[61]	Saudi Arabia	WPC	CED, GWP, ODP, AP, EP, POCP	E + P + T + C + O + M + EOL	The study examined the environmental impact of a building, a villa, from start to finish. The study determined that the operating usage phase had the highest GWP and AP as it examined the environmental impact of developing a villa from conception through disintegration. To put it in another way, the operation usage phase was determined to have a GWP of 2.61×10^6 kg CO_2-eq and 1.75×10^4 kg SO_2-eq, respectively.

TABLE 2: Continued.

Reference	Country of study	Type of study	LCA indicators	LC phases	Outcome
[62]	Brazil	BMCC	EQ, HH, Res	NA	This paper has an insight that the masonry concrete blocks have a higher environmental impact with 46% and 69%, mainly because of the brick burning and production of concrete blocks.
[63]	India	WPC	NA	D + C + O	There are hotspots in the construction industry in the form of building components, materials, and techniques. Phases identified in this article examine the environmental impact associated with a residential house at various stages of construction, such as construction, operation, and demolition.

MCM: multicriteria methodology, Res: resources, E: extraction, P: production, C: construction, M: maintenance, O: operation, T: transportation, D: design, R: recycling and reuse, EOL: end of life, NA: not available.

consumption and the demand for heating and/or cooling by improving insulation, using alternative materials, and controlling ventilation.

Many countries have taken steps to improve the quality of construction processes and materials. These steps change to the extent of building construction. For example, few researchers [12, 47, 58, 59, 66] considered different construction methods and materials used, and environmental burdens were studied using LCA. Each of the studies reveals an interesting aspect of using different methods and materials across different regions. Moreover, all studies quoted that the assessment helped to deduce optimal strategies to reduce material and energy consumption. Furthermore, there have been fewer studies performed on the end of life, demolition, and recycling of materials [49–51, 67]. However, neither the full lifecycle nor the full impact categories are included in the LCA studies.

Despite the fair ease of use, the LCA method has been criticized for its complexity, the need for exhaustive data and information, and skewed/inaccurate results because of the intricacy of the construction sector. LCA entails the collection of sufficient data for each unit process and data on air, water, and land emissions. As a result, the restrictions connected with data gathering influence the overall credibility of LCA conclusions. Indeed, these statistics vary in terms of their limits, energy source assumptions, product and manufacturing parameters, and economic activity from source to source. Additionally, geographical variances have the largest impact, as each country has its own knowledge based on its local resources and construction sector traditions [52].

Additionally, the quality of LCA is inextricably linked to the quality of data, which includes completeness, dependability, and transparency. Data quality indicators should be used to improve the data collection process, allowing the researcher to identify and resolve critical data issues. Similarly, data shortage may necessitate a revision in the study's scope and/or objectives. Thus, data completeness is crucial. The data source, methods, and procedures used to obtain them contribute to the data's dependability. As a result, greater completeness and dependability of data enables a

more precise and correct conclusion. Because of a lack of transparency among data centers, the results are impossible to compare. Although most LCA evaluations on windows use standard datasets, it is obvious that no one examines actual window features and field performance [52].

On the other hand, LCA has been used as an early-stage decision-making tool at various levels [4, 68]. LCA has been integrated into green building codes and standards and rating systems to compare buildings in the planning and design stage based on their impacts and to make informed choices about the materials they use [54]. With growing interest in sustainable development, LCA benefits from the integration of economic (LCC) and social aspects (S-LCA) in residential buildings. Therefore, different studies are designed to provide intrinsic parameters to assess building performance with improved building accuracy and sustainability [18]. The following life cycle aspects were evaluated: GWP, HTP, EP, FDP, AP, LCC, and SLCA. The results revealed the varied level of emissions between different structural designs at all stages and helped in decision making to select suitable materials [55, 66, 69]. Similarly, a multicriteria framework for comparing retrofit solutions is proposed. LCA and LCC are integrated to analyze housing blocks in Spain by quantifying environmental impacts in monetary terms. The findings demonstrated how Madrid's existing renovation techniques are far from optimal [18, 53], with a minimal focus on the social impacts of buildings [18, 51, 86]. However, current studies have not considered region-specific indicators and involve the participation of stakeholders in the selection of indicators [70].

2.2. Environmental Assessment-BEA. BREEAM and LEED, which are market-focused assessment methods, have been developed for both new and existing buildings. They are among the oldest methods. Table 3 shows the main features of all selected assessment methods. CASBEE is designed to enhance the quality of life and reduce environmental loads. The method is used exclusively in Japan. However, the usage of CASBEE outside Japan may not apply for certification by an accredited body, however, it is possible to use manuals

TABLE 3: Main features of selected building environment assessment methods [31].

Method and country	Launch year	Last update	Categories	Assessment	Rating levels	Schemes w.r.t. residential buildings
BREEAM, UK	1990	2020	(i) Energy (ii) Waste (iii) Water (iv) Pollution (v) Materials (vi) Transport (vii) Land use and ecology (viii) Management (ix) Health and well-being (x) Innovation	Applied to each level	Unclassified, pass, good, very good, Excellent, outstanding	(i) New construction (ii) In-use (iii) Refurbishment and Fit-out
CASBEE, Japan	2001	2015	(i) Energy (ii) Indoor environment (iii) Resources and materials (iv) Quality service (v) Outdoor environment (vi) Off-site environment	Complex weighting system applied at every category	S, A, B+, B−, C	(i) CASBEE for new detached houses (ii) CASBEE for existing detached houses (iii) CASBEE for housing units (iv) CASBEE for housing renovation checklist (v) CASBEE housing health checklist
DGNB, Germany	2007	2020	(i) Ecological (ii) Economic (iii) Technical (iv) Process (v) Sociocultural and functional (vi) Quality of the location	Applied to each level	Bronze, silver, gold, platinum	(i) Residential buildings (ii) New buildings: small residential buildings
GREEN STAR, Australia	2002	2021	(i) Energy (ii) Water (iii) Materials (iv) Land use and ecology (v) Transport (vi) Emissions (vii) Indoor environmental quality (viii) Management (ix) Innovation	Applied to each category and single scored	0,1, 2, 3, 5, 6	(i) Homes (ii) Design and as built (iii) Design and construction of new buildings
HQE, France	1994	2016	(i) Eco construction (ii) Eco management (iii) Comfort (iv) Health	Not available	Pass, good, very good, excellent, exceptional	(i) HQE for residential buildings and detached houses

TABLE 3: Continued.

Method and country	Launch year	Last update	Categories	Assessment	Rating levels	Schemes w.r.t. residential buildings
LEED, USA	1998	2019	(i) Energy (ii) Materials and resources (iii) Water efficiency (iv) Indoor environmental quality (v) Innovative design (vi) Sustainable sites (vii) Regional priority	All credits are equally weighted	Certified, silver, gold, platinum	(i) LEED 4.1 residential (ii) LEED 4.1 building design and construction
WELL, USA	2014	2021	(i) Air (ii) Water (iii) Nourishment (iv) Light (v) Fitness (vi) Comfort (vii) Mind	Weighing system applied at every level	WELL bronze, silver, gold, platinum	(i) Multifamily residential

and software for references [21]. HQE certification has the strongest presence in Europe and focuses on overall quality by balancing energy performance, health, and well-being, while BREEAM and LEED allocate considerable coverage to the environmental and energy aspects of a building [5]. DGNB aims to promote sustainable building using the certification of buildings, interiors, and districts, translating into sustainable planning, construction, and operation. It has approximately 1,200 members throughout the world, with Europe as its largest network [22]. DGNB and HQE cover a wide assessment range of buildings, from individual to community development structures [48]. The DGNB categories are comparable to those in BREEAM and LEED but include social and economic aspects. The Green Star was designed in response to the popularity of BREEAM and LEED in Australia, New Zealand, and South Africa. This technique assesses nine performance parameters and promotes the choice of materials that adhere to environmental best practices [30]. The WELL Building certification was created based on seven concepts that assess the building's performance in addition to its health, well-being, and mindful eating. This accreditation offers a holistic approach to the built environment's health, including behavior, operations, and design. Several of the components in WELL are designed to influence behavior through education, culture, habits, policy, and encouragement to make healthy lifestyle choices [56]. These assessments are performed on a variety of different types of buildings, including educational institutions, businesses, residential structures, commercial kitchens, and communities. To ensure a thorough assessment, each assessment has built its own module, covering various types of buildings. For example, CASBEE includes pertinent extra information on detached housing, temporary building, and urban growth. There are different modules available under BREEAM, LEED, and others, exclusively focusing on multifamily buildings, commercial spaces, and

so on. Similarly, categories for modules are revised, for example, BREEAM achieved development by revising the weight assigned to credits from its 2014 to 2018 scheme [57]. Overall, all assessment methods are revised continually to keep up with international standards.

Previous studies (Table 4) attempted a comprehensive comparison of all existing assessment methodologies individually [60] and compared different building assessment methods [30, 32, 34, 41, 42, 45, 46, 60–63, 80], and several studies compared specific assessment methods LEED and ITACA [42, 80]. Chu and Cheung (2017) studied BEAM and LEED, and Illankoon et al. (2017) compared eight rating systems [26, 41]. Mattoni et al. (2018) and Doan et al. (2017) compared building environmental methods, including CASBEE, Green Star, BREEAM, LEED, and ITACA [43, 81]. Similarly, Suzer (2015) compared LEED with BREEAM, SBTool, CASBEE, and Green Star [34]. LEED and BREEAM are the two commonly studied systems, probably because of their wide usage, and few other studies extended beyond the comparison of these two systems to the comparison of other regional assessment methods [26, 30, 35, 63, 71, 72, 82]. Moreover, few attempted to study the incorporation of sustainability aspects into building assessment methods [70] [45, 49, 71]. Therefore, the studies have raised a common concern about existing assessment methods, thereby providing different suggestions and conclusions based on the available resources.

A contemporary-built environment is created and managed by utilizing large amounts of energy and materials, thus impacting the health and well-being of the occupant [73]. The assessment systems cover the same features related to the functional condition, such as acoustic comfort, thermal comfort, noise, lighting, fire protection, waste reduction, operations and maintenance, energy efficiency, material efficiency, aesthetics, and appearance of the buildings [28, 36]. Each BEA method conducts an evaluation

TABLE 4: Review of building environmental assessment from previous studies.

Reference	Country of study	Buildings assessed	Study outcomes
[71]	NA	Residential	Eco-homes (BREEAM) were developed for household usage, and this study investigates the spread of indicators used and attempts to close any gaps. The indicator analysis revealed that environmental and social variables were adequately covered. However, the economic dimension was completely ignored.
[32]	NA	All buildings	Review of different integrated strategies for sustainability assessment, new rating systems developed for industrial projects with the following criteria: approaches, strategies, models, appraisals, and methodologies.
[30]	Europe	All buildings	Different environmental tools were compared with each other and evaluated according to ISO standards. Methodology, criteria, lifecycle phases, and costs are covered.
[72]	Lithuania	Residential (multiapartment)	The study recommended using sustainable building assessment standards, such as BREEAM and LEED, for multiapartment buildings and their surrounding environment. In all systems, the most critical requirements were energy consumption, resource conservation, waste management and recycling, material quality, longevity, and the building's ability to be used for another purpose.
[73]	Portugal	Residential	Comparing the weighting of criteria used by LiderA, SBToolPT, the code for sustainable homes, and LEED for homes (2012)to determine the sustainability of a residential project in Portugal.
[74]	NA	All buildings	The article proposes a simplified way for evaluating the sustainability of buildings by utilizing the AHP method and focusing on sustainable construction professionals.
[75]	Spain	Residential	The research resulted in the development of an easy-to-use tool for homeowners that provides the same level of rigor as current sustainability credentials for experts in the building and real estate development industries. A case study of a residential structure is used to validate the system.
[35]	Africa, Latin America, Middle East	All buildings	By incorporating the building rating value (BRaVe) methodology into current tools, this study analyzes and evaluates tools in poor nations.
[28]	Italy	Residential	Glass wool, expanded polystyrene (EPS), wood fiber, and kenaf are some of the thermal insulating materials studied in this paper, which examines how these materials affect a building's energy and environmental performance.
[76]	Spain	Residential (high rise)	Integrated value methodology for sustainability assessment (IVMSA) has been used to create a sustainability assessment model for, high-rise residential construction structures (MIVES).
[46]	Slovakia	Family houses	A building's design, construction, and operation are simply rated or ranked by the BEA. An examination of selected family homes in several categories, such as site location, building constructions, energy efficiency, water conservation, and waste reduction were discussed in this study.
[42]	Italy	Residential	The comparison of LEED and ITACA schemes. ITACA scheme was applied on residential buildings chosen in Italy.
[41]	Hong Kong	All buildings	The comparison of two assessment systems, BEAM plus and LEED, in the aspect of materials, indoor quality, and water management.
[45]	NA	All buildings	A descriptive statistical analysis of the 11 most widely used green building rating system to conclude discrepancies and similarities.
[77]	Spain	Residential	The OERCO$_2$ Erasmus+ project explored an open-source online tool for nonspecialists to estimate the carbon footprint of residential structures. This tool's inner workings, including calculations, data management, and operation, are thoroughly described. Because of the tool's simplicity, even nonspecialists can assess a building's long-term viability.
[78]	Malaysia	Residential	The tropical climate of Malaysia, the environmental and development backdrop, and cultural and social requirements have been considered in the design and development of the green building Index (GBI). These tools were compared to show the differences and similarities between them.
[70]	NA	Residential	The review of different aspects of sustainability, including LCA, LCC, and SLCA, examined the research gaps.
[26]	Australia	All buildings	The research compared different rating tools and found that selected tools lack mandatory criteria and regulations, incentives in Australia.

TABLE 4: Continued.

Reference	Country of study	Buildings assessed	Study outcomes
[25]	Denmark	All buildings	Categorizing different assessment tools in terms of sustainability aspects at regional, international, and local scale. The distinction and gaps are presented.
[79]	Spain	All buildings	For the sake of global consensus, this study analyzes the 10 leading rating systems, focusing on their rating categories, the subsets of sustainable development, innovative considerations, and rating procedures.

at different levels with multiple parameters and relevant weightage across project phases of a building. Nevertheless, these methods follow a common approach to evaluating the performance of buildings [30]. Moreover, studies have investigated whether, by the application of building assessments, there is a vast decrease in the environmental influence of buildings [27]. Numerous studies on building assessment systems have been conducted, however, there has been a dearth of comparisons of important BEA across a comprehensive range of evaluation criteria and clarity in the weights used for comparison [28].

2.3. Comparative Analysis of BEA. This section will describe and compare the assessment tools that have been chosen based on the various criteria that have been embraced by the most widely used performance tools worldwide. The purpose of this section is to provide an overview of the structure and components of the tools used to assess environmental performance. To investigate the different assessment tools, they were compared based on the following criteria: (1) the scope of buildings assessed, (2) typology of buildings, (3) lifecycle phases assessed, (4) indicators, (5) the user of tools, and (6) sustainability. The major objective of the study is to compare selected BEAs for determining the building's environmental impact. Table 5 analyzes the scope of the selected assessment methods to determine the extent to which the assessment methods investigate the building performance.

2.3.1. Scope and Typology of Building. Each assessment method is unique in its application to various types of buildings, including industrial, commercial, educational, residential, and healthcare, and it focuses on the building's management in relation to the local and global environment [62]. WELL certification specializes in commercial kitchens, restaurants, and multifamily residential buildings. Additionally, BREEAM, CASBEE, DGNB, Green Star, HQE, LEED, and WELL include specialized schemes for a variety of solutions, such as new or refurbished buildings.

2.3.2. Lifecycle Phases. BREEAM, CASBEE, DGNB, HQE, and WELL cover four stages of a building's lifecycle (design, construction, operation, and maintenance). Except for HQE and DGNB, no other instrument evaluates a building's demolition and deconstruction phases. Additionally, all methods, except HQE, exclude planning and predesign stages. WELL does not contain any information about the renovation phase in any of the modules.

2.3.3. User of Tools. The usage and availability of systems for a different audience make the system robust and identify the level of social inclusiveness. WELL certification has the maximum reach extending to public healthcare experts and anyone who has an interest in social and well-being. On the other hand, systems, such as BREEAM, DGNB, HQE, and LEED, have been developed based on an academic framework. Therefore, accessibility ranges from experts and researchers to building owners and users [55]. CASBEE limits its access to building users and researchers [83]. However, all the assessment methods suggest having an exclusive expert from their respective systems to audit the performance of a building.

2.3.4. Indicators. To investigate the quality of the building, different assessment methods use different parameters and indicators to study environmental impacts and weigh them to certify the performance [4]. Based on the analysis, all major evaluation systems have focused on the following categories: energy use, materials, project management, pollution, waste management, and water. Similarly, other indicators, such as indoor quality, visual comfort, and identities, such as economic, cultural, and social identities, have been given the highest priority in terms of sustainability [83]. The shown categories (Table 6) often refer to the same items or different items in the same or different categories. Sometimes they do not assess the same attributes. For example, in LEED, transport is not assessed as a separate criterion, whereas it is included under the site selection category. Similarly, DGNB does not assess transport, indoor quality, and ecology as separate categories. These are summed up under ecological quality. Similarly, olfactory comfort is considered in HQE and WELL, whereas the other systems are included in the general category of air quality. WELL considers more social aspects, such as fitness, nourishment, air, and water, exclusively as separate categories. Therefore, the elements are represented and grouped as per the scope of the module and method of assessment.

2.3.5. Sustainability. With so many options available in the market and also to keep up with global updates, many assessment methods have included some aspects of sustainability. Therefore, the purpose of this section is to analyze the selected BEAs with relevance to the definition of sustainability. It is noticeable that each BEA system allocated weightage and credits for categories and subcategories. It is also possible to understand that all BEA methods follow different evaluation patterns and different indicators placement under categories.

TABLE 5: Criteria considered for comparison.

Criteria	Assessment methods						
	BREEAM	CASBEE	DGNB	Green star	HQE	LEED	WELL
Scope							
New	✓	✓	✓	✓	✓	✓	✓
Existing	✓	✓	✓	✓	✓	✓	✓
Refurbishment	✓	✓	✓	✗	✓	✓	✓
Typology							
Residential	✓✓	✓	✓	✓	✓✓	✓✓	✓✓
Offices	✓	✓	✓	✓	✓	✓	✓
Urban planning and communities	✓	✓	✗	✓	✓	✓	✗
Commercial	✓	✓	✓	✓	✓	✓	✓✓✓
Educational Institutions	✓	✓	✓	✗	✓	✓	✓
Healthcare	✓	✓	✗	✓	✗	✓	✓
Industrial	✓	✓	✓	✓	✓	✗	✗
Lifecycle phases							
Predesign	✗	✗	✗	✗	✗	✗	✗
Design	✓	✓	✓	✓	✓	✗	✓
Manufacture	✗	✗	✓	✗	✓	✗	✗
Construction	✓	✓	✓	✓	✓	✓	✓
Use/Operation	✓	✗	✓	✓	✓	✓	✓
Maintenance	✓	✗	✓	✗	✓	✓	✗
Demolition and disposal	✗	✗	✓	✗	✓	✗	✗
Users of tools							
Academicians	✓	✗	✓	✗	✓	✓	✓
Authorities	✓	✓	✗	✓	✓	✓	✗
Building professionals and Consultants	✓	✓	✓	✓	✓	✓	☑
Building owners/partners	✗	✗	✗	✓	✓	✓	✓
Occupants	✓	✗	✗	✗	✓		✓
Construction products Manufacturers	✓	✗	✗	✗	✓	✗	✗

✓ included in the criteria, ✗ not included in the criteria, ✓✓ multifamily residential, ✓✓✓ include commercial kitchen and restaurants, and ☑ include public healthcare experts.

TABLE 6: Distribution of indicators under assessment categories.

Indicators	BREEAM	CASBEE	DGNB	Green star	HQE	LEED	WELL
Energy							
Energy performance (en)	✓	✓	✓	✗	+	✓	✗
Greenhouse emissions (en)	✓	✗	✗	✓	+	✓	✗
Transport							
Public transport accessibility (sc)	✓	✗	✓	✓	✗	☑	✗
Alternative transportation (sc)	✓	✗	✗	✓	✗	✗	✗
Green vehicles (en, sc)	✓	✗	✓	✗	✗	☑	✗
Pollution							
Construction waste management (en)	✓	✗	✗	✗	✗	✓	✓
Noise pollution (en)	✓	✗	✗	✓	✗	✓	✓✓
Light pollution (en)	✓	✓	✗	✓	✗	✓	✓✓
Air pollution (en)	✓	✓	✗	✓	✗	✓	✓✓
Impacts of refrigerants (en)	✓	✗	✗	✓	✗	☑	✗
Waste (en)	✗	✗	✗	✓	✓	✗	✗
Water efficiency							
Water consumption (en)	✗	✗	✗	✗	+	✓	✓
Water Quality (en)	✓	✗	✗	✓	+	✓	✓
Potable water and demand (en)	✗	✗	✓	✓	+	✗	✗
Wastewater (en)	✗	✗	✓	✗	+	✗	✗
Indoor comfort and Quality							
Indoor air quality (en)	✗	✓	✓	✓	✗	✓	✗
Thermal comfort (sc)	✓	✓	✓	✓	✓	✓	✓
Acoustic performances (sc)	✗	✓	✓	✓	✓	✓	✓
Visual comfort (sc)	✓	✗	✗	✗	✓	✓	✓

TABLE 6: Continued.

Indicators	BREEAM	CASBEE	DGNB	Green star	HQE	LEED	WELL
Olfactory comfort (sc)	✗	✗	✗	✗	✓	✗	✓
User comfort and satisfaction (sc)	✗	✗	✓	✓	✗	✗	✗
Smoke control (sc)	✗	✗	✗	✗	✗	✓	✓
Humidity control (sc)	✗	✗	✗	✗	✗	✓	✓
Resources and Materials							
Material efficiency (en)	✓	✗	✗	✗	✗	✗	✗
Responsible procurement (ec, en)	✓	✓	✓	✓	☑	×	×
Fundamental material safety (en)	✗	✗	✗	✗	☑	✓	✓
Land-use and ecology (en)	✓	✗	✓	✗	✓	✗	✗
Ecological value (en)	✗	✗	✗	✓	✗	✗	✗
Local environment Impact (en)	✗	✗	✓	✗	✓	✗	✗
Site assessment and development (en)	✓	✗	✗	✗	✓	✗	✗
Health and well-being							
Hazards (sc)	✓	✗	✓	✗	✓	✗	✓
Quality of outdoor spaces (sc)	✗	✗	✗	✓	✓	✓	✗
Safety and security (sc)	✗	✗	☑	✗	✗	✓	✗
Toxic material reduction (en)	☑	✗	☑	☑	✗	☑	✓
Quality of indoor spaces(sc)	✗	✗	✗	✓	✗	✗	✗
Nourishment (sc)	✗	✗	✗	✗	✗	✗	✓✓
Fitness (sc)	✗	✗	✗	✗	✗	✗	✓✓
Management							
Project brief and design (sc)	✓	✗	✓	✗	✗	✗	✗
Commissioning and handover (sc)	✓	✗	✓	✓	✗	✓	✗
Responsible construction practices (en)	✓	✗	✗	✗	✗	✗	✗
Environmental management (sc)	✗	✗	✗	✓	✗	✗	✗
Building information (sc)	✗	✗	✗	✓	✗	✗	✗
Cleaning and maintenance (sc)	✗	✗	✗	✓	✓	✗	✗
Innovation (sc)	✓	✗	✗	✓	✗	✓	✓
Functional and Technical aspects							
Adaptability (en, ec)	✓	✓	✓	✗	✗	✗	✗
Durability and resilience (ec, en)	✓	✓	✗	✗	✗	✗	✗
Flexibility (ec, en)	✓	✓	✓	✗	✗	✗	✗
Design and quality of construction (en)	✗	✗	✓	✗	✗	✗	✗
Lifecycle impacts (en)	✓	✗	✓	✗	✗	✓	✗
Lifecycle costs (ec)	✓	✗	✗	✗	✗	✗	✗
Commercial viability (ec)	✗	✗	✗	✗	✗	✓	✗
Deconstruction (en)	✗	✗	✓	✗	✗	✗	✗

✓ included, ✓✓ included as a separate category, ☑ considered under another category, + included together with other indicators, ✗ not included, en: environment, ec: economy, and sc: social.

BREEAM, DGNB, Green Star, LEED, and WELL are compared directly based on their individual categories and the percentage of allocation. However, methods, such as CASBEE and HQE, could not be compared because of their allocation in the system. For instance, CASBEE evaluates building projects through the lens of three metrics: building environmental efficiency (BEE), built environmental quality (Q), and built environmental load (LR). Similarly, HQE does not assign a weighting factor to each category because this framework assigns equal weight to each category throughout the assessment [5]. It gives a picture of how each indicator has spread across the groups and their weightage assigned. Therefore, all indicators were analyzed to group them under three aspects, such as environment, society, and economy, based on the credit points from the system (Table 7). The grouping of categories under sustainable aspects is completely based on the author's understanding and perspective.

Figure 2 shows the breakdown of the three pillars analyzed based on the credit points.

Environment is the primary aspect focused by all BEA methods. More than 75% of indicators are adopted based on environmental aspects. On average, 60% of all BEA methods focus on environment factors. The utmost significance is given to energy efficiency, water utilization, and materials under environment category. Social category has got attention in recent times. However, the categories show good percentage (50% overall) on social categories. However, except for WELL, other BEA methods are exhaustive to cover in terms of social indicators. The functional aspects, such as aestheticism, indoor quality, and thermal quality, visual comfort, and occupant well-being, are significantly scored indicators. In terms of economy, BREEAM, Green Star, and WELL modestly contribute with an average of 3%, approximately. On the other hand, DGNB assigns equal

TABLE 7: Distribution of credit points for sustainable aspects by categories [43].

|	BREEAM (pts)	CASBEE (score)	DGNB (pts)	Green star (pts)	HQE (targets)	LEED (pts)	WELL (pts)
Environment	Energy ~22.5 Waste ~6.5 Water ~6.5 Pollution ~9 Materials ~6 Ecology ~15	Energy ~2 IE ~2 Resources and Materials ~1.5 Quality Service ~1.5	Ecological ~40	Energy~24 Water~12 Materials ~10 Ecology~6 Emissions ~6	Eco-construction ~4	Energy~38 Water efficiency ~12 Sustainable Sites ~7	Air ~3 Resources ~10 Water ~2 Light ~2
	Total ~78%	Total ~70%	Total ~40%	Total ~64%	Total ~25%	Total ~62%	Total ~12%
Social	Health ~6 Innovation ~10 Management ~6.5	Outdoor Environment~1.5 Off-site Environment~1.5	Socio-cultural and functional ~30	Transport~7 IEQ ~18 Innovation~10 Management ~14	Comfort ~4 Health~4	IEQ ~16 Innovation ~6 Transportation ~15 Regional priority ~4	Fitness ~7 Comfort ~12 Mind ~15 Air ~25 Water ~7 Light ~8 Innovation ~2
	Total ~20%	Total ~30%	Total ~30%	Total ~33%	Total ~50%	Total ~38%	Total ~87%
Economy	Management ~2		Economic ~30	Management ~3	Eco management ~4		Innovation ~1
	Total ~2%	Total 0%	Total ~30%	Total ~3%	Total ~25%	Total 0%	Total ~1%
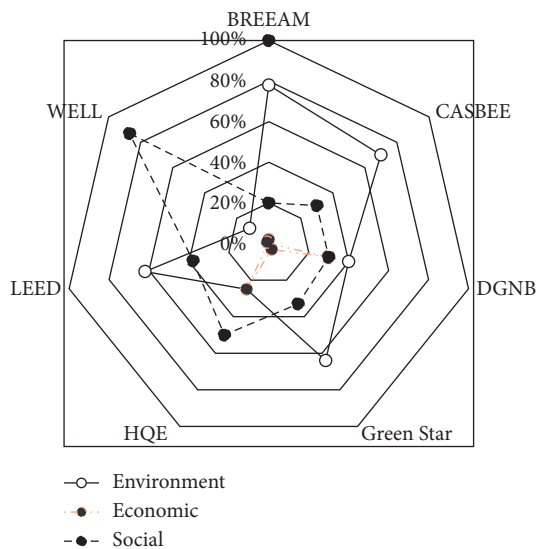
FIGURE 2: Distribution of sustainable aspects among BEA methods.

weightage on all three pillars of sustainability. However, the indicators under categories provide more insight and brings to attention that few indicators need to be looked beyond social aspects. For example, procedural, management, and innovation categories should be reconsidered under sustainability [26, 43].

From the analysis, it is evident that not all existing methods have equal priority to all three aspects of sustainable pillars. Neither of these categories is classified under any sustainable pillar. Therefore, most of the credit points are based on the stakeholders and different local contexts. It brings to a point to question the global consensus or common language for these indicators

[5, 38]. Hence, it is quite unsure how these methods may achieve sustainability.

3. Integration of LCA in Building Assessment Methods

Firstly, it should be noted that the LCA method and indicators are integrated within the BEA methods. Subsequently, these methods focus more on the aspects of sustainability via lifecycle phases, such as design, construction, operation, maintenance, renovation, and demolition. Thus, relevant procedures have been implemented from a lifecycle perspective [38, 77]. The purpose of this section is to understand the LCA protocols that have been applied in seven BEA methods. For this, information on the LCA components was collected through technical manuals, websites, and research papers. Table 8 outlines the comparison of selected BEA methods and the integration of LCA within each system. It is classified based on the scope, LCA credits, and related LCA indicators provided in each BEA method to show the utility level and importance given to these LCA components.

(a) Implementation of LCA in BREEAM: the credits are awarded in Mat 01 for lifecycle impacts. It requires environmental product declaration (EPD) data to calculate greenhouse gas emissions. Similarly, "Materials for hard landscaping and boundary protection" Mat 02 was directly accessed using the BRE tool [45, 76]. To encourage the minimum operational energy demand, Ene 01 "Reduction of energy use and carbon emissions" is assessed based on CO_2 emissions. The criteria are evaluated in two ways: 1) energy performance with authorized building energy calculation software and 2) energy-efficient design features. They were given 25 credits

TABLE 8: A comparison table to investigate the integration of LCA in BEA methods [45].

	Scope of LCA		LCA categories	LCA indicators	Total LCA weightage (%)
BREEAM	Material level	Whole building level	(i) Energy (ii) Materials	Ene 01 energy efficiency Mat 01 life cycle Impacts Mat 02 hard landscaping and boundary protection Mat 03 responsible construction products Wst 05 adaptation to climate change Man 02 lifecycle costing	5.9
CASBEE	Whole building level**		(i) Energy (ii) Materials (iii) Resources	Calculating the BEE* value life cycle CO_2	15
DGNB	Material level	Whole building level	(i) Global, local Impacts (ii) Environment (iii) Resource (iv) Waste	Env 1.1 life cycle Impact assessment Env 2.1 LCA – Primary energy	13.5
Green Star	Material level	Whole building level	(i) Materials (ii) Energy	Ene 01 greenhouse gas emissions Mat 01 life cycle assessment	7
HQE	Material level		(i) Materials	2.2 environmental Quality of the Materials, products, and Equipment used 4.1 Thermal design	9
LEED	Material level	Whole building level	(i) Materials (ii) Resources	MRc1 building life cycle Impact Reduction MRc2 environmental product declarations and product optimization MRc3 Sourcing of raw materials	2.7
WELL	Building level		(i) Air	Life cycle CO_2 – minimizing source of indoor air pollution	3

plus extra four credits for innovation and 5 credits for energy-positive buildings [57]. However, BREEAM, as a whole building assessment method, does not endorse specific products as "BREEAM compliant." Compliance with applicable criteria and performance of selected products will be demonstrated for evaluation purposes [19].

(b) Implementation of LCA in CASBEE: the method includes LCA as an optional assessment for building materials. GHG emissions can be calculated using an internally developed calculator. Lifecycle CO_2 (LCCO$_2$) calculations are performed for each stage of the building's lifecycle. There are two ways to calculate LCCO$_2$, one using the reference value of a 3-level performance building and the other one by individual calculation with accurate LCCO$_2$ estimation [5, 16]. The categories linked with this are within Q2, LR1, and LR2 as the quality of service, energy, resources, and materials [21].

(c) Implementation of LCA in DGNB: the system assigns equal weightage to the following categories: ecological, economic, sociocultural, and functional quality. The tool integrates LCA and LCC along with the building process. The scores of the individual criteria were applied as a fixed weighting factor, and a performance score was calculated for each criterion relative to a reference building. The LCA was analyzed for raw materials, construction, operation, and end-of-life stages. The data are acquired from the European Sustainable Construction database

(ESUCO), the Association of German Engineers (VDI), or project-specific data [30, 45, 76]. The points are given to those that conform with the reference values, and additional points are given for carbon neutrality in design and construction as per agenda 2030 [22].

(d) Implementation of LCA in Green Star: the system assesses categories on two levels: materials and the whole building. The Green Star Energy Calculator and NABERS are used for building calculations. The assessment allows access to Ene-01 to reduce greenhouse gas emissions. The system promotes the usage of EPDs and encourages auditing independently. The system relies on Australian and international LCI EN 15978 databases. In the evaluation criteria, up to 7% of credits were awarded for the LCA assessment. However, the method does not clearly indicate which part of the evaluation should be considered for LCA. The credits depend on the cumulative percentage of impact reduction. Usually, the assessment results are compared with similar construction types and operations [84].

(e) Implementation of LCA in HQE: the certification is based on four themes: construction, comfort, health, and environmental management. The environmental performance of a building can be assessed by focusing on primary nonrenewable energy sources and emission control. The assessment relies on data based on environmental product declarations (EPDs) [76].

(f) Implementation of LCA in LEED: LCA is incorporated at the materials and resources level, which encompasses both materials and the building itself. LCA calculated for six environmental impacts, such as GHGs, the depletion of stratospheric ozone, eutrophication, the acidification of water and land, and the formation of tropospheric ozone, demonstrating a minimum of 10 percent reduction [78]. Up to five points were granted in 2013 for reducing a building's lifecycle impacts in new building design and construction. The weightage was calculated based on LCA-TRACI [76].

(g) Implementation of LCA in WELL: the assessment measures seven attributes that impact the occupant's health (promoting clean air or reducing emissions) and measures CO_2 emissions [56]. The certification is given at the whole building level and developed based on American norms and metrics. As per practical books, the integration of LCA is not clearly stated in the certification system. However, the system relies on EPDs to assess the products and materials within buildings to reduce emissions [16].

The relationship with LCA in all seven BEA methods provides insights into what level these indicators are used within the system. Looking at the entire table, in DGNB, the evaluation system covers the whole building and all phases, while in BREEAM and LEED, it is only applied at the material level. In the case of BREEAM, the crediting of indicators (materials and energy) is not entirely transparent at each phase of the process. The LEED method gives more points for energy efficiency in the operational stage, where a high score is awarded for embodied energy. As mentioned earlier, the credits for building emission reduction for both new and renovation cases are based on the baseline building requirements (requirements are based on ASHRAE) [48]. The building reference should be self-declared as a baseline design that must be comparable to function, size, orientation, and so on to establish a reference. A distinction between BREEAM and LEED, in terms of calculation, is that LEED provides a direct score based on evaluation, and the credits are awarded based on the fulfillment of the category [39].

DGNB, HQE, Green Star, and WELL methods rely mostly on the EPDs of building products to award credits to the LCA component. HQE awards credits, however, it is not necessarily based on the evaluation of LCA results, and it does not clearly implement LCA and does not specify technical criteria. Similarly, Green Star provides no guidance on how to evaluate LCA. The primary issue is with the border as it is unclear which portion of the system should be evaluated, resulting in contradictory outcomes [16, 44]. WELL does not directly address any aspect of LCA in its system, and Green Star provides no guidance on evaluation. However, WELL is designed to "cross walk" assessment methods such as BREEAM, LEED, and Greenstar. In comparison to other approaches, DGNB is the most comprehensive in terms of lifecycle impacts as it considers the energy demand of the building throughout its life, including the construction and renovation stages, as well as the operational stage. DGNB is the most comprehensive in terms of providing credits based on LCA [16]. On the other hand, DGNB's reference values establish a limit as they are self-proclaimed based on previously conducted and certified studies [16, 44]. Therefore, it does not showcase the full spectrum of the construction industry to validate the certification and to create a benchmark. It is said to be a major limitation in the DGNB system [85].

In terms of indicator point calculation, each BEA method uses a different LCA tool or its own internal calculation tools [86]. In the case of BREEAM, the tools for calculations are internally developed (e.g., the Mat01 Calculator), which is not available as an open resource [19]. Similarly, the software, such as IMPACT, e-tool, and One Click LCA, used for life cycle impact assessment must be recognized by BREEAM. DGNB and HQE assess the impact based on the project-specific data or from region specifications. CASBEE has an internally developed tool to evaluate parameters. Similarly, Green Star uses two ways to evaluate the indicators using the Green Star energy calculator and NABERS [74]. LEED used the LCA software that recognized data based on ISO 14044, for example, Athena Impact Estimator, GaBi, and SimaPro [45].

In summary, seven BEA methods have integrated the LCA approach and some strived to include disposal and reuse, recycling the potentials of BMCCs. Some methods have included LCA indicators and EPD requirements within their credits, however, the methods adopt different approaches and weight relevance to the outputs. However, the real question is how far these indicators compute the actual impacts and demonstrate a real reduction in impacts [38]. This lack of clarity leads to confusion for practitioners. Moreover, these types of credits are relatively lower in weightage than the energy-related credits in most of the BEA methods. However, on the brighter side, the growing attention to construction materials and usage of EPDs has stimulated the practitioners positively.

4. Discussions

From the preceding analysis, we can conclude that there is a concern on how to reduce environmental impacts. In this context, many comprehensive building assessment methods have been developed to assess and provide global standards to evaluate the value of buildings. Since the 1970s, assessment methods have attempted to evaluate a building beyond its energy losses and turned around to focus on conservation methods. The prime objective of these methods is to improve the environmental performance of buildings, allowing multiple indicators, such as energy consumption, air quality, land use, materials, water, waste, etc. Initially, BREEAM attempted to evaluate a building beyond its energy factors. Since then, many assessment methods have emerged globally. The performance of these methods varies significantly in certain countries because of diverse locations, cultures, and climatic zones. For instance, if different tools are used to evaluate the same building, the results may differ

[26]. However, the use of these methods is not apparent, as it is unclear or not defined when the assessment should be performed, or who should carry out the assessment or what type of assessment methods to be selected, and how the results from evaluation should be interpreted or used.

Furthermore, seven well-known building environmental assessment systems (BREEAM, CASBEE, DGNB, Green Star, HQE, LEED, and WELL) were analyzed and compared to understand the fundamental differences and similarities by means of a methodological approach. The comparison among the systems was carried out on features, performance criteria, fundamental aspects of sustainability, and integration of LCA. All seven assessments cover a wide range of typologies (residential, commercial, etc.) and lifecycle stages (raw material extraction, production, construction, operation, recycling, and demolition). In terms of lifecycle stages, all methods, except HQE, do not consider planning or predesign stages, whereas WELL does not include the renovation phase in its system. These methods also evaluate buildings that are new or existing. Hence, all systems proposed different schemes based on building typologies. Refurbishment/renovation practice is becoming important because of the increasing number of energy-inefficient existing buildings [2]. Renovation and fit-out schemes are presented in BREEAM, LEED, and DGNB, individually. Systems cover refurbishment combined with other schemes. Moreover, refurbishment is also a complicated process that requires extensive analysis in terms of materials, cost, and comfort [33]. Therefore, it is crucial to inspect and evaluate the performance of existing buildings before and after renovation. At present, most of these methods are applied predominantly to the new construction, operation, and maintenance phases of an existing building. The authors feel that these systems shall propose/integrate a scheme or method to identify the best renovation strategies that could be useful for the early stage of renovation projects.

The comparison among the categories of all systems was carried out from a qualitative point of view. From the preceding analysis, it is evident that the "energy" category is given the highest importance in all assessment systems, except for CASBEE and WELL. It is because of the common consensus on energy reduction and its significance in terms of sustainable development among countries [2, 7]. The second common category observed among all systems was "water," and it was the lowest scored on credits after "outdoor environment" and "materials." The most significant dissimilarities can be observed in "comfort and safety" and "outdoor quality" areas. Categories, such as olfactory discomfort and natural disasters, are rarely focused on these assessment methods. On the other hand, WELL has a comprehensive coverage of topics dedicated to environmental impact reduction on all six methods but highlighting majorly on health and well-being of the occupant. However, it is quite time-consuming and deep for a lot of users [75]. LEED and DGNB set good examples in terms of the weightage of credits on topics, such as health and well-being requirements. However, there are several drawbacks in terms of evaluation standards and baseline reference information. Therefore, global standards are a major concern in most of the assessment methods, which lack uniformity. At the same time, it is important to mention that some of the study methods are already setting specific standards for the type and use of a building.

Based on the analysis, it is feasible to infer that many assessment methods place a low quality on economic and social factors. It also implies that not all factors of sustainability are distributed equally in all systems. The concept of sustainability is different across different countries regarding different priorities and approaches. It was possible to look at the distribution of different categories based on the weights assigned in the respective assessment methods. However, the score assigned greatly varies in each assessment method. BREEAM and LEED, as widely used methods, do not focus much on the economic, social, and cultural aspects of buildings. None of the certification systems has the largest focus on the economy, although DGNB focuses almost equally on the three aspects of sustainability. The weightage of categories is summed up with 100 points or percentage, in which the DGNB system shows an equal distribution of weightage in all groups. Raslanas and Alchimoviene confirm that the majority of building evaluation techniques fall short of adequately addressing social and economic issues [62]. Additionally, Bannani et al. [29] highlighted that because of geographic and cultural variance, the local context dictates the importance of environmental, economic, social, and cultural variables [24]. It is because of two main reasons: (1) the knowledge or concept of sustainability is vague, and (2) the countries face challenges in proposing their own methods for the evaluation of economic, social, and cultural dimensions. In the opinion of authors, assessment methods should have a common consensus on parameters and equally distribute indicators over three dimensions to achieve a proper sustainable assessment method.

As mentioned before, there are two approaches for the evaluation of building performance: the BEA method and the LCA method. The LCA-based approach provides the possibility to quantify the environmental impacts at all stages and easily compares the results to implement effective solutions. LCA is well-established, is accessible to users, and has a greater influence on the decision-making process [4, 79]. However, there are some impediments in the use of these tools because of their complexity, unclear nature, and the lack of data inventory and transparency, a common consensus on datasets, and conversion factors [70]. Few authors have recommended the integration of LCA with building assessment methods to assess the overall impact of buildings [16, 36, 40, 43, 87–89]. According to Bisegna et al., the building assessment methods should include LCA in their evaluation procedure for assessing sustainable materials throughout the lifecycle [80]. By introducing LCA, the assessment systems would benefit from the improved performance on credits and scores, providing a basis for empirical evidence for users [16]. All seven assessment methods incorporate LCA indicators at different levels and categories. It makes the comparison and deriving relationship between the assessment methods very difficult. However, the comparison provides insights into the method that provides completeness in terms of evaluating LCA in its assessment methods.

Most of the assessments cover the reduction of greenhouse gases and the evaluation of CO_2 emissions. BREEAM is the only method that calculates the construction project's emissions [19]. Both BREEAM and LEED have given limited scope to LCA credits and indicators in their systems. In contrast, CASBEE and DGNB allocated significant credits in their systems. Although DGNB has incorporated LCA into all stages, it lacks clarity to deduce the results based on the reference values [85]. However, few authors have pointed out improvements in the DGNB and LEED systems to achieve and standardize the templates of collection, evaluation, and results of LCA [44, 45, 78, 85]. A similar evaluation was performed by Collinge et al., who found contradictions when evaluating BEA-related materials through LCA. On the other hand, WELL contributes much on the social front (not complete S-LCA) rather than E-LCA, as most of the categories correspond to the well-being and health of the occupants. Thus, by compromising the other two aspects, however, it is still unclear how all seven assessment methods assign weightage and credits to the categories related to LCA, except for the BREEAM and LEED assessment methods.

Finally, in the longer run, the integration of LCA tools into the whole BEA will yield significant benefits, not only in the improved understanding and crediting of holistic performance but also in reduced assessment complexity and cost. However, at present, there are very few integrated systems available that can identify similar indicators for the meaningful integration of LCA. Buildings' environmental performance must, therefore, be evaluated using benchmark values over the course of their whole lifecycle. A future research opportunity is to undertake statistical analysis [44] to identify the most relevant LCA factors for residential structures and other types of buildings.

5. Conclusions

Concurrent with technological advancements, building environmental assessments have evolved and have been updated over the years. This paper reviews seven BEA methods, namely, BREEAM, CASBEE, DGNB, Green Star, HQE, LEED, and WELL, to identify the similarities and differences of the BEA methods, to examine the distribution of sustainability in each system, and to assess the level of integration of LCA in each system. During the research, 20 papers precisely dealt with BEA and sustainability, and 22 articles were related to LCA. A review of the literature reveals that several studies focus on the energy and operational phases of buildings, and few studies have investigated the whole lifecycle of buildings, integrating LCA and S-LCA. BREEAM and LEED are the most widely used certifications across the globe, with more than 10,000 projects. Therefore, the articles focusing on LEED and BREEAM were significantly higher than CASBEE, Green Star, HQE, DGNB, and WELL. However, CASBEE-, Green Star-, and WELL-related articles are still limited.

Based on the analysis performed, the main conclusions were drawn as follows: most of the assessment methods use weighting to evaluate the performance criteria,

covering different typologies and lifecycle stages. This study shows that the analyzed BEAs focus more on the operational stage but do not fully address the implications of embodied energy. BREEAM and LEED, claiming to be the most widely used methods, have recently made changes to take embodied carbon into account. Similarly, most of the tools are updated on "new construction" schemes to keep in line with sustainability. Categories, such as "energy," "resources," "water," "waste," and "management" are commonly considered from a quantitative point of view. On the other hand, WELL shows more about the health, well-being, quality, and comfort of the occupant and building than the environmental and economic dimensions. Therefore, it is clear from the analysis that all seven assessment methods have contributed to three aspects of sustainability. However, the weight assigned greatly varies in each assessment, proving that these methods are diversified in terms of their users, criteria, and regions and create a niche among assessment methods.

All seven BEAs incorporate the LCA approach at distinct levels and categories, which makes the comparison and deriving relationship between the assessment methods difficult. Most of the assessments cover the reduction of greenhouse gases and the evaluation of CO_2 emissions. However, the comparison provides insights into the method that supplies completeness in terms of evaluating LCA in its assessment methods. BREEAM is the only method that calculates the construction project's emissions. Although DGNB has incorporated LCA into all stages, it lacks clarity to deduce the results based on the reference values [81]. On the other hand, WELL contributes much on the social front (not complete S-LCA) rather than the environmental and economic aspects, as most of the categories correspond to the well-being and health of the occupants. However, it is still unclear how all seven assessment methods assign weights and credits to the categories related to LCA, except for the BREEAM and LEED assessment methods.

Furthermore, it is recommended to focus on better implementation of LCA functionalities at each stage, as well as complement by integrating socioeconomic-based LCA models to achieve and measure sustainability. One of the major limitations is that these assessment methods specialize in environmental attributes and have minimal contribution toward the cost and social dimensions that are required to evaluate the overall performance of the building. Moreover, establishing common criteria with a global consensus that fit across different geographies is still a visionary in building assessment methods. Therefore, future research could focus on the development of a hybrid method that harmonizes all potential sustainable indicators that can be applied at all stages of residential building assessment [90].

Abbreviations

AP: Acidification potential
ADP: Abiotic depletion potential

ASHRAE: American society of heating, refrigerating and air-conditioning engineers
BEA: Building environmental assessment
BMCC: Building materials and component combinations
BREEAM: Building research establishment environmental assessment method
CED: Cumulative energy demand
CASBEE: Comprehensive assessment system for built environment efficiency
DGNB: Deutsche Gesellschaft für Nachhaltiges Bauen
EE: Embodied energy
EQ: Ecosystem quality
EP: Eutrophication potential
ET: Ecotoxicity
EPD: Environmental product declaration
ESUCO: European sustainable construction database
FDP: Fossil depletion potential
GHG: Greenhouse gases
GWP: Global warming potential
HH: Human health
HQE: Haute qualite environnementale
HTP: Human toxicity potential
ITACA: Instituto per l'innovazione e trasparenza degli appalti e lacompatibilita ambientale
LCA: Life cycle assessment
LCE: Life cycle energy
LCC: Life cycle cost
LEED: Leadership in energy and environmental design
SLCA: Social life cycle assessment
ODP: Ozone depletion potential
PE: Primary energy
PM: Particulate matter
PCOP: Photochemical oxidation potential
REP: Respiratory effects potential
TPE: Total primary energy
WPC: Whole process of construction.

Data Availability

The data generated and analyzed during the study are included.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

References

[1] A. Sharma, A. Saxena, M. Sethi, and V. Shree, "Life cycle assessment of buildings: a review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 871–875, 2011.

[2] European Commission, "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives," Accessed December 11, 2020: https://ec.europa.eu/transparency/regdoc/rep/1/2020/EN/COM-2020-662-F1-EN-MAIN-PART-1.PDF, October 14, 2020.

[3] European Commission, "Energy performance of buildings directive | energy," Accessed June 9, 2020: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en, 2020.

[4] J. Markelj, M. Kuzman, and M. Zbasnik-Senegacnik, "A review of building sustainability assessment methods," *AR: Architecture Research*, vol. 14, pp. 22–31, 2013.

[5] E. Bernardi, S. Carlucci, C. Cornaro, and R. Bohne, "An analysis of the most adopted rating systems for assessing the environmental impact of buildings," *Sustainability*, vol. 9, no. 7, p. 1226, 2017.

[6] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, "Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review," *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 394–416, 2014.

[7] A. Kashkooli and H. Altan, "Critical building life-cycle assessment methodology: developing a simple tool," in *Proceedings of the 9th International Detail Design in Architecture Conference*, Preston, UK, 4&5 November 2010.

[8] International Organization for Standardization, "ISO (2006a) Environmental management - life cycle assessment - principles and framework. ISO," Accessed January 29, 2019: https://archive.org/details/gov.in.is.iso.14040.2006/page/n25/mode/2up, 2016a.

[9] International Organization for Standardization, "ISO (2006b) environmental management - life cycle assessment - requirements and guidelines. ISO," Accessed January 29, 2019: https://archive.org/details/gov.in.is.iso.14044.2006/page/n3/mode/2up, 2016b.

[10] M. Khasreen, P. F. Banfill, and G. Menzies, "Life-cycle assessment and the environmental impact of buildings: a review," *Sustainability*, vol. 1, no. 3, pp. 674–701, 2009.

[11] I. Blom, L. Itard, and A. Meijer, "Environmental impact of building-related and user-related energy consumption in dwellings," *Building and Environment*, vol. 46, no. 8, pp. 1657–1669, 2011.

[12] O. Dahlstrøm, K. Sørnes, S. T. Eriksen, and E. G. Hertwich, "Life cycle assessment of a single-family residence built to either conventional- or passive house standard," *Energy and Buildings*, vol. 54, pp. 470–479, 2012.

[13] V. Motuziene and V. Gediminas, "Environmental performance of energy efficient residential building–a case study of Lithuania," in *Proceedings of the Sustainable Building Conference 2013: Sustainable Buildings-Construction Products & Technologies*, pp. 25–28, Graz University of Technology, Graz, Austria, September 2013.

[14] R. Ramírez-Villegas, O. Eriksson, and T. Olofsson, "Life cycle assessment of building renovation measures-trade-off between building materials and energy," *Energies*, vol. 12, no. 3, p. 344, 2019.

[15] M. Swing Gustafsson, M. Gustafsson, J. A. Myhren, and E. Dotzauer, "Primary energy use in buildings in a Swedish perspective," *Energy and Buildings*, vol. 130, pp. 202–209, 2016.

[16] T. Sartori, R. Drogemuller, S. Omrani, and F. Lamari, "A schematic framework for life cycle assessment (LCA) and green building rating system (GBRS)," *Journal of Building Engineering*, vol. 38, p. 102180, 2021.

[17] M. Baitz, S. Albrecht, E. Brauner et al., "LCA's theory and practice: like ebony and ivory living in perfect harmony?" *International Journal of Life Cycle Assessment*, vol. 18, no. 1, pp. 5–13, 2013.

[18] M. U. Hossain and S. T. Ng, "Strategies for enhancing the accuracy of evaluation and sustainability performance of building," *Journal of Environmental Management*, vol. 261, p. 110230, 2020.

[19] Building Research Establishment Ltd, "Breeam," Accessed June 1, 2019: https://www.breeam.com/, 2020.

[20] LEED Rating System, "LEED v4.1," January 2019, https://www.usgbc.org/leed.

[21] Comprehenisve Assessment System for Built Environment Efficiency (CASBEE), "Casbee," Accessed January 1, 2019: https://www.ibec.or.jp/CASBEE/english/, 2017.

[22] The DGNB System, "Dgnb," 2020, https://www.dgnb-system.de/en/system/version-2020-international/ Accessed January 5, 2020.

[23] Certifications, "Alliance HQE," Accessed June 1, 2019: http://www.hqegbc.org/home/, 2020.

[24] R. Banani, M. M. Vahdati, M. Shahrestani, and D. Clements-Croome, "The development of building assessment criteria framework for sustainable non-residential buildings in Saudi Arabia," *Sustainable Cities and Society*, vol. 26, pp. 289–305, 2016.

[25] R. K. Zimmermann, O. Skjelmose, K. G. Jensen, K. K. Jensen, and H. Birgisdottir, "Categorizing building certification systems according to the definition of sustainable building," *IOP Conference Series: Materials Science and Engineering*, vol. 471, p. 092060, 2019.

[26] I. M. C. S. Illankoon, V. W. Y. Tam, K. N. Le, C. N. N. Tran, and M. Ma, "Review on green building rating tools worldwide: recommendations for Australia," *Journal of Civil Engineering and Management*, vol. 25, no. 8, pp. 831–847, 2019.

[27] S. Tokbolat, F. Nazipov, J. R. Kim, and F. Karaca, "Evaluation of the environmental performance of residential building envelope components," *Energies*, vol. 13, no. 1, p. 174, 2020.

[28] Y. Kajikawa, T. Inoue, and T. N. Goh, "Analysis of building environment assessment frameworks and their implications for sustainability indicators," *Sustainability Science*, vol. 6, no. 2, pp. 233–246, 2011.

[29] R. Bannani, M. Vahdati, M. Shahrestani, and D. Clements-Croome, "The development of building assessment criteria framework for sustainable non-residential buildings in Saudi Arabia," *Sustainable Cities and Society*, vol. 26, pp. 289–305, 2016.

[30] E. Giama and A. M. Papadopoulos, "Sustainable building management: overview of certification schemes and standards," *Advances in Building Energy Research*, vol. 6, no. 2, pp. 242–258, 2012.

[31] S. H. Alyami and Y. Rezgui, "Sustainable building assessment tool development approach," *Sustainable Cities and Society*, vol. 5, pp. 52–62, 2012.

[32] C. A. Poveda and M. Lipsett, "A review of sustainability assessment and sustainability/environmental rating systems and credit weighting tools," *Journal of Sustainable Development*, vol. 4, no. 6, p. 4, 2011.

[33] P. Boarin, D. Guglielmino, A. L. Pisello, and F. Cotana, "Sustainability assessment of historic buildings: lesson learnt from an Italian case study through LEED rating system," *Energy Procedia*, vol. 61, pp. 1029–1032, 2014.

[34] O. Suzer, "A comparative review of environmental concern prioritization: LEED vs other major certification systems," *Journal of Environmental Management*, vol. 154, pp. 266–283, 2015.

[35] S. Gobbi, V. Puglisi, and A. Ciaramella, "A rating system for integrating building performance tools in developing countries," *Energy Procedia*, vol. 96, pp. 333–344, 2016.

[36] K. H. D. Tang, C. Y. H. Foo, and I. S. Tan, "A review of the green building rating systems," *IOP Conference Series: Materials Science and Engineering*, vol. 943, no. 1, p. 012060, 2020.

[37] A. Sánchez Cordero, S. Gómez Melgar, and J. M. Andújar Márquez, "Green building rating systems and the new framework level(s): a critical review of sustainability certification within Europe," *Energies*, vol. 13, no. 1, p. 66, 2020.

[38] L. Florez, "Sustainability and green building rating systems: a critical analysis to advance sustainable performance," *Encyclopedia of Renewable and Sustainable Materials*, vol. 4, pp. 211–220, 2020.

[39] A. Rezaallah, C. Bolognesi, and R. Afghani Khoraskani, "LEED and BREEAM; comparison between policies, assessment criteria and calculation methods," in *Proceedings of the 1st International Conference on Building Sustainability Assessment*, Porto, Portugal, 23 May 2012.

[40] N. Lee, S. Tae, Y. Gong, and S. Roh, "Integrated building life-cycle assessment model to support South Korea's green building certification system (G-SEED)," *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 43–50, 2017.

[41] C. Ka-Waia and R. C. Yun-Hing, "A comparison on two certification systems: leadership in energy and environmental design (LEED) and building environmental assessment method (BEAM) on green building in Hong Kong," in *Proceedings of the World Sustainable Built Environment Conference, Track 3: Advancing SBE Assessments*, pp. 1022–1030, Hong Kong, June 2017.

[42] F. Asdrubali, G. Baldinelli, F. Bianchi, and S. Sambuco, "A comparison between environmental sustainability rating systems LEED and ITACA for residential buildings," *Building and Environment*, vol. 86, pp. 98–108, 2015.

[43] D. T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, and J. Tookey, "A critical comparison of green building rating systems," *Building and Environment*, vol. 123, pp. 243–260, 2017.

[44] F. Schlegl, J. Gantner, R. Traunspurger, S. Albrecht, and P. Leistner, "LCA of buildings in Germany: proposal for a future benchmark based on existing databases," *Energy and Buildings*, vol. 194, pp. 342–350, 2019.

[45] W. S. E. Ismaeel, "Midpoint and endpoint impact categories in Green building rating systems," *Journal of Cleaner Production*, vol. 182, pp. 783–793, 2018.

[46] S. Vilcekova, I. Selecka, and E. K. Burdova, "Sustainability assessment of family house," *Energy Procedia*, vol. 96, pp. 551–559, 2016.

[47] C. K. Chau, T. M. Leung, and W. Y. Ng, "A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings," *Applied Energy*, vol. 143, pp. 395–413, 2015.

[48] E. Vazquez, M. Miguez, L. Alves, J. Valente, and G. Rossi, "Certifications in construction: a case study comparing LEED and HQE," *WIT Transactions on Ecology and the Environment*, vol. 144, p. 264, 2011.

[49] W. Zhang, S. Tan, Y. Lei, and S. Wang, "Life cycle assessment of a single-family residential building in Canada: a case study," *Building Simulation*, vol. 7, no. 4, pp. 429–438, 2014.

[50] I. Zygomalas and C. Baniotopoulos, "Life cycle assessment environmental data for structural steel construction in Greece," *International Journal of Sustainable Engineering*, vol. 7, no. 1, pp. 13–23, 2014.

[51] Y. H. Dong and S. T. Ng, "A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong," *Building and Environment*, vol. 89, pp. 183–191, 2015.

[52] F. Intini, G. Rospi, N. Cardinale, S. Kühtz, and M. Dassisti, "Life cycle assessment of Italian residential windows: sensitivity of analysis," *International Journal of Heat and Technology*, vol. 34, no. S2, pp. S235–S241, 2016.

[53] O. Pombo, K. Allacker, B. Rivela, and J. Neila, "Sustainability assessment of energy saving measures: a multi-criteria approach for residential buildings retrofitting-A case study of the Spanish housing stock," *Energy and Buildings*, vol. 116, pp. 384–394, 2016.

[54] A. G. Martínez and J. N. Casas, "Life cicle assesments of three dwellings in andalusia (Spain): the significance of the regional context/trijų gyvenamųjų būstų andalūzijoje (ispanija) gyvavimo ciklo vertinimas: reikšmė regiono kontekste," *Mokslas - Lietuvos ateitis*, vol. 4, no. 2, pp. 106–112, 2012.

[55] A. T. Balasbaneh, A. K. B. Marsono, and S. J. Khaleghi, "Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: environmental, economic and social assessment," *Journal of Building Engineering*, vol. 20, pp. 235–247, 2018.

[56] The WELL Building standard, "WELL," Accessed January 2, 2020: https://v2.wellcertified.com/wellv2/en/overview, 2020.

[57] Energy, "BREEAM International new construction 2016," Accessed August 20, 2019: https://www.breeam.com/BREEAMInt2016SchemeDocument/content/06_energy/energy.htm, 2017.

[58] M. Kamali, K. Hewage, and R. Sadiq, "Conventional versus modular construction methods: a comparative cradle-to-gate LCA for residential buildings," *Energy and Buildings*, vol. 204, p. 109479, 2019.

[59] P. Piroozfar, F. Pomponi, and F. El-Alem, "Life cycle environmental impact assessment of contemporary and traditional housing in Palestine," *Energy and Buildings*, vol. 202, p. 109333, 2019.

[60] D. Forbes, M. El-Haram, S. Smith, and M. Horner, "Incorporating an economic measure in sustainability assessment," *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, vol. 164, no. 3, pp. 147–154, 2011.

[61] Z. S. Teshnizi, A. Pilon, S. Storey, D. Lopez, and T. M. Froese, "Lessons learned from life cycle assessment and life cycle costing of two residential towers at the university of British columbia," *Procedia CIRP*, vol. 69, pp. 172–177, 2018.

[62] S. Raslanas and J. Alchimoviene, "Assessment of the sustainability of the renovation of multi-apartment buildings in residential areas/Daugiabuciu namu lietuvoje atnaujinimo darnumo ivertinimas," *Engineering Structures and Technologies*, vol. 4, no. 4, p. 145, 2012.

[63] J. Ferreira, M. D. Pinheiro, and J. de Brito, "Portuguese sustainable construction assessment tools benchmarked with BREEAM and LEED: an energy analysis," *Energy and Buildings*, vol. 69, pp. 451–463, 2014.

[64] J. Liang, Y. Qiu, T. James et al., "Do energy retrofits work? Evidence from commercial and residential buildings in Phoenix," *Journal of Environmental Economics and Management*, vol. 92, pp. 726–743, 2018.

[65] T. Ramesh, R. Prakash, and K. K. Shukla, "Life cycle energy analysis of buildings: an overview," *Energy and Buildings*, vol. 42, no. 10, pp. 1592–1600, 2010.

[66] L. M. Muneron, A. W. Hammad, M. K. Najjar, A. Haddad, and E. G. Vazquez, "Comparison of the environmental performance of ceramic brick and concrete blocks in the vertical seals' subsystem in residential buildings using life cycle assessment," *Cleaner Engineering and Technology*, vol. 5, p. 100243, 2021.

[67] G. A. Blengini, "Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy," *Building and Environment*, vol. 44, no. 2, pp. 319–330, 2009.

[68] S. Politi, E. Antonini, and S. Wilkinson, "Overview of building LCA from the sustainability rating tools perspective," 2018.

[69] M. Sakhlecha, S. Bajpai, and R. K. Singh, "Evaluating the environmental impact score of a residential building using life cycle assessment," *Research Anthology on Environmental and Societal Well-Being Considerations in Buildings and Architecture*, pp. 142–159, 2021.

[70] S. Y. Janjua, P. K. Sarker, and W. K. Biswas, "A review of residential buildings' sustainability performance using a life cycle assessment approach," *Journal of Sustainability Research*, vol. 1, no. 1, p. e190006, 2019.

[71] O. Pons, A. de la Fuente, and A. Aguado, "The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications," *Sustainability*, vol. 8, no. 5, p. 460, 2016.

[72] A. Usman and K. Abdullah, "Comparative study on the Malaysian sustainable building rating systems," *International Journal of Integrated Engineering*, p. 10, 2018.

[73] G. Ioppolo, S. Cucurachi, R. Salomone, L. Shi, and T. Yigitcanlar, "Integrating strategic environmental assessment and material flow accounting: a novel approach for moving towards sustainable urban futures," *International Journal of Life Cycle Assessment*, vol. 24, no. 7, pp. 1269–1284, 2019.

[74] Green Star, "Green star Australia," Accessed January 25, 2019: https://new.gbca.org.au/green-star/rating-system/design-and-built/, 2020.

[75] T. Potrč Obrecht, R. Kunič, S. Jordan, and M. Dovjak, "Comparison of health and well-being aspects in building certification schemes," *Sustainability*, vol. 11, no. 9, p. 2616, 2019.

[76] A. Schmidt, "Analysis of five approaches to environmental assessment of building components in a whole building context," p. 58, 2012 Accessed August 17, 2019: https://www.eurima.org/uploads/ModuleXtender/Publications/97/Force_Study_Building_certification_systems_May_2012.pdf.

[77] L. Marchi, E. Antonini, and S. Politi, "Green building rating systems (GBRSs)," *Encyclopedia*, vol. 1, no. 4, pp. 998–1009, 2021.

[78] Y. Lessard, C. Anand, P. Blanchet, C. Frenette, and B. Amor, "LEED v4: where are we now? Critical assessment through the LCA of an office building using a low impact energy consumption mix," *Journal of Industrial Ecology*, vol. 22, no. 5, pp. 1105–1116, 2018.

[79] J. Markelj, M. K. Kuzman, P. Grošelj, and M. Zbašnik-Senegačnik, "A simplified method for evaluating building sustainability in the early design phase for architects," *Sustainability*, vol. 6, no. 12, pp. 1–21, 2014.

[80] F. Bisegna, B. Mattoni, P. Gori et al., "Influence of insulating materials on green building rating system results," *Energies*, vol. 9, no. 9, p. 712, 2016.

[81] B. Mattoni, C. Guattari, L. Evangelisti, F. Bisegna, P. Gori, and F. Asdrubali, "Critical review and methodological approach to evaluate the differences among international green building rating tools," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 950–960, 2018.

[82] J. Solís-Guzmán, C. Rivero-Camacho, D. Alba-Rodríguez, and A. Martínez-Rocamora, "Carbon footprint estimation tool for residential buildings for non-specialized users: OERCO2 project," *Sustainability*, vol. 10, no. 5, p. 1359, 2018.

[83] L. Bragança, R. Mateus, and H. Koukkari, "Building sustainability assessment," *Sustainability*, vol. 2, no. 7, pp. 2010–2023, 2010.

[84] M. Belucio, C. Rodrigues, C. H. Antunes, F. Freire, and L. C. Dias, "Eco-efficiency in early design decisions: a multimethodology approach," *Journal of Cleaner Production*, vol. 283, p. 124630, 2021.

[85] T. Mattinzioli, M. Sol-Sánchez, B. Moreno, J. Alegre, and G. Martínez, "Sustainable building rating systems: a critical review for achieving a common consensus," *Critical Reviews in Environmental Science and Technology*, vol. 55, no. 5, pp. 1–23, 2020.

[86] A. Oviir, "Life cycle assessment (LCA) in the framework of the next generation Estonian building standard building certification as a strategy for enhancing sustainability," *Energy Procedia*, vol. 96, pp. 351–362, 2016.

[87] J. Castellano, A. Ribera, and J. Ciurana, "Integrated system approach to evaluate social, environmental and economics impacts of buildings for users of housings," *Energy and Buildings*, vol. 123, pp. 106–118, 2016.

[88] J. Bastos, S. A. Batterman, and F. Freire, "Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon," *Energy and Buildings*, vol. 69, pp. 344–353, 2014.

[89] H. Alhazmi, A. K. Alduwais, T. Tabbakh, S. Aljamlani, B. Alkahlan, and A. Kurdi, "Environmental performance of residential buildings: a life cycle assessment study in Saudi Arabia," *Sustainability*, vol. 13, no. 6, p. 3542, 2021.

[90] H. Gervasio, S. Dimova, and A. Pinto, "Benchmarking the life-cycle environmental performance of buildings," *Sustainability*, vol. 10, no. 5, p. 1454, 2018.