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Review

Sustainability and building information modelling: Integration, research gaps, and future directions

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ABSTRACT

Scientific contributions to BIM-sustainability integration have gained momentum in recent years due to the influential role of BIM as a well-accepted approach for sustainable construction practices. In this regard, some systematic reviews and informatic analysis papers have addressed this topic. Although these papers have provided useful insights, we go deeper into the body of knowledge through a critical lens. In addition, in this paper, keyword combination is broadened as opposed to other reviews, and critical insight is applied to synergies between BIM and sustainability through gap-spotting. For this purpose, 98 journal articles are selected and grouped into four major categories, namely: (i) BIM-based Life-Cycle Sustainability Assessment (LCSA); (ii) BIM for green buildings; (iii) BIM-aided construction waste management; (iv) state-of-the-art topics. The work's novelty lies in giving a holistic understanding of previously dismissed issues and a critical area review. Finally, the research gaps and future opportunities are discussed and tabulated.

1. Introduction

The imperative of sustainability within the built environment has become increasingly pronounced as the world struggles with the challenges posed by climate change, resource depletion, and population growth. The built environment, historically a major contributor to environmental deterioration, now stands at the forefront of efforts to mitigate its impact and transition towards a more sustainable future [14]. In this context, emerging technologies play a pivotal role, offering innovative solutions to reshape traditional construction practices. Among these, Building Information Modelling (BIM) has emerged as a transformative force, transcending its initial role as a design and documentation tool to become a comprehensive platform for sustainable construction [34]. The synergy between sustainability and BIM presents a paradigm shift in the construction industry, offering a potential resolution to the inefficiencies and environmental costs associated with traditional practices. The comprehensive integration of environmental, social, and economical considerations into the design, construction,

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Abbreviations: API, Application Programming Interface; AM, Asset Management; BREEAM, Building Research Establishment Environment; BEAM plus, Building Environmental Assessment Method Plus,; BIM, Building Information Modelling,; BPA, Building performance Analysis; BSA, Building Sustainability Assessment; CDE, Common data environment; C&D, Construction and Demolition; COBie, Construction Operations Building Information; CWM, construction waste management; DT, Digital twin; DLCA, Dynamic Life Cycle Assessment; EPDs, Environmental Product Declarations; FM, Facility Management; gbXML, Green Building Extensible Markup Language; GBI, Green Building Index; GBRSs, Green building rating systems; HVAC, Heating Ventilation and Air Conditioning; HBIM, Historical BIM; IFC, Industry Foundation Classes; IDM, Information Delivery Manual; IPD, Integrated Project Delivery; LEED, Leadership in Energy and Environmental Design; IoT, Internet of Things; LOD, Level Of Development; LCA, Life Cycle Assessment; LCC, Life Cycle Cost; LCI, Life Cycle Inventory; LCSA, Life cycle Sustainability Analysis; LCCE, Life-Cycle Carbon Emission; LCCE, Lifecycle Cost Estimate; LCGGE, Life-Cycle Greenhouse Gas Emissions; LCSA, Life-Cycle Sustainability Assessment; MEP, Mechanical, Electrical, and Plumbing; MVD, Model View Definition; S-LCA, Social Life-Cycle Assessment; GBAs, sustainability/ green-BIM assessments; SBD, sustainable building design; SBTool, Sustainable Building Tool; SP, Sustainable Procurement; SD, system dynamic,; IFC, The Industry Foundation Classes; TBL, Triple Bottom Line; TVM, Time Value of Money; USGBC, United States Green Building Council; UI, User Interference; VPL, Visual Programming Language.

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operation, and decommissioning phases through BIM has the potential to revolutionize the sector [97].

BIM-sustainability nexus encompasses various components, including life-cycle environmental assessment [105], lifecycle cost analysis [95], life-cycle social evaluation [63], construction and demolition waste [45], green building practices [84] and integration of cutting-edge technologies [123]. BIM has revolutionized the approach to life-cycle assessment in the construction industry by providing a dynamic platform for the comprehensive analysis of buildings' environmental, social and economical impacts throughout their entire life cycle [34]. Through integrating multi-dimensional information, BIM facilitates simulations and assessments from the initial design phase to demolition, including construction, operation, maintenance, and end-of-life stages [21]. In terms of the environment, this capability facilitates the optimization of materials and energy use, significantly reducing a building's carbon footprint and enhancing sustainability [35]. Socially, it promotes well-being and inclusivity by ensuring buildings are designed for user comfort and safety [63]. Economically, through the early identification of potential issues, and allowing project teams to evaluate various alternatives in the design phase, BIM reduces waste, unexpected expenses, and increases profitability [111]. By incorporating these three pillars, BIM lifecycle assessment serves as a pivotal tool in achieving resilient, sustainable, and user-centric built environments [14].

The intersection of BIM and sustainable practices significantly impacts the management of construction and demolition (C&D) waste, paving the way for more mindful approaches to reducing, recycling, and reusing materials [45]. Through the integration of BIM with sustainable waste management practices, those involved in construction projects gain a deeper insight into the lifecycle of materials from procurement to demolition. Furthermore, 3D modelling with a high level of detail and simulation capabilities enables precise quantification and optimization of materials required, thereby minimizing over-ordering and excess use [71]. Moreover, by simulating construction processes in a virtual environment, BIM facilitates the identification of potential waste streams early in the design phase which allows incorporating of waste reduction strategies such as modular construction and the use of recycled materials [41]. This synergy not only enhances resource efficiency but also contributes to the circular economy by encouraging the reuse of C&D waste in new construction projects, ultimately leading to a reduction in the environmental footprint of the built environment [14].

In addition, BIM is highlighted as a highly effective approach for streamlining the evaluation of green buildings [86]. BIM and its associated tools demonstrate proficiency in handling multidisciplinary information across the project life cycle. Consequently, this capability presents avenues to support green building practices. These applications cover various aspects, including but not limited to acoustic analysis, carbon emission assessment, efficient management of construction and demolition waste, lighting analysis, optimization of operational energy use, and monitoring of water utilization, all contributing to the optimization of building performance [44].

Emerging technologies like digital twins, blockchain, the Internet of Things (IoT), and artificial intelligence (AI) have been integrated with BIM to provide more sustainable and efficient building and infrastructure projects. They support data-driven decision-making, provide security and transparency in sustainable development initiatives, and improve energy efficiency through process automation and consumption optimisation [97,119].

While previous literature has provided valuable insights into the synergy between BIM and sustainability, our present work expands on this foundation. It encompasses a wider spectrum, delving into the environmental, economic, and social dimensions. Additionally, it explores the concepts of green building, the BSA (Building Sustainability Assessment) methods, lifecycle sustainability assessment, and incorporates cutting-edge technologies within the context of the BIM-sustainability nexus. By conducting a comprehensive and critical review, this research seeks to navigate the diverse perspectives surrounding BIM, clarify its role beyond a mere tool, and illuminate the multifaceted dimensions of sustainability within the construction industry. As the transformative potential of BIM in shaping sustainable construction practices is witnessed, it is endeavoured by this research to contribute to the ongoing discourse, offering clarity, insights, and a roadmap for stakeholders to navigate the dynamic intersection of sustainability and BIM. In order to realize this aim, the following research questions have been established:

RQ1: How Life Cycle Sustainability Assessment (LCSA) approaches are integrated with BIM?

RQ2: What are the future research directions and the most potential state-of-the-art topics in the BIM-Sustainability domain?

RQ3: What challenges and technical solutions have been proposed by other scholars in the realm of BIM and sustainability synergy?

RQ4: What gaps fall into the categories of "under-researched," "overlooked," and "lack of empirical support"?

RQ5: Which concepts in the literature are ambiguous and in conflict with one another (confusion gap)?

To address the above research objectives and answer to questions stated, the remainder of the study is structured as follows. In Section 2, the background of previous reviews and their deficiencies is discussed. Section 3 illustrates the research methods and the design of the study. Finally, by critically reviewing studies within the research field, Section 4 identifies gaps in the body of knowledge and future research directions. In contrast, Section 5 concludes this article by summarising the contributions and limitations.

2. Related review studies

Though many literature studies have been conducted, they are commonly based on systematic review and informatics analysis except the review of Olanrewaju et al. [84] which explored the synergies between BIM and Green Building Certification Systems (GBCS) using systematic literature review and gap-spotting methods. However, Life cycle Sustainability Analysis (LCSA), waste management, and state-of-the-art areas remained under-researched.

In the realm of Building Sustainability Assessment (BSA) methodologies, Carvalho et al. [22] recently conducted a systematic review with a specific focus on publications dedicated to the practical evaluation of criteria associated with select BSA methods. However, their study is subject to certain limitations, notably stemming from the application of restricted databases and suboptimal keyword combinations. Additionally, noteworthy BSA methodologies such as Green Star and the Building Environmental Assessment Method (BEAM) were conspicuously absent from their analysis. Ansah, et al. [10] conducted a review that identified some frameworks and practical assessment approaches. Nonetheless, their examination needed to adequately address identifying the most effective software tools and emerging trends within the domain. Shukra and Zhou [118] systematically scrutinized research and implementation trends in the context of green Building Information Modelling (BIM) using a mixed-method approach. Their study shed light on the potential for comprehensive green BIM integration. In contrast, Wong et al. [134], while presenting a substantive review of academic research endeavors about BIM and green building initiatives, allocated relatively less attention to the comprehensive comparative analysis of diverse BIM applications within the context of the green building industry.

Chang et al. [28] adopted a systematic review procedure to examine two major sources of literature: BIM guidelines and peer-reviewed academic publications. On the other hand, Santos et al. [110] expanded the scope of the study by including environmental, economic, and social aspects, as well as their interactions. They also performed an informetric study of the literature and categorised it using content analysis; nevertheless, their review lacked a critical lens.

Table 1 summarises such related review studies currently available within the research field. It can be inferred from this table that there is

Table 1
Previous reviews in the realm of BIM-sustainability.

Reference	Objective							Primary Method				
	LCSA			Green building	BSA	TBL	Construction and demolition (C&D) waste	SLR	Critical review	Gap analysis	State-of-the-art review	Scientometric & informetric
	LCA	LCC	S-LCA									
[134]	✓			✓			✓					✓
[66]	✓	✓	✓			✓	✓	✓				
[10]				✓	✓			✓	✓	✓		
[65]				✓	✓				✓			✓
[7]				✓	✓	✓	✓			✓		✓
[32]				✓	✓		✓		✓			
[5]	✓						✓	✓			✓	
[94]	✓							✓			✓	
[105]	✓							✓		✓		
[22]				✓	✓			✓				
[136]	✓								✓			✓
[118]	✓			✓			✓	✓				✓
[31]	✓										✓	
[68]	✓	✓						✓	✓			
[28]	✓					✓		✓			✓	
[110]	✓	✓				✓		✓	✓		✓	✓
[25]								✓			✓	
[29]	✓							✓				
[69]				✓	✓			✓		✓		
[121]	✓								✓			
[84]				✓	✓			✓		✓		
This study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

no all-encompassing critical analysis, illustrating the necessity of doing a thorough gap analysis of the current corpus of knowledge. Moreover, unlike prior reviews on this topic, the current work has a broader scope that covers the environmental, economic, and social dimensions. The concepts of green building, the BSA methods, and the lifecycle sustainability assessment are all covered independently. In terms of research methods, gap analysis and critical review have been conducted as part of systematic literature review process.

3. Research methodology

This paper seeks to thoroughly review the current literature concerning the integration of sustainability and Building Information Modelling (BIM). It also aims to pinpoint areas where further research is needed and identify potential research opportunities in this field. This section describes the process of systematic review and gap spot. As illustrated in Fig. 1, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework [89] followed by content analysis, critical review and gap spotting were established and applied to meet the study's objectives.

3.1. *Systematic literature review*

In this stage, the following steps are performed on the relevant collected papers, based on the PRISMA flowchart guidelines described below.

3.1.1. *Identification*

The search query was devised by integrating pertinent keywords and their synonyms related to Building information Modelling (BIM) and sustainability, employing Boolean operators such as "AND" and "OR" (as depicted in Table 2). This search was executed across various databases, specifically Google Scholar, ScienceDirect, and Scopus. To prevent missing any relevant works, the date range was adjusted to "all years to present". The preliminary search yielded a cumulative total of 24,599 articles. These search engines were chosen due to cover a wider variety of construction management and construction IT-related journals.

The initial set of identified papers underwent a comprehensive screening and review process through multiple steps. Various filters offered by Scopus, ScienceDirect, and Google Scholar during the initial search were applied to narrow down the pool of papers. These filters encompassed document type (restricted to journal articles), subject area (confined to engineering fields and environmental science), and publication stage (confined to final published papers). This initial stage aimed to reduce the number of articles and exclude those that did not align with the predefined eligibility criteria. Additionally, duplicate records were meticulously eliminated during this phase. Consequently, the outcome at the end of this phase comprised 543 papers, which constituted the pool for the subsequent screening process.

3.1.2. *Eligibility criteria*

Several inclusion and exclusion criteria were applied to assess the quality of the chosen articles, assure their relevance to the research objectives and ensure methodological rigour, as outlined in Table 3.

3.1.3. *Screening process*

A screening process involved screening the title and abstract, applying inclusion and exclusion criteria, and screening the full text of the papers to exclude publications lacking relevance to the construction field or those that only partially aligned with the search terms within their title, abstract, and keywords section. Following this filtration, 445 articles were removed from the dataset. Eventually, 98 papers were selected for content analysis, critical review, and gap spotting.

3.1.4. *Gap spotting*

One of the primary objectives of a literature review is to identify research gaps and issues to direct future research topics based on them. Gap analysis is one of the most fruitful approaches of developing research questions to perform research that could contribute to the body of knowledge [8,104]. However, it has been rarely used in construction-related research. Scholars can spot three modes of gap analysis in the literature: 1) recognising conflicting explanations (confusion spotting); 2) delineating overlooked areas (neglect spotting); and 3) outlining deficiencies of a particular hypothesis or perspective (application spotting). Following is a brief discussion of the application modes based on the Alvesson and Sandberg [8] approach:

3.1.4.1. *Confusion.* The first sub-category identified by Alvesson and

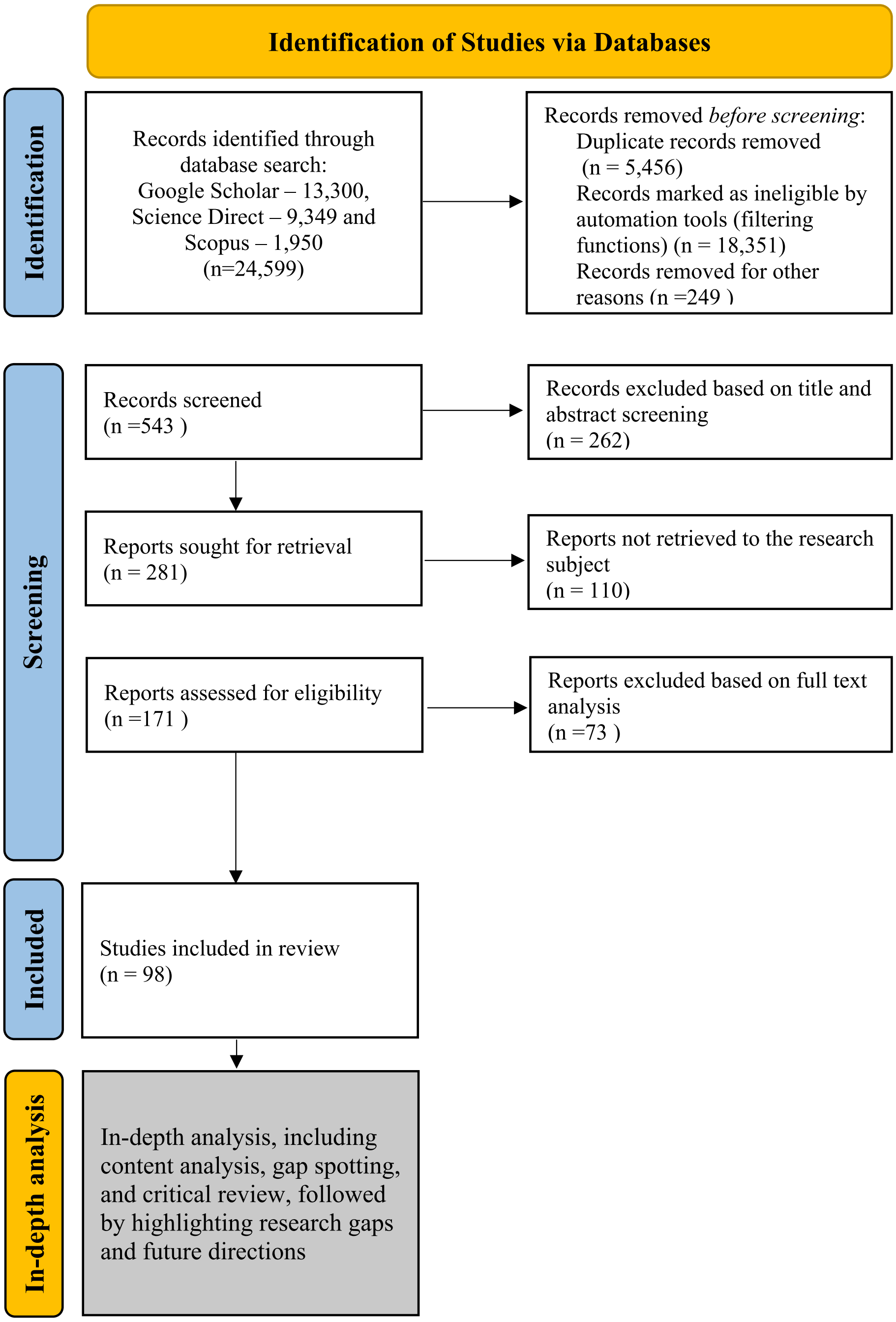

Fig. 1. Outline of the research method [89].

Sandberg [8] is confusion spotting. Confusion exists where a collection of published papers within a theme fails to agree on a subject or where the evidence from the literature is unclear and contradictory.

3.1.4.2. Neglect. As a second mode, neglect spotting is deemed the most dominant gap analysis method. It is classified into three categories: an overlooked area, an under-researched area, or a lack of empirical support. The most typical contention was overlooking a specific area, essentially when the area is targeted but lacks a specific concentration. An under-researched area occurs when there is an inclination towards a particular perspective without considering other areas. The third subgroup of neglect spotting is intertwined with studies addressing theoretical concepts and models but lacking empirical evidence, indicating that more research is required.

3.1.4.3. Application. Application spot is the third and last approach to spotting a gap in a lack of a precise theory or a unique perspective in a certain field of study. This mode is used in research that focuses only on a few case studies without contributing to the body of knowledge [8].

4. Critical evaluation of literature and identification of research gaps

To conduct a critical review, the 98 selected journal articles are grouped into four major categories, namely: (i) BIM-based Life-Cycle Sustainability Assessment (LCSA); (ii) BIM for green buildings; (iii) BIM-aided construction waste management, and (iv) state-of-the-art topics. Further details on the classification of technical information in the studied BIM-sustainability publications are presented in Fig. 2 and

Table 2
Search query.

Search database	Search query	Subject area
Google Scholar	allintitle: "BIM AND sustainability", "Building Information Modelling AND sustainability", "BIM AND sustainable development", Building information Modelling AND sustainable development "	–
ScienceDirect & Scopus	("Building Information Modelling" OR "BIM") AND ("sustainability" OR "sustainable development" OR "LEED" OR "Environment" OR "BREEAM" OR "SB Tool" OR "Green Building" OR "LCA" OR "Life-Cycle Assessment" OR "LCC" OR "Economic" OR "Social")	Engineering fields, Environmental science

Table 3
Applied eligibility criteria.

Inclusion criteria	Exclusion criteria
Written in English	Articles written in languages other than English
Peer-reviewed publications from reputable academic publishers (Elsevier, Springer, Emerald, T&F, MDPI, and ASCE)	Book reviews, editorials and conference papers, conference proceedings, and technical reports
Relevant to the aims of this research (BIM-sustainability nexus)	Articles that may not entirely align with the research objectives, particularly those concentrating on terms such as "cost reduction" and "BIM environment."
In the context of the construction sector	Irrelevant to the construction sector.

discussed in the following subsections.

4.1. Group I – BIM-based life cycle sustainability assessment (LCSA)

This section addresses the initial research query outlined in the introduction, specifically concerning the integration of Life Cycle Sustainability Assessment (LCSA) approaches into BIM. Life-Cycle Sustainability Assessment (LCSA) is a well-known methodology for evaluating sustainability, considering the triple bottom line of sustainability to integrate: i) Life Cycle Assessment (LCA), representing the environmental dimension; ii) Social Life-Cycle Assessment (S-LCA), representing the social dimension; and iii) Life Cycle Costing (LCC), describing the economic dimension [35]. This integrated approach, depicted in Fig. 3, seeks to holistically assess the environmental, social, and economic dimensions.

It is imperative to acknowledge that the three dimensions of sustainability, as encapsulated by LCSA, may exhibit varying levels of maturity. Despite the recognised potential of LCSA, its complete and widespread implementation remains a work in progress, marked by the ongoing evolution of each sustainability dimension. Concerning the selection of construction material, applications of the LCSA method are still underdeveloped, and there are some limitations. By proposing a framework based on the Life-Cycle Sustainability Assessment (LCSA), Figueiredo et al. [35] evaluated building materials' environmental, social, and economic impacts to make an appropriate choice. However, only one social impact category was assessed in this study, which can be considered a significant drawback. Moreover, due to the absence of reliable social and economic databases, the construction materials in the production phase, from the extraction of raw materials to the manufacturing processes, are not covered. The following subsections provide more details about how BIM is connected to social, environmental, and economic assessments.

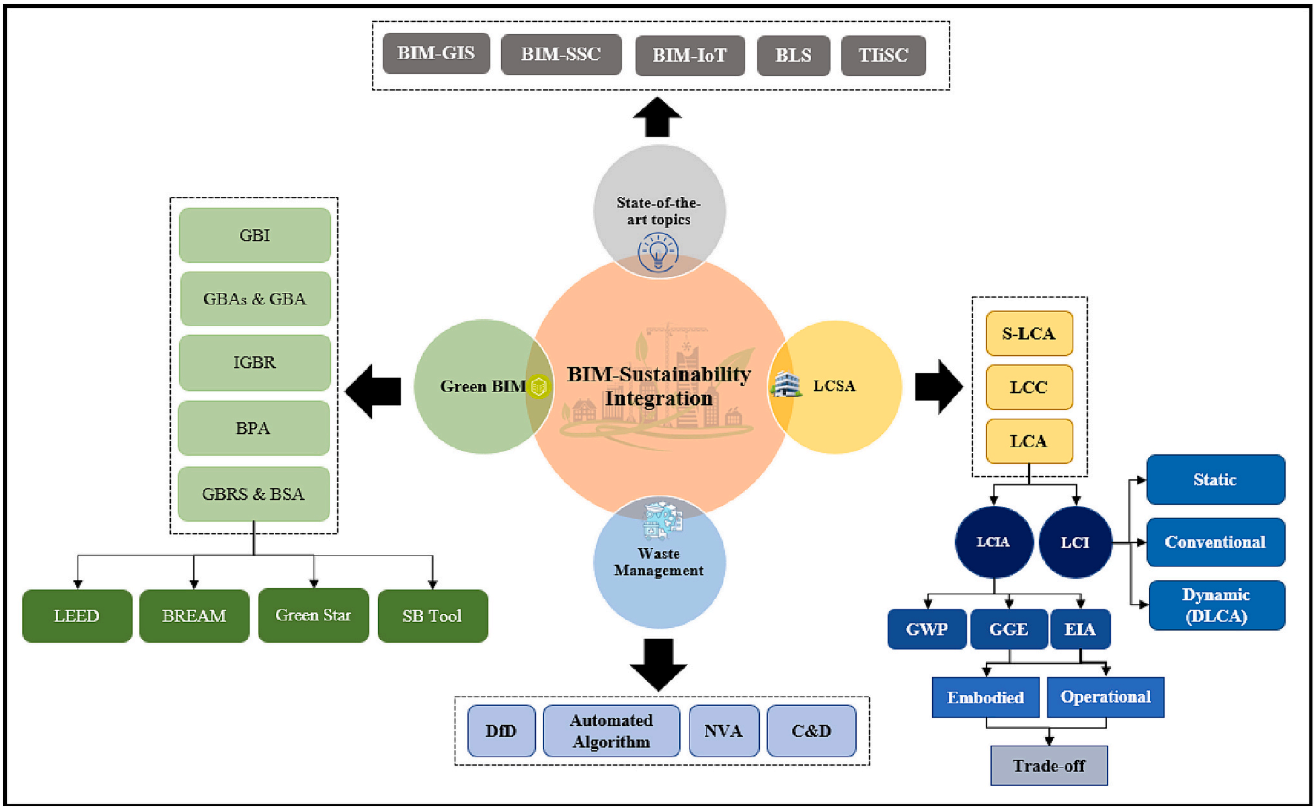

Fig. 2. Classification of the technical information in the reviewed BIM-Sustainability publications (created by authors).

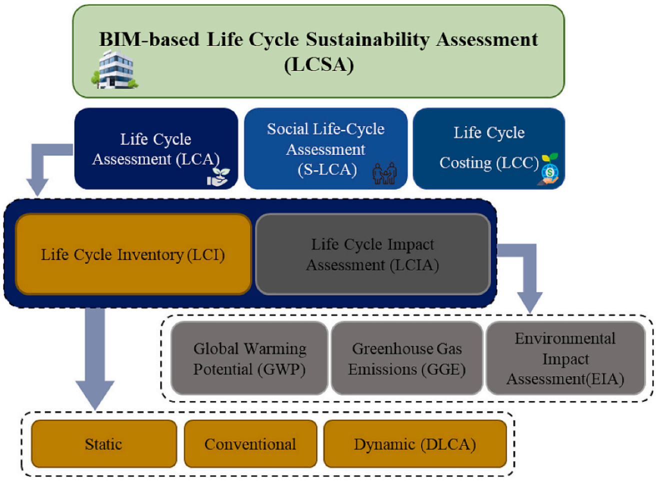

Fig. 3. Classification of reviewed findings for BIM-based lifecycle sustainability assessment (created by authors).

4.1.1. BIM-based social assessment

Among LCSA techniques, the S-LCA is usually the least addressed method since most social indicators are qualitative [63,66]. This aspect is an unexplored area for research and needs a more comprehensive understanding. This section generally addresses indoor comfort, safety, and BIM uses to maintain cultural heritage. For the sake of the considerable number of records in the realm of safety-BIM integration for sustainable construction, we overlooked such papers, accounting for one of our significant limitations. To present an all-inclusive social sustainability performance value of residential structures, Ahmad and Thaheem [3] proposed an assessment framework that used a weighted aggregation approach by determining the weights of indicators, parameters, and sub-indicators, based on the empirical knowledge of a focus group, which cannot be generalised for another context.

One of the most prominent social benefits of BIM is its function in enhancing user comfort and evaluating building performance. This aspect has been under-researched, as most previous studies have paid little attention to end-user comfort [110]. In this regard, Welle et al. [131] were among the pioneer researchers studying the potential of BIM for daylighting modelling during the design process. They evaluated the building's daylighting performance based on the geometric information provided in the BIM model.

The social application of BIM throughout the operating phase of structures has been established in Historical BIM (HBIM) studies [15,109], representing a recent topic in literature. Biagini et al. [15] applied laser scanning technology to produce an as-built BIM model of ancient buildings. In this regard, creating historical national BIM libraries (e.g., comprising objects with historical and geographical data) is highly recommended for enhancing analysis automation. Another gap in this domain is the absence of an ontology-based BIM model for representing and managing semantic information concerning cultural heritage [2]. Rea et al. [98] investigated the application of a drone outfitted with a laser scanner and camera, allowing the construction of an as-built BIM model. They recommended developing a model for quality control of cultural heritage during operating stages in the future.

4.1.2. BIM-based environmental assessment

The environmental impact of construction projects is the most researched aspect of sustainability in the literature [91]. LCA is the most commonly used method of quantifying the environmental impacts of the building sector over its lifecycle and making decisions on more environmentally friendly options. Due to the advancement of BIM and the growing interest in the issue of BIM-LCA, 31 of the 98 papers reviewed in this study belong to this category.

The Life Cycle Assessment (LCA) approach is broken down into four key steps: (i) Goal and Scope definition; (ii) Life Cycle Inventory (LCI) analysis; (iii) Life Cycle Impact Assessment (LCIA); and (iv) Interpretation. This four-phase LCA framework can also be applied to LCC and S-LCA [35,38]. The literature review revealed that many impact categories, sub-categories, and indicators must be considered for LCIA. Most coincidences occurred during the Environmental Impact Assessment (EIA), where Global Warming Potential (GWP), GHG emissions, or climate change categories are evaluated [66]. To enhance clarity regarding the conducted studies in BIM-environmental sustainability, the following four subsections categorize and discuss advancements. These include the classification of BIM-LCA integration, full automation of the integration process, life-cycle carbon emission (LCCE) and energy consumption, as well as exploration of other research gaps and limitations in the realm of BIM and LCA.

4.1.2.1. Typologies of BIM-enabled lifecycle environmental assessment integration. Regarding the Life Cycle Inventory (LCI) as the most time-consuming phase of LCA, the numerous approaches to BIM-LCA integration are classified into three categories: conventional, static, and dynamic [30]. In conventional LCIs, the information derived from the BIM model is systematically transferred into an Excel spreadsheet, which subsequently serves as the primary reservoir of input data for established LCA software solutions, including SimaPro and OpenLCA. Alternatively, the data extracted from the BIM model may be inputted manually into the LCA tools. Thereafter, rigorous environmental computations and assessments are conducted [23,67].

In the static approach, the BIM model outputs will undergo a conversion process into the Industry Foundation Classes (IFC) format, which serves as an essential input for LCA tools [17,29,52,73]. Several researchers have employed programming languages, including C# and Visual Basic, to formulate and implement their methodologies. For instance, Marzouk and Othman [73] proficiently assessed comprehensive emissions by introducing a model developed within the Microsoft Visual Studio framework, drawing from the structural foundations of the C programming language within the .NET environment. Furthermore, Bueno et al. [17] developed an approach for automatically incorporating environmental information into building objects using the Dynamo Visual Programming Language (VPL). Santos et al. [111] developed an Information Delivery Manual (IDM) and a Model View Definition (MVD), to exchange information within a BIM-based environment. However, the IDM and MVD provided by the authors in this study were limited to the BIM-LCA/LCC framework. Furthermore, the proposed IDM/MVD disregarded the Mechanical, Electrical, and Plumbing (MEP) domain (e.g., heating, ventilation, and air conditioning systems).

In the dynamic BIM-LCA approach, LCA is adopted to make appropriate decisions whenever change orders are issued over the lifecycle of a building. This approach offers greater accuracy than the other two methods, yielding time-dependent Life Cycle Assessment (LCA) results by considering changing factors over time. Nevertheless, despite the partially automated matching process, it does not encompass some LCA aspects, like the environmental effects associated with transportation and installation.

Scholars have also proposed a more dynamic approach to Life Cycle Assessment (LCA) known as Dynamic Life Cycle Assessment (DLCA). This method considers the changing factors over time and establishes a connection between building data and the Life Cycle Inventory (LCI) database. Su et al. [122] have recommended augmenting DLCA with advanced information technologies such as big data and the Internet of Things (IoT). Using DLCA data from all buildings in a region, a big data platform can serve as a standard for assessing new constructions. In addition, IoT systems in buildings can continuously monitor and record operational data, providing more accurate information for dynamic assessments. These research directions show promise for improving DLCA in the future. In addition, developing a web-based platform using a semi-automatic workflow was recommended. Likewise, Jalaei et al. [51] developed a semi-automatic model, requiring users to combine the BIM model's information. As the focus was on the conceptual design, the level of accuracy in the estimation of the costs of proposed projects was also considered low.

4.1.2.2. Advancing full automation in BIM-environmental assessments. Achieving full automation in the integration process signifies the automatic exchange of data between Building Information Modelling (BIM) models and Life Cycle Assessment (LCA) tools, eliminating the need for manual intervention or intermediate steps [94]. While previous researchers predominantly focused on manual and semi-automatic solutions for BIM-LCA integration, Potrč Potrč Obrecht et al. [94] introduced a groundbreaking approach by enabling real-time evaluation of project options without manual data entry. However, this approach faced challenges and was not fully established. Notably, two studies [1,60] demonstrated successful full automation. Abanda et al. [1] integrated a BIM-based tool with the .NET Framework to automate data import into Excel, and Luo [60] achieved automatic information exchange from BIM to Excel by combining C# with the .NET Framework. Moreover, Genova [39] presented multiple LCA workflows within a BIM framework, utilizing Revit as the BIM authoring tool and Dynamo as an integrated parametric solution. The demonstration illustrated the process of associating building elements and their material specifications with national LCA databases.

Despite these advancements, Potrč Obrecht et al. [94], Tam, et al. [123], and Dalla Mora, et al. [31] assert that achieving full automation remains a challenge due to technical, informational, organizational, and functional issues. These issues include the lack of standardized data formats and protocols for BIM and LCA, inconsistencies in environmental product declarations (EPDs), difficulty in mapping BIM elements to LCA inventory items, variability in LCA parameters and methods, and the necessity for user-friendly and interoperable BIM-LCA software and tools.

4.1.2.3. Life-cycle carbon emission (LCCE) and energy consumption. Efforts to mitigate carbon emissions and energy consumption in construction have been extensively studied, with a focus on selecting appropriate materials [62]. For instance, González and Navarro [40] estimated the carbon emission and embodied energy of many different materials in the same unit. They did not, however, take material prices into account.

Early research in this field has led to models that forecast the environmental footprint of construction activities over building life cycles [43,59,92,134]. Yet, the call for a robust, user-friendly tool to automate and visualize emission data analysis remains strong. In this regard, Wong et al. [133] responded by creating a visualisation tool that aids project teams in estimating construction-phase emissions, enabling contractors to pinpoint emission sources and quantify their volume. Furthermore, Hollberg et al. [46] demonstrated that certain construction elements, notably walls, slabs, mechanical equipment, and ducts, significantly contribute to a building's overall embodied carbon. Notably, among scholars, only Kiamili et al. [57] have provided an LCA framework for Heating Ventilation and Air Conditioning (HVAC) systems. Their findings revealed that HVAC emissions constitute a substantial portion, ranging from 15% to 36%, of the overall Life Cycle Emissions (LCE).

In the realm of green building assessment, Cheng et al. [27] sought to offer an approach to green building assessment by calculating the generated Life-Cycle Greenhouse Gas Emissions (LCGGE) of a museum using the combination of LCA and BIM. However, they did not assess the impact of other Greenhouse Gas Emissions (GGE) reduction initiatives, such as using recycled materials.

The integration of BIM further highlights in evaluating buildings' embodied environmental impacts, underlining the importance of considering both embodied and operational energy [32].

Notably, the operational aspect remains less explored, as seen in Schneider-Marin et al. [112] and Theißen et al. [124] studies, allowing potential for a more holistic approach in future studies that weigh both operational and embodied life cycle phases.

The automation of evaluating embodied impacts at each design stage through BIM has been advanced by Hollberg et al. [46] in a real case study. Notably, their computations relied on surface area data, as opposed to volumetric models, which was found to yield notably diminished precision in the certification of the as-built model. Similarly, Shadram et al. [113] presented a comprehensive BIM-based framework aimed at reducing embodied energy within the context of architectural design. However, a notable challenge they encountered was the absence of a universally standardized format for Environmental Product Declarations (EPDs), such as Industry Foundation Classes (IFC), which significantly hindered the automation of the process. Consequently, it is imperative to emphasize the necessity for further research to address the automation of EPDs that are seamlessly compatible with BIM-based tools.

Some studies disregard the building lifecycle while calculating embodied energy. In other words, the scope of these investigations is constrained from the cradle to the gate. For instance, Nizam et al. [82] proposed a fully automated process for estimating embodied energy without considering the influence of the construction phase on the computations. Additionally, the system lacked the potential to present intelligent options for lowering embodied energy. Further attempts can be made to propose an intelligent tool by providing scenario-development capabilities. Shrivastava and Chini [117] assessed the initial embodied energy of a building through BIM by entering the input of material sustainability data into the material properties database.

Meanwhile, efforts to minimize operational and embodied carbon, such as those by Gan et al. [37], and to assess greenhouse gas emissions in building renovations, such as those by Feng et al. [33]. However, there are limitations, such as neglecting demolition impacts at the end of life. These studies, while focused on densely populated areas, underscore the variability of results based on geographical and energy supply differences.

In sum, while substantial progress has been made in assessing and reducing the environmental impact of construction, the field still faces challenges in standardization, comprehensive lifecycle analysis, and the integration of cost considerations into sustainable design practices. The development of multi-objective optimization models, like Liu et al. [62]'s for BIM-based sustainable design, shows promise, though they often focus on specific aspects like thermal performance, overlooking critical systems like HVAC. This narrative underscores the ongoing journey towards more sustainable construction practices, where balancing environmental concerns with cost-effectiveness remains paramount.

4.1.2.4. BIM and LCA: other research gaps and limitations. There are some constraints, problems, and research gaps facing BIM-LCA integration in the current body of knowledge, as follows:

One common research gap in the field involves a tendency to focus on specific building components rather than considering the entire building. For example, in their study, Bueno and Fabricio [17], compared the environmental impacts of different non-structural external wall systems using two methods: a simulation in a Tally™ plug-in and a detailed ad-hoc analysis with Gabi 6 software. One notable gap in this research is the limited availability of alternatives that can be effectively linked with the construction systems used in the Revit model.

The absence of explicit data structure restricts the interoperability of the developed solutions [111,121]. The majority of the continuous BIM-based LCA frameworks, due to lack of access to accurate data, disregard transportation of the material, which is one of the most integral parts of the environmental impact assessment of the projects [111,113]. For example, Hollberg et al. [46] considered technical equipment, such as electrical equipment, lighting, ducts, plumbing, pipes, mechanical equipment, cable trays, air terminals, fire alarm devices, and conduits, in their study. However, transportation impacts on the construction site, operational energy consumption, and water consumption were neglected. Similarly, Cavalliere et al. [23] did not consider the effects of transportation to the construction site, operational energy consumption, and water use.

On the other hand, LCA results are commonly presented in external reports (i.e., a combination of graphs and numerical values) or 3D [111]. Therefore, the semantic modelling of LCA results in the BIM model enables online visualisation of the LCA results in the native BIM design platform and facilities the simple tracing of design modifications.

Lack of consistency in LCA data sources is another research gap in this area. Bueno et al. [17] examined different data sources linked into two design tools: a complete LCA on Gabi 6 software and a BIM-LCA plug-in. According to the study, no consistent outcomes can be guaranteed. To tackle inconsistency, Palumbo et al. [90] proposed EPD as a tool for selecting appropriate materials and obtaining accurate and consistent LCA results. Similarly, Santos et al. [111] proposed using generic environmental information (e.g., generic databases) for lower LODs and more specific information (e.g., EPD) for higher LODs. In theory, this would be a suitable way of including EPD indicators in the BIM-based LCA; however, there may be virtually no correspondence or consistency between the LCA results and the LOD of the BIM model in the design stages. This reinforces the assertion that there are still research gaps regarding data consistency in LCA studies.

LCA can be performed either in a simplified manner at the commencement of the building process using uncertain approaches or when all the required information is available, which would be considered too late for decision-making. To tackle this issue, Naneva et al. [81] developed a BIM-LCA integration model for the whole building process, linked to an existing workflow. The method, however, was heavily reliant on the cost-planning structure and LCA databases of Switzerland. Moreover, this study did not consider the embodied energy impact of MEP elements and the operational energy impact.

An early-stage BIM-based evaluation necessitates extensive manual input, making the process complicated and time-consuming. As a result, most BIM-LCA studies perform an ex-post evaluation. To address this issue, Röck et al. [102] proposed a conceptual BIM model for testing a wide variety of possible construction options to support decision-making in the early stages. However, they considered only the impacts of those building materials available in the initial LCA database, and the impacts of the building's operational energy and water consumption remained uncovered. Furthermore, this paper did not consider the technical equipment for the heating system and the water supply and electricity distribution. Although such components have a major impact on the final results, they are regularly neglected or poorly modelled in LCA.

Similarly, Sandberg et al. [108] proposed a framework for neutral BIM-based cross-disciplinary optimisation of life cycle energy and cost. However, due to insufficient data on embodied energy, they overlooked the main energy use and capital expenses deriving from manufacturing materials connected to mechanical systems (e.g., Heating, Ventilation, and Air Conditioning systems).

4.1.3. BIM-based economic assessment

Economic sustainability refers to actions undertaken to achieve long-term economic growth without inducing negative social and environmental implications for communities [78]. It is concerned with reducing the associated time and schedules of building projects to ensure that such valuable resources are used effectively and sustainably [7,110]. The generic word "cost" in conjunction with "BIM" came extremely high in the search process. As a result, this section addresses articles focusing on the economic aspects of BIM adoption while avoiding studies that concentrate merely on cost estimation and the Lifecycle Cost Analysis (LCCA) of construction projects.

In addition to LCC, Ahmad and Thaheem [4] applied novel economic variables, such as affordability, manageability, adaptability, and flexibility, to analyse the economic performance, emphasizing residential buildings only. This study demonstrated that, in practice, a building could not perform effectively in all of its economic sustainability indices simultaneously.

LCCA is used to examine economic viability based on LCC calculations [68]. Although many criteria, such as resiliency, operation cost, maintenance cost, repair cost, and the social cost of carbon, are required for calculating a building's overall cost, most studies concentrate on limited parameters, impeding the full achievement of economic sustainability. For instance, in the study by Rad et al. [95], initial expenditures, such as material, labour, transportation costs, and ancillary costs, such as land possession and site preparation, were not included. Furthermore, water consumption was not taken into account while calculating operating costs.

Marzouk et al. [72] proposed a framework for measuring the economic effect of sustainability across all phases of green construction and rated the degree of environmental sustainability of building systems using the Leadership in Energy and Environmental Design (LEED) grading system by considering the time value of money (TVM). Five of the seven LEED credits were chosen, leaving two others (building reuse and construction waste management credits) unresearched in this article.

Oti and Tizani [88] leveraged a combination of Life-Cycle costing, ecological footprint, and carbon footprint to provide sustainability analyses of different design solutions based on the economic and environmental sustainability pillars. A prototype system was built in .NET and coupled with Revit StructuresTM, a BIM-enabled program. Since the study was aimed at the conceptual design stage of structural steel framing systems, further research into other structural framing systems, such as reinforced concrete, is required.

Liu et al. [62] demonstrated the trade-off optimisation between LCC (construction and operation cost) and LCCE of buildings by integrating Autodesk Ecotect with particle swarm optimisation. However, there was no master model offered in this study, and the interoperability issue was completely disregarded [108].

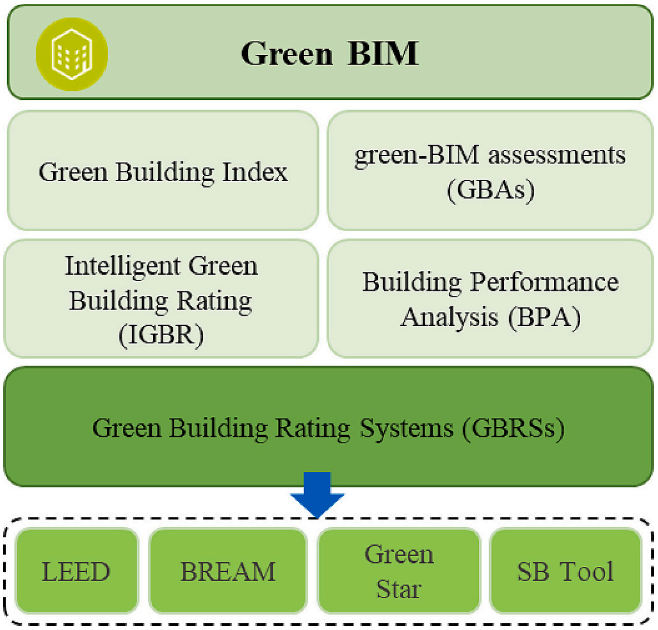

Fig. 4. Classification of reviewed findings for BIM-based green buildings (created by authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Group II – BIM for green buildings

The Classification of this group's findings is indicated in Fig. 4 and discussed in detail in the following subsections.

4.2.1. Green BIM definition

Although green BIM research has gained momentum in recent years, the number of publications in top journals is still very few compared with the research progress in the BIM sustainability area. In addition, despite its widespread use, there is significant ambiguity in the definition of a "green BIM" concept. In line with this, Wu and Issa [135] defined green BIM as the synergies of BIM and green building applied to improve sustainable outcomes of building development, which is an oversimplified definition. According to Wong et al. [134], the application of "green BIM" should be extended to the whole Life-Cycle of a project, including operation, maintenance, and demolition stages. Based on this conclusion, and to prevent confusion regarding the definition of green BIM, the notion of holistic green BIM application was offered by Shukra et al. [118]. Their findings indicate that most green BIM studies, which focus solely on energy analysis and sustainable design parameters — such as green material selection, sustainable site, waste management, and water-use efficiency — fall into the "under-researched gap" category.

To fulfil green mandates and achieve the concept of holistic green BIM, the adoption of various types of building performance analysis (BPA) is vital. Lu et al. [69] provide an all-inclusive insight into green BIM research by introducing a "green BIM triangle" based on four project phases, six green features, and four BIM qualities. Nevertheless, several major BPA variants are overlooked in their work. In terms of other possible BPA, biodiversity and social sustainability are two significant aspects of green building that have been generally disregarded [74]. More research on the concept of holistic green BIM and other green building parameters is thus required.

4.2.2. Green building rating systems (GBRSs) and building sustainability assessment (BSA)

Different nations have established various green building rating systems, the most frequently used of which are the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), United States Green Building Council (USGBC), Sustainable Building Tool (SBTool), and Green Star. BREEAM, originating in the UK, and LEED, originating in the USA, are the most commonly used rating systems and are based on credits scored by a weighting factor that reflects the country's sustainability goal [21,22].

The lack of a unified GBRS across the globe is an evident research gap in this regard. Furthermore, each assessment criterion in each rating system can be affected by the regional context so that in one country, some criteria might be considered important, while in another, these are of a lower priority. To fill this gap, Mahmoud et al. [70] developed a green building rating tool that considers geographical variations by determining fuzzy weights. The low accuracy of BIM-based certificates is another research gap. Most green building certifications, such as LEED, are based on predicted rather than actual performance [69]. Therefore, it would be valuable to mandate all LEED projects to record and report actual energy performance to benchmark their energy efficiency.

The number of points earned by the project determines the LEED certification level, and each section of the LEED® system includes prerequisites that must be met, even though they do not count towards a building's total points. Azhar et al. [13] were among the first researchers to develop a nexus between the BIM method and the LEED® certification. In their research, the LEED® credits were divided into six categories based on LEED® ver. 2.2. Although there were 17 LEED® credits and two prerequisites, 12 LEED® credits and one prerequisite remain under-researched.

In the study by Alwan et al. [9], a LEED procedure was conducted simultaneously within the design stage. Only 14 LEED credits were covered in this study, and a virtual simulation was run rather than a real-world asset case study. At the same time, Jalaei and Jrade [50] established a mechanism for unifying BIM with LEED-NC to evaluate some credits automatically. Although they demonstrated the viability of BIM and LEED integration, the expenses associated with the various materials utilised for each credit or point were not considered.

Rather than evaluating and identifying a limited number of LEED criteria, Jalaei et al. [48] proposed a methodology that allows users to consider all the criteria simultaneously to pinpoint the potential number of points that a newly constructed building needs to satisfy the specified level of certification. The proposed framework, however, was not fully automatic, as the CSV exported file format of GBS in the process did not include some earned LEED points, such as glazing, water efficiency, and monthly energy consumption; accordingly, users were required to transfer the information manually from the GBS to the plug-in.

Despite the growing attention paid to LEED, a few studies on other rating systems have been conducted. Due to its adaptability to the particular circumstances of each region, the SBTool is another popular BSA method [75]. Carvalho [20] presented a BIM-based methodological framework using an Application Programming Interface (API) within three stages to automate the assessment of 24 out of the 25 sustainability indicators of the Portuguese version of SBTool. Despite applying a wide range of software in this study, the nonexistence of a plug-in for aggregating the results is considered a serious pitfall. Later, they [19] explored the correlation between LCA and BSA within the BIM context by conducting LCA for a Portuguese case study and evaluating a set of sustainability criteria from SBTool during the process. The authors referred to some constraints, such as heterogeneous databases of BSA/LCA and the necessity of performing the process manually. Afterwards, they [21] put their previous study [20] to the test by implementing a case study in Autodesk Revit using 14 shared parameters and 13 out of 25 SBTool PT-H criteria. The need for user interference (UI) to assign the related LCIA data manually to each building element or material, and the absence of interoperability, were reported as major gaps.

The study by Veselka et al. [127] is the only one that has identified the possible application of BIM in a Hong Kong residential construction project pursuing BEAM Plus sustainable building certification. However, in this study, only 15 eligible BEAM Plus credits were grouped based on BIM features, and the other 11 credits were not included. Therefore, a more rigorous investigation was proposed to verify these 15 BEAM Plus credits based on a real case study.

As the second internationally adopted evaluation system, BREEAM comprises more than ten categories: Energy, Health and well-being, Innovation, Land Use, Materials, Management, Pollution, Transport, Waste, and Water [77]. However, no record of BIM and BREEAM integration has been found.

Jalaei and Jrade [49] merged BIM and energy analysis tools with green building certification systems based on data obtained from a small number of recognised components. The authors reported the lack of interoperability (missing information during the transformation process from the BIM tool to the energy analysis tool) and the manual data exchange process as the main issues of this study.

To evaluate the design, construction, and operation stages of green buildings, the Malaysian green building rating system, the Green Building Index (GBI), can also be utilised [120]. Despite its growing usage, only a few studies integrate GBI with BIM. Raffee et al. [96] proposed a BIM-based method to evaluate GBI criteria. However, due to the study's lack of focus on precise criteria and practical application, a verifiable methodology for assessment still needs to be provided [10].

4.2.3. Intelligent green building rating (IGBR)

To realize a real-time rating for the building design, Zhang et al. [139] suggested an intelligent green building rating (IGBR) framework supported by a semantic and social approach to realize real-time rating in building design. Autodesk BIM 360 Design and Autodesk Forge were combined in this research to create an online cloud-based collaboration environment.

4.3. Group III– BIM-aided construction waste management

The construction and demolition sector is considered one of the largest waste producers. As an ever-growing menace, waste generation needs to be managed. The contribution of BIM to construction waste management (CWM) should not be restricted to environmental issues; it has economic and social benefits. To make the studies on BIM and CWM more organized and detailed, Fig. 5 categorizes the relevant topics. Also, subsequent discussions clarify the identified clusters in this regard.

In this group, the disconnection between BIM and CWD tools can be seen strongly in the literature as a first issue. In addition, there are no IFC guidelines or MVDs that address waste management activities in BIM-based tools. As buildings always face a loss of information in the demolition phase, BIM can provide an information storage platform for primary data regarding their life cycle. To evaluate building waste, Bilal et al. [16] employed BIM models as information repositories (e.g., gross floor area and material specification). Their innovation used big data methods to predict the volume of waste generated.

CWM is viewed as a complex system that encompasses a variety of dynamic actions, such as recycling, reusing, sorting, and transporting, all of which necessitate dynamic analyses of all effective factors and their interrelationships [140]. Recent CWM studies have been conducted statically by neglecting the dynamic nature of parameters and their correlation. In addition, the current studies of BIM-based CWM are not being used as often as expected due to the lack of quantitative economic benchmarks. To tackle these gaps, Lu et al. [68] created a system dynamic (SD) model to investigate construction and demolition (C&D) waste economically, using BIM while ignoring social performance evaluation and the efficiency analysis of human resource management in BIM-based CWM. Guerra et al. [42] proposed an automated CW quantification approach based on BIM. CW estimation algorithms were established to analyse the production of concrete and drywall waste streams. This study, however, overlooked several applications associated with CW quantification, such as material flow analysis and CWM practices, including reuse, recycling, and resource efficiency.

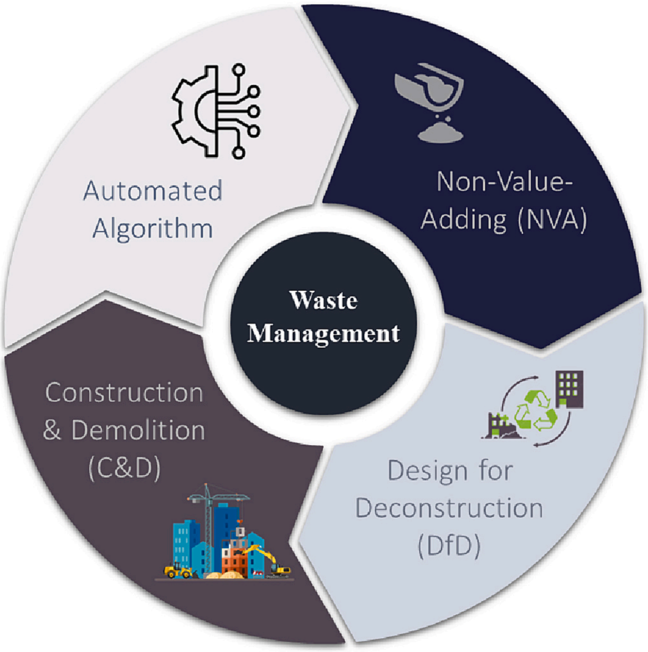

Fig. 5. Classification of reviewed findings for BIM-aided construction waste management (created by authors).

Despite the favourable outcomes of the studies mentioned above, the focus has almost been on the management of C&D waste rather than on reducing the main reasons that contribute to its generation. Jalaei et al. [52] represented the first attempt to quantify the total waste produced in the building's life cycle. The primary causes of waste were thoroughly investigated, and various waste-reduction methods were presented. However, this study did not sufficiently consider the Life-cycle cost of the recycling process. Additionally, using some simulation tools, such as Symphony and Arena, particularly in the deconstruction phase, was recommended by the authors for further studies.

Another problem that has received little, if any, attention is that of non-value-adding (NVA) BIM implementation techniques. In this respect, the study by Liao et al. [61] is the only research that has identified 38 critical NVA BIM implementation activities. Aside from extending this research to other geographical locations, future research can develop this study through a few case studies.

BIM-based EoL is a leading-edge topic in BIM-related studies with enormous potential to drive us towards more sustainable construction. The chosen EoL scenario determines the amounts and types of waste generated by a building. There are three EoL options: destruction, selective demolition, or deconstruction [5]. However, only a few studies have focused on the demolition and end-of-life phases of a building's Life-cycle.

BIM-based Design for Deconstruction (DfD) and BIM-based deconstruction are other controversial issues concerning the BIM-based EoL domain. Despite their close associations, deconstruction and DfD should be used in a different context [5]. Deconstruction is only carried out at the end of an asset's lifecycle, whereas DfD is adopted early in the design process [5]. Additionally, there needs to be more clarity in the literature regarding the appropriate data quality for a BIM-based deconstruction and BIM-based DfD [128].

Furthermore, the potential for utilizing BIM in renovation projects to achieve sustainability criteria has yet to be thoroughly investigated. For the first time, Edwards [32] concentrated on using BIM for sustainable design in renovation projects to achieve energy-efficient construction. Moreover, Okakpu et al. [83] presented empirical insights into how environmental factors could positively or negatively affect refurbishment project stakeholders for BIM adoption in the New Zealand construction sector.

4.4. Group IV– State-of-the-art topics in BIM-sustainability Nexus

This section discusses the second research question posited in the introduction, specifically inquiring into the prospective avenues for future research and identifying the most promising state-of-the-art topics within the realm of BIM-Sustainability. The classification of suggested cutting-edge topics for the BIM-Sustainability nexus is illustrated in Fig. 6, and detailed as follows:

4.4.1. BIM-GIS integration for sustainable built environments

The research on BIM-GIS integration by Wang et al. [130] provides a comprehensive examination of the current state of integration and identifies key areas for further exploration in sustainable built environments. The study emphasizes the importance of asset/facilities management, human behaviour analysis using big data, and the role of BIM in the development of digital/smart cities and the Internet of Things (IoT). This category delves into the evolving landscape of spatial information and its integration with BIM for sustainable building outcomes.

4.4.2. Sustainability in smart cities with BIM applications

This category centres on the work of Liu et al. [64] and Marrero et al. [71], investigating the application of BIM in the context of smart cities for enhanced sustainability. Liu et al. [64] explored the impact of blockchain and BIM integration, while Marrero et al. [71] presented a methodology assessing the environmental impact of urbanization processes through several ecological indicators (carbon footprint, water

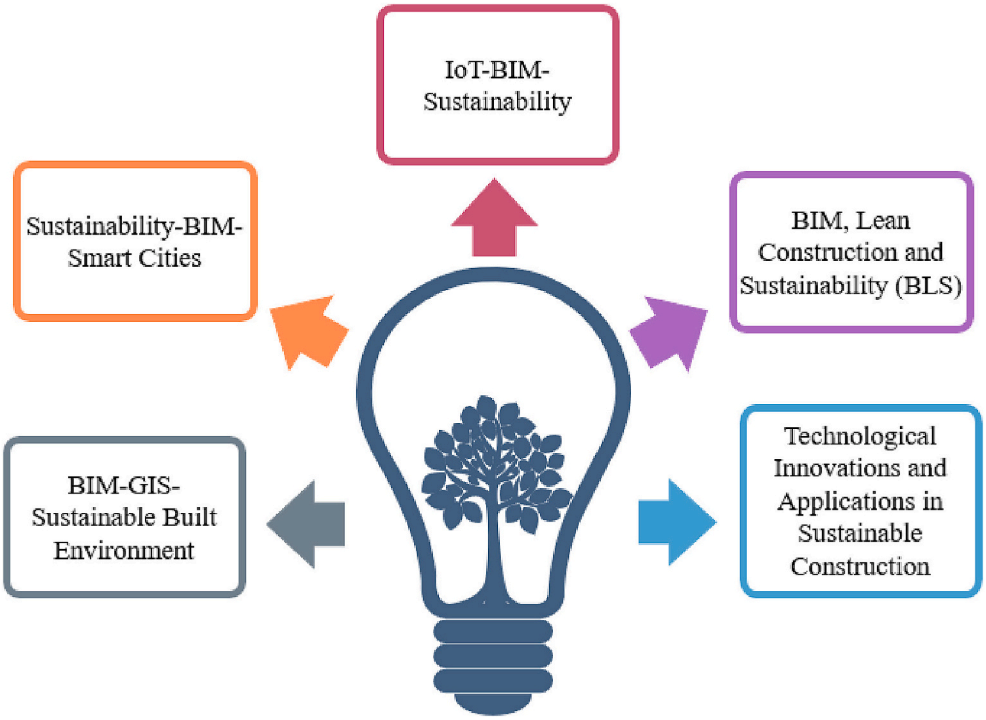

Fig. 6. Classification of reviewed findings for state-of-the-art topics in the realm of BIM-Sustainability (created by authors).

footprint, and embodied energy). A confusion gap was observed in this study, as the authors misused BIM as a “software tool”. The discussion in this section highlights the role of BIM in advancing sustainability within the broader framework of smart city development.

4.4.3. *Internet of things (IoT) integration in BIM-sustainability*

Crippa et al. [29] research focused on the potential synergy between BIM, life cycle assessment (LCA) systems, and sensors, emphasizing the integration of IoT for sustainable building practices. The discussion underscores the significance of sensors in enhancing energy consumption monitoring within the BIM framework, contributing to the ongoing discourse on IoT applications in the construction industry [110].

4.4.4. *Synergy between BIM, lean construction, and sustainability (BLS)*

The convergence of BIM, Lean construction, and sustainability represents a critical area of research in the construction industry. The work reviewed in this category emphasized waste reduction as a central theme among these three concepts [18]. To further analyse this synergy, Saieg et al. [106] carried out a systematic review of the literature. They found while waste reduction is widely acknowledged, there is a need for more practical evidence and an in-depth understanding of their integration for sustainable development in architecture, engineering, and construction (AEC). The shared critical success factors, including coordination, communication, collaboration, training, safety and health, commitment, qualified staff, and organizational culture, underscore the interconnectedness of these methodologies. Moreover, novel green construction methods, including prefabricated buildings and lean construction, can be linked to green BIM applications. Further research is required to address the application of BIM in this area [69]. This category highlights the call for in-depth research to bridge existing gaps and optimize the holistic benefits of BIM, Lean construction, and sustainability in construction practices [114–116].

4.4.5. *Technological innovations and applications in sustainable construction*

This category encompasses a spectrum of technological advancements that are shaping sustainable construction practices. Kaewunruen et al. [54] exploration of digital twin (DT) applications provided insights into risk-based maintenance and retrofit within subway stations. The authors proposed developing the algorithm using Dynamo scripts to re-update the BIM automatically as the project changes. The integration of machine learning and complex algorithms in Life Cycle Assessment (LCA) studies, as demonstrated by Naganathan et al. [79], showcased the potential for predictive modelling in operational building performance. Cloud-based Sustainable Decision Support Systems (C-SDSS), as implemented by Olawumi et al. [86], offered a digital framework for Green Building Assessments (GBAs). This study highlighted the potential of cloud-based solutions in enhancing decision-making processes for sustainable construction. A research gap exists in utilizing cloud-based common data environments (CDEs) to support sustainability assessments (GBAs) due to the inadequacy of as-built BIM models for facility (FM) or asset management (AM) purposes. Addressing this gap is vital for enhancing the practical use of BIM models in FM and AM scenarios.

Moreover, this category explores innovative procurement systems as discussed by Rosayuru et al. [103]. The focus is on BIM-based Sustainable Procurement (SP) and Integrated Project Delivery (IPD) as alternative approaches to traditional procurement concerns. This section underscores the significance of technological innovations, calling for continued research to unlock the full potential of these tools and systems in driving sustainability across the construction industry.

5. Discussion

Having examined and critically reviewed the papers in the previous sections, the following sections shed light on the discussions surrounding research questions 3 to 5.

5.1. *Technical challenges in BIM-enabled sustainability studies*

Even though BIM capabilities can contribute to mitigating technological challenges, little progress has been achieved in investigating technical issues. Therefore, this section begins with the most common issues, i.e., level of development and data exchange, followed by a summary of technical challenges and future directions.

5.1.1. *Data exchange and interoperability issues*

Despite being extensively investigated in the literature, interoperability remains one of the most challenging issues in the sustainable adoption of BIM. Therefore, developing a fully automated approach using artificial intelligence techniques is a potential future research direction to deal with the interoperability problem.

The Industry Foundation Classes (IFC) is currently the most advanced non-proprietary information exchange format for the building sector [93], followed by green building Extensible Markup Language (gbXML) as the second most prevalent data exchange platform across BIM-based tools. IFC can hold more geometrical shapes than gbXML, but when it comes to sensing information, gbXML performs better. In case of data loss, other exchange platforms, such as Open Database Connectivity (ODBC) and Construction Operations Building Information Exchange (COBie), can be utilised to enrich transmitted models [10].

According to Karan and Irizarry [56], the IFC model lacks an energy domain, and therefore, an extension should be established to facilitate green data sharing. Although gbXML is a standard format for transferring data between BIM and BPA applications, it can only record rectangular forms in geometric information [49].

As a result, researchers believe that interchange file formats (such as IFC and gbXML) are yet to be improved to address more sustainable difficulties [5,21,22]. Venugopal et al. [126] contended that the IFC schema lacked a clear definition of its entities and attributes, resulting in a confusion gap. Santos et al. [111] devised an object-oriented technique known as the MVD concept (i.e. information required for the same element but considering different contexts). However, the proposed IDM and MVD were project-specific, focusing primarily on the architectural and structural domains while neglecting MEP.

Similarly, to avoid the risk of data loss, software incompatibility, and the incompatibility of BIM data with the LCA database in BIM-LCA studies, Visual Programming Language (VPL) has recently been applied in several papers to implement LCA parametrically to overcome interoperability issues existing in other data exchange file formats (e.g., the current gbXML and IFC schema) [12,105]. Asl et al. [11] showed how BIM and VPL might be used to generate optimisation options. Utilizing the Revit API and the gbXML open schema, an analytical energy model was created from the design model, using project information, geometry data, and the thermal characteristics of construction materials (window size and material are design variables). Nevertheless, the framework was only capable of simulating energy and daylight.

Mohammed [77] attempted to address the issue of achieving the highest interoperability performance by establishing a Sustainable BIM Model within projects throughout their life-cycles. However, they did not test or check the validity of the proposed model, which needs further investigation.

5.1.2. *Level of development (LOD) challenges on BIM efficacy for sustainability assessments*

Using an inaccurate and inappropriate level of development (LOD) in the body of knowledge widens the interoperability gap. Objects must have a LOD ranging from LOD 100, the conceptual project model, to LOD 500, to indicate the amount and type of information associated with a BIM object, depending on the purpose of the BIM model [20]. The fundamental problem with BIM-Sustainability studies is that they either do not define LOD or have a low LOD, leading to erroneous findings. Except for three publications that conducted their studies at LOD 300 [24,100,137] and two additional studies that specified LOD 100 and 200 [101,138], most of the reviewed papers did not declare a LOD. To conduct a continuous LCA throughout the development of construction phases, Cavalliere et al. [24] proposed a novel method that used many databases with different LODs, corresponding to the LODs of the BIM model. Likewise, Hollberg et al. [46] stated that “allocating a fixed LOD for all building components would be impractical, and updating the LOD would be crucial throughout the Project Lifecycle”.

5.2. *Summary of technical challenges and future directions*

The literature review reveals that the BIM-sustainability nexus has been studied across diverse contexts. In Table 4, the technical challenges and prospective directions are briefly summarized and discussed.

The challenges and future directions in Table 4 outline a comprehensive roadmap for advancing Life Cycle Assessment (LCA)

Table 4
Summary of the challenges and research opportunities in building BIM-LCA studies.

No.	Technical challenges/ Limitations	Future directions	References
1	• 3D visualisations of the LCA results	• The semantic modelling of LCA results	[111,133]
2	• The lack of consistency in LCA data sources	• Use of generic environmental information /Applying different databases with different LODs	[17,90,111]
3	• Most green building certificates, such as LEED, are based on predicted performance.	• Adopting actual performance in green building certificates	[69]
4	• Absence of a widely accepted approach for assigning weights to the sustainability assessment criteria	• Establishing a globally working rating tool using a multilevel weighting scheme	[70]
5	• Lack of CDE	• A cloud-based and decentralized CDE	[86]
6	• Absence of a formal definition regarding entities and attributes of IFC schema	• An object-oriented mechanism, known as MVD, to add semantic meaning to the model views	[21,111,113]
7	• Data loss, software incompatibility, as well as incompatibility of BIM data with the LCA database	• Using VPL to overcome interoperability issues	[12,105]
8	• Absence of LOD declaration	• Performing a continuous LCA calculation and updating the LOD level	[24,100,137]
9	• LCA databases are inconsistent in terms of the variability of proposed building components and materials used in them	• Applying different databases with different LODs	[24,46]
10	• Manual data collection and matching process in dynamic Life-cycle assessment	• Using IoT and exploring data through algorithms	[122]
11	• Nonexistence of an ontology-based model for the representation and management of cultural heritage information	• Use of drones to generate as-built models	[2]
12	• The manual process of linking and re-updating critical information, such as time-dependent damages	• Development of a new algorithm using Dynamo Scripts	[54]
13	• Different functional units of material data (for example, EPDs)	• BIM tools should enable the structuring of data compatible with the functional units	[90,111]
14	• Disregard for uncertainty in the whole Life-cycle results	• The major drivers of uncertainty should be identified, and the extent to which uncertainty can be reduced should be investigated	[81,112]

methodologies in the realm of construction and environmental impact assessments. The difficulties encompass various aspects, including data consistency, the predictive nature of green building certificates, interoperability issues, and the absence of standardized approaches. To overcome these challenges, the proposed future directions are multifaceted. They include adopting semantic modelling for LCA results to enhance interpretability, using generic environmental information and different databases with varying Levels of Development (LODs) to ensure data consistency, and transitioning from predicted to actual performance in green building certificates. The incorporation of a globally accepted rating tool with a multilevel weighting scheme, cloud-based Common Data Environment (CDE), and object-oriented mechanisms like Model View Definitions (MVD) in Industry Foundation Classes (IFC) schema further strengthens the foundations of LCA. Additionally, solutions involving visual programming languages, continuous LCA calculations, and IoT-driven data collection signify a paradigm shift towards automation and real-time updates. The integration of drones for cultural heritage information, advanced algorithms for dynamic life-cycle assessments, and structured data compatible with different functional units emphasize the importance of technological innovation. Addressing uncertainty in life-cycle results by identifying major drivers and investigating reduction strategies underscores the commitment to robust and reliable assessments. Overall, this comprehensive discussion highlights the interconnectedness of these challenges and proposed solutions, emphasizing the need for a holistic and technologically advanced approach to propel the field of Life Cycle Assessment forward.

5.3. Discussing the existing gaps

As discussed in the research methodology section, this review reveals the gap-spotting categorised in three modes: confusion, neglect, and application in the BIM-sustainability nexus, as shown in Table 5.

5.3.1. Confusion spotting

According to the findings, this category comprises eight of the 98 articles. The most frequent ambiguity in the literature is between BIM as a tool and BIM as a process, recorded in four studies (Table 5). Likewise, Wu et al. [135] encountered confusion surrounding the definition of “green building,” emphasizing a need for clarity in terminologies associated with sustainable practices. Moreover, the confusion extends to Sustainable Building Design (SBD), where a lack of a common definition and divergent interpretations of a BIM-enabled SBD process prevail. This poses a substantial obstacle as SBD must be precisely defined to ensure the accurate delivery of sustainability information, as highlighted by the imperative put forth in [138].

To address these gaps, future research should focus on establishing a standardized framework for the terminology, clarifying the roles of BIM as a tool versus a process, providing a clear definition for “green building,” and establishing a consensus on the conceptualization of a BIM-enabled SBD process. Moreover, interdisciplinary collaboration between BIM experts, sustainable design professionals, and terminologists could contribute to a more cohesive and universally accepted understanding within the field.

5.3.2. Neglect spotting

The unseen realms of BIM-sustainability account for 49 records, breaking down into a 24–14 split in terms of items for overlooked and under-researched areas, respectively, and 11 publications in the “lack of empirical research” category. Reviewing the studies shows that most are focused primarily on embodied energy, with operational energy remaining under-researched in seven papers. Overlooking the costs

Table 5
Identified gaps categorised in different modes.

Gap-spotting modes	Specific versions of gap-spotting modes	Identified gaps	Reviewed journal articles
Neglect spotting	Overlooked area	• The time value of money (TVM) and discounted present value were overlooked	[6,26,51]
		• Costs associated with different materials were overlooked	[36,40,50,52,95]
		• Mechanical systems were not covered	[62,102,108,111]
		• Transportation of material to the construction site was disregarded	[23,30,46]
		• Several important BPA types were overlooked	[10,18,35,53]
		• CWM practices, including reuse, recycling, and resource efficiency use. Were overlooked	[5,42,140]
		• The social impact of using BIM was overlooked	[18,35,140]
		• Some categories of BSA credits were under-researched	[9,13,72,132]
	Under-researched	• Operational energy impact was under-researched	[13,24,70,102,112,122,124]
		• Embodied energy impact was under-researched	[13,70,79]
	Lack of empirical support	• Only the theoretical framework was provided, without a case study	[12,45–47,76,87,88,102,103,107,135]
		• Confusion between BIM as a tool and BIM as a concept	[20,54,71,99,113]
Confusion spotting	Competing explanations	• Lack of a common definition and different interpretation of a BIM-enabled SBD process	[13,36,88,99,125]
		• Lack of a clear definition of green BIM	[69,76,135]
		• Absence of the Level of Development (LOD) declaration/ very low LOD	[52,82]
		• Weak interoperability	[49,120,122]
		• Low accuracy and incomplete data	[51,129]
		• Regionally specific/using regional databases	[33,70,81,83,86,94,102]
		• Limited to specific kinds of buildings	[4,58,88]
		• Applicable only to the proposed study	[64,85,111]
		• Over-simplified cost calculation	[99]
Application spotting	Extending and complementing existing literature	• Manual data entry	[19,21,48,49,54,113,127]
		• Over-simplified energy calculation	[62,108]
		• Lack of validation/absence of reliable databases	[66,77,78,85,138]
		• Using specific types of building materials	[35,80]
		• Focusing on a few specific building components instead of on the entire building	[17]
		• Lack of consistency in data sources	[90]
		• The absence of a technique to aggregate the results from several different software	[20]

associated with different materials denotes another overlooked area of the topic, exemplified in five papers. As the third subgroup of the neglect gaps, “lack of empirical support” is the less common mode identified in 11 papers. The results of papers trapped in this category are inconclusive and more research would be required.

To bridge these gaps, future research endeavors should prioritize a more comprehensive exploration of operational energy impacts, delve into the economic considerations associated with diverse materials, and conduct empirical studies to strengthen the empirical foundation of BIM-sustainability research. This would contribute to a more holistic understanding and application of BIM principles in sustainable design processes.

5.3.3. Application spotting

In tabulating 98 records, roughly 30% of papers (36 records) are labelled with the application gap. For the most part, this mode of gap includes studies that focus on project-based outcomes but lack the general framework that could be extrapolated to other projects. Nor can the related findings of these kinds of case-specific studies be extrapolated to other projects. Additionally, it was observed that there is an insufficient number of studies on infrastructure projects with non-residential applications, such as hospitals, bridges, and commercial centres [55].

To address these gaps, future research directions should prioritize the development of comprehensive frameworks that transcend project-specific contexts. Emphasis should be placed on creating methodologies that allow for the extrapolation of findings to diverse projects, promoting a more universally applicable understanding of the implications of BIM in infrastructure projects with a focus on non-residential applications. Additionally, targeted efforts and studies should be initiated to bridge the existing research gap concerning the underrepresentation of certain types of projects in the current literature. This approach ensures a more holistic and inclusive exploration of BIM applications across various infrastructural domains.

6. Implications and future directions

This section delves into the implications derived from the extensive examination of findings in four critical domains: BIM-based Life Cycle Sustainability Assessment (LCSA), BIM for Green Buildings, BIM-aided Construction Waste Management, and state-of-the-art topics within the realm of BIM-Sustainability nexus. The focus is on making clear the key takeaways from the current state of research and providing insights into potential avenues for future investigations.

6.1. BIM-based life cycle sustainability assessment (LCSA)

This section addresses the findings and implications of the research on BIM-based Life Cycle Sustainability Assessment (LCSA) and outlines potential future directions within this domain. The integration of Life Cycle Sustainability Assessment (LCSA) into BIM represents a significant stride towards a holistic evaluation of sustainability, encompassing environmental, social, and economic dimensions, as follows.

6.1.1. BIM-based social assessment

The Social Life-Cycle Assessment (S-LCA) within LCSA emerges as an underexplored facet, primarily due to the qualitative nature of social indicators. Research within this realm has predominantly focused on indoor comfort, safety, and cultural heritage maintenance, overlooking potential contributions to broader social sustainability concerns.

Future research should delve into the development of standardized frameworks for assessing diverse social indicators within the context of construction projects. Overcoming the qualitative nature of social indicators and expanding beyond safety and comfort considerations are imperative. Furthermore, collaborative efforts should bridge the gap between BIM and S-LCA, ensuring that social sustainability is integrated seamlessly into BIM processes. Initiatives to establish comprehensive national BIM libraries, particularly focusing on cultural heritage, can significantly contribute to enhancing the social sustainability performance of residential structures.

6.1.2. BIM-based environmental assessment

The environmental dimension of LCSA, particularly Life Cycle Assessment (LCA), is the most researched aspect, with a notable emphasis on the integration of BIM-LCA. However, current research highlights challenges in Life Cycle Inventory (LCI) classification, integration approaches (conventional, static, and dynamic), and the need for full automation.

Future research should address the challenges in BIM-LCA integration by standardizing data formats, protocols, and parameters. Advancing from conventional and static approaches towards dynamic BIM-LCA integration, with a focus on real-time decision-making, is crucial. Overcoming technical barriers and developing user-friendly, interoperable BIM-LCA tools are essential steps towards achieving full automation. Exploring the potential of Dynamic Life Cycle Assessment (DLCA) augmented with advanced technologies like big data and the Internet of Things (IoT) signifies a promising avenue for future research.

6.1.3. BIM-based economic assessment

The exploration of BIM-based Economic Assessment underscores the intricate interplay between economic variables and sustainability within the construction sector. The incorporation of novel parameters like affordability, manageability, adaptability, and flexibility reflects a commendable effort to move beyond traditional cost-centric approaches. However, the existing literature reveals a somewhat fragmented understanding of economic sustainability, marked by a tendency to focus on specific facets while neglecting comprehensive indices. This limitation implies that current practices might fall short in providing a holistic economic perspective, potentially hindering informed decision-making in building projects.

Future research in the realm of BIM-based Economic Assessment should aim for a more exhaustive exploration of economic sustainability indices, moving beyond traditional Life Cycle Cost Analysis (LCCA). This involves considering a broader range of criteria, including resiliency, operation cost, maintenance cost, repair cost, and the social cost of carbon. Additionally, investigations should extend to diverse structural framing systems, ensuring a comprehensive understanding of economic sustainability across different building materials and methodologies.

Exploring the trade-off optimisation between Life Cycle Cost Analysis (LCCA) and Life Cycle Carbon Emission (LCCE) represents an uncharted territory that holds immense potential for shaping more informed decision-making processes. Integrating additional project objectives, such as energy consumption during the operation phase, will contribute to a more holistic evaluation of economic sustainability. Furthermore, addressing the interoperability challenges and developing master models that can accommodate various economic variables across different stages of construction projects will be pivotal in advancing the field.

6.2. BIM for green buildings

The findings in the realm of BIM for Green Buildings shed light on significant implications. The absence of a unified global green building rating system (GBRS) underscores the need for collaborative efforts to standardize sustainability assessments worldwide. Concerns about the accuracy of BIM-based certifications, particularly in the context of predicted rather than actual performance, highlight the importance of refining assessment methodologies. Additionally, the identification of under-researched LEED credits signifies specific areas within green building certification that warrant dedicated investigation.

Global collaboration is essential to establish a universally accepted GBRS, minimizing regional variations and enhancing the applicability of

BIM in diverse contexts. Research on underexplored LEED credits is needed to ensure a comprehensive understanding of various aspects of sustainable building design and construction.

6.3. *BIM-aided construction waste management*

The investigation of BIM-aided Construction Waste Management (CWM) has significant implications. The disconnection between BIM and CWM tools emphasizes the challenges in achieving seamless integration, highlighting the necessity for interoperability standards and improved data exchange processes. Furthermore, the limited attention to demolition and end-of-life (EoL) phases indicates a potential gap in understanding and managing the entire life cycle of a building, including sustainable deconstruction practices.

Future research should prioritize enhancing the integration of BIM with CWM tools, addressing interoperability issues and streamlining data exchange processes. Additionally, comprehensive investigations into waste management throughout the entire life cycle, including EoL phases, are essential to develop sustainable practices for building deconstruction and minimizing construction waste generation.

6.4. *State-of-the-art topics*

The examination of state-of-the-art topics reveals critical implications for the future of BIM-sustainability integration. The exploration of emerging technologies, such as BIM-GIS integration, IoT, Digital Twins, and Machine Learning in LCA, underscores the importance of integrating these innovations for advanced and accurate sustainability assessments. The identification of shared critical success factors among BIM, Lean Construction, and Sustainability (BLS) highlights the need for interdisciplinary research, addressing common challenges and maximizing synergies. Additionally, the emphasis on organizational elements and the need for effective workflow management suggests that future research should address not only technological advancements but also organizational and procedural challenges in sustainable construction.

Future research should concentrate on the holistic integration of emerging technologies to enhance sustainability assessments and decision-making processes. Investigating organizational adaptation strategies will be crucial to facilitate the successful adoption of BIM for sustainable construction, addressing challenges related to project delivery, procurement, and stakeholder collaboration.

7. Conclusions

Scientific contributions to BIM-sustainability integration have gained momentum in recent years due to the influential role of BIM as a well-accepted approach for sustainable construction practices. As a result, some systematic reviews and content analysis research have been conducted in line with BIM uses in sustainable construction. As opposed to previous reviews, in this paper keyword combination was broadened, and critical insight was given into synergies between BIM and sustainability. This work's novelty lies in giving a holistic understanding of dismissed issues and a thorough review of all aspects of synergy between BIM and sustainability.

This work has contributed to the corpus of knowledge on BIM and sustainable integration by critically reviewing 98 journal papers. Unlike earlier review papers in this area, the current study went beyond the environmental pillar of sustainability by considering the social and economic dimensions. To conduct a critical analysis of the body of knowledge, the selected articles were categorised into four major groups, namely: (i) BIM-based Life-Cycle Sustainability Assessment (LCSA); (ii) BIM for green buildings; (iii) BIM-aided construction waste management; (iv) state-of-the-art topics.

While the first category (BIM-based LCSA) accounted for over a third of the papers (32 out of 98), the third group (BIM-aided construction waste management) was the less-talked-about domain with just seven papers. Based on the literature review, whereas the BIM-LCA and BIM-LCC have received the most attention, S-LCA has mainly remained under-researched. Furthermore, the study depicted 14 state-of-the-art sustainable BIM adoption papers. Future research needs to shed light on the state-of-the-art subject discussed in Section 4 and strive to bridge the gaps highlighted in this study. Possible research directions are summarized in Table 2. Despite research efforts in "BIM-GBRS" synergy, investigations in these areas have mostly been limited to LEED certification. Future studies can also go far beyond LEED by demonstrating the assessment of other GBRS, such as BREEAM and BEAM Plus.

The detected gaps were tabulated at the end of the study to provide a solid foundation for spotting areas that should be investigated further. The unseen realm of gap spotting was the most prevalent model in the literature, accounting for 49 records among the total papers. In this regard, 24 papers lacked a certain emphasis and indicated an overlooked gap, and there were 14 and 11 gaps respectively in the "under-researched" and "lack of empirical study" categories.

In addition, it was observed that BIM-sustainability integration has been mostly addressed for construction projects and rarely implemented in infrastructure projects. This is problematic since the detrimental impacts of infrastructure projects on the built environment are considerable.

In this study, conference papers were disregarded, and descriptive trends (such as the annual and regional distribution of the publications) were also overlooked. As a result, scientometric and informatic analysis can be thoroughly carried out in future studies. In addition, the query was restricted to certain journals, leading to a smaller number of results.

While BIM is widely recognised as a suitable digitised representation of the physical building, this paper concludes that there is still a long way to go before it fulfils its potential. For instance, although much progress has been made in automating the exchange process, the integration method has still not been entirely automated, indicating the absence of a common and comprehensive framework to improve interoperability. In this regard, many BIM applications suffer from low visualisation. As a result, future research into visualisation and semantic interoperability is required. Furthermore, while COBIE and ODBC — for transferring and maintaining diverse types of data — have received minimal attention in peer-reviewed papers, a future study can be expanded beyond IFC and gbXML to address some of the data-interoperability difficulties.

CRediT authorship contribution statement

Moslem Sheikhkhoshkar: Writing – original draft, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Farzad Pour Rahimian:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Hind Bril El Haouzi:** Writing – review & editing, Methodology. **Mina Najafi:** Writing – review & editing, Methodology, Conceptualization. **Saeed Talebi:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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