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Review article

Green buildings and digital technologies: A pathway to sustainable development

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ABSTRACT

Digital technologies have the potential to enhance the performance of green buildings to address climate change impacts. Therefore, this study explores the nexus between green buildings and digital technologies, which is a crucial point that has the potential to reshape the field of sustainable development. This examination is done with the utilization of bibliometric analysis and qualitative systematic approach. This review aims to conduct a thorough analysis of green buildings and digital technologies for a sustainable future, with a focus on the integration of digital technologies, associated challenges and solutions, key research techniques, knowledge gaps, and future research directions within the realm of green buildings. To do this, a bibliometric analysis was initially conducted after retrieving 135 articles from the Scopus database. Next, a qualitative systematic approach was conducted. In addition, five challenges and technological solutions were identified; (i) high initial costs, (ii) limited availability of sustainable materials, (iii) energy inefficiency and performance variability, (iv) regulatory compliance and certification requirements, and (v) waste management and recycling. Key research techniques were identified (i) simulation and modeling, (ii) decision-making techniques and (iii) surveys and interviews (qualitative and quantitative techniques). This review study offers both theoretical and practical contributions to the current research on green buildings and digital technologies, with the aim of improving sustainability. Theoretically, this review study strengthens the body of knowledge by integrating sustainable practices with advanced digital technologies, hence improving energy efficiency and sustainability. It provides practical insights for researchers, practitioners, and policymakers to implement digital technologies in construction projects, promoting sustainable designs. These insights can assist researchers in refining technology-driven sustainability models, guide practitioners in implementing these solutions more effectively, and enable policymakers to craft regulations that promote innovation and environmental stewardship in the sector.

1. Introduction

The building sector is a primary contributor to climate change. Buildings in the US, for instance, consume 70% of the US electricity and release over 30% of the US greenhouse gas emissions [1]. To enhance energy efficiency, some countries have introduced green building rating systems, such as the US LEED and UK BREEAM [2]. Green buildings are designed, built, and operated in a manner that diminishes or eradicates adverse effects on the environment and occupants. They minimize energy and water consumption while maximizing resource efficiency, occupants' health and well-being, and carbon neutrality [3]. The increasing global concerns about the impacts of climate change and resource depletion, have driven a need for the advancement of green building. Thus, the integration of green buildings and digital technologies has become a viable way to promote sustainability in the built environment in recent years [4].

Green buildings have attracted considerable attention from researchers and professionals worldwide, leading to an increase in empirical studies on the topic [5–8]. Furthermore, there are exist numerous review studies concerning green buildings that specifically examine digital technologies, such as building information modeling (BIM) [9–12] artificial intelligence (AI) [13,14] blockchain [15,16] machine learning (ML) [17,18] digital twin (DT) [19] and the Internet of Things (IoT) [20]. However, there is a paucity of comprehensive studies on green buildings-digital technologies integration (GBs-DTs integration) that include all digital technologies under one umbrella. The current study is required as the construction and building sectors seek novel

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Table 1
Summary of reviews on green buildings and digital technologies.

Sr.	Research methodology	Technologies	Description/Limitation	Timespan	Source
1	Literature review	BIM	Concept of Green BIM	1999–2016	[9]
2.	Bibliometric analysis	AI	Provide a comprehensive analysis with the help of bibliometric analysis of the publication productivity in the subject, including the most impactful papers and the major players involved such as authors, research centers, and countries.	2002–2020	[22]
3.	Systematic literature review	Sensors, BIM, Building Management Systems (BMS), smart meters, 3D printing/additive manufacturing, robotics, big data analytics, IoT, ML, AL, digital twin, blockchain, and cyber security	Conducted a systematic literature review to analyze the present state of applications in the building lifecycle.	2013–2023	[21]
4.	Quantitative and qualitative systematicanalysis	AI	This work consolidates AI knowledge in green building. It analyzes the current research in this field to find ways to improve the sustainability and efficiency of the architecture, engineering, and construction (AEC) sector.	2002–2021	[13]
5.	Comprehensive literature review	Computer simulation and optimization	The current state of simulation optimization for energy-efficient green buildings and the developments that are expected to emerge in the future	1999–2019	[23]
6.	Qualitative analysis	AI-IoT	The integration of AI and IoT greatly enhances energy savings, improves the performance of buildings, and promotes to environmental sustainability.	2023	[24]
7.	Literature review	IoT	Examining the utilization of Internet of Things in the advancement of smart buildings	2018	[20]
8.	Literature review	Digital twins	Integrating green metrics and digital twins for sustainable planning and governance of intelligent buildings and urban areas	2022	[25]
9.	Systematic literature review	BIM	Addressed current AEC industry concerns such sustainable buildings BIM, interoperability, and their intersection.	2006 to mid-2018	[26]
10.	Systematic literature review	BIM	BIM-sustainability nexus	Not-specified	[27]

approaches to enhance sustainability and tackle the challenges posed by climate change consequences. While existing reviews are useful, they have primarily depended on qualitative assessments of the literature that were completed manually. This approach is prone to problems such as inconsistency, bias, and prejudice, which ultimately reduce the reliability of the findings. For example, a recent review conducted by Asif et al. [21] examined the digitalization of sustainable buildings, but solely used a qualitative method. In addition, existing reviews focus on individual uses of BIM, AI, DT, blockchain, ML and IoT in the context of green buildings. This gap in the literature hinders the ability to inform future research and improve sustainability practices in the building and construction sectors. This synthesis would not only enhance sustainability, but it would also encourage the adoption of digital technologies by tapping their untapped potential in green buildings.

To fill this gap, this study aims to conduct a thorough examination of current literature on GBs-DTs integration. The study addresses three research questions:

(1) Explain the overview of integration of digital technologies in context of sustainability of green buildings.
(2) What are the challenges and technological solutions associated with green buildings?
(3) What are the key research techniques utilized to enhance sustainability in green buildings?

2. Previous work

To identify and address the gaps in the current literature, this section examines previous reviews conducted on GBs-DTs integration. Table 1 summarizes such reviews.

Table 1 shows that existing reviews have limitations. Rodríguez-Gracia et al. [22] reviewed the AI techniques in green buildings by using bibliometric analysis. Furthermore, a qualitative analysis was undertaken by Umoh et al. [24] to investigate the integration of AI-IoT in sustainable building design. Similarly, Debrah et al. [13] examined the utilization of AI in the AEC industry through quantitative and qualitative analyses. Asif et al. 2024 [21] investigated the contribution of digitalization to sustainable buildings through a systematic literature review. These reviews primarily utilize the systematic literature review or bibliometric analysis approach. Therefore, there is a lack of comprehensive study that incorporates a "mixed- methods review", which combines a qualitative review (known as systematic approach) with a quantitative review (known as a bibliometric approach). None of the studies have conducted a comprehensive examination of the nexus between green buildings and digital technologies to promote the sustainability in future. Furthermore, digitization is advancing rapidly in both technology solutions and applications within the building and construction sectors. Given the broader patterns of digitization, it is imperative to carefully assess the capabilities of digital technologies in the construction and building sectors. Gaining a comprehensive understanding of how to effectively utilize current and emerging digital technologies over the entire lifespan of a building is essential for improving the sustainability of buildings.

3. Research methodology

In literature, various studies adopt either quantitative analysis or qualitative analysis. However, there are various limitations to use quantitative and qualitative analysis. Qualitative analysis entails the act of interpreting and making subjective judgments, which can potentially add bias into the review process. The interpretation of data

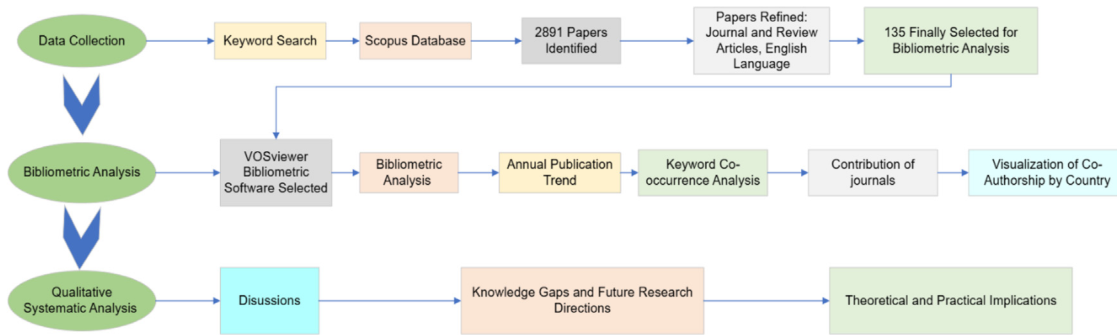

Fig. 1. Research methodology overview.

and findings can be influenced by the personal viewpoints, experiences, and prejudices of researchers. Qualitative findings are dependent on the particular context and may not be generalizable beyond the unique instances or conditions that were studied [28]. The comprehensive scope of qualitative research may lead to restricted applicability to different people or circumstances. On the other hand, quantitative study, frequently depend significantly on bibliometric measures, such as citation counts, impact factors, and publication counts. Although these metrics offer unbiased indicators of research output and influence, they might not encompass the complete spectrum of research excellence or importance. Bibliometric analyses are prone to publication bias, which refers to the tendency for some types of research or discoveries to have a higher likelihood of being published or cited than others [29]. This bias has the potential to alter the portrayal of study patterns and misrepresent the interpretation of results. To overcome this limitation, this study adopted a "mixed-methods review" which combines a qualitative review with a quantitative review. Mixed-methods review offer the benefit of enhancing comprehension of the research environment through the integration of qualitative and quantitative methods. Qualitative analysis allows for a thorough examination of themes, concepts, and contexts, while quantitative analysis yields numerical data on publication patterns, citations, and influence [30]. Moreover, the "mixed-methods review" provides researchers with the ability to adjust their strategy according to the study topic, objectives, and available resources, thereby offering flexibility. By combining both approaches, the review process is improved in terms of its accuracy and consistency [31].

3.1. Data collection

This study used data from Scopus rather than other databases such as Google Scholar and the Web of Science. This is justified by the fact that Scopus has a wide array of academic publications, conference proceedings, and other scholarly literature across multiple fields [32,33]. Furthermore, it has been widely accepted in previous studies [13,14,34–36]. In addition, Scopus incorporates content from esteemed publishers and scholarly sources, guaranteeing the excellence and reliability of the data [37]. The Scopus bibliographic data was retrieved using the keywords and the Boolean operators "OR" and "AND". The following keywords were used for the literature search, with the query string being: "Green building*" OR "Sustainable building*" OR "Green construction" OR "Green technology" OR "Sustainable building*" OR "Sustainable construction" AND "Digital technology*".

To create a comprehensive dataset, searches were performed in Scopus using phrases extracted from the title, abstract, and keywords sections of papers. The search yielded 2,891 articles as of July 2024. The study focused on journal articles, omitting conference papers, book chapters, and brief surveys. This is because articles generally exhibit superior quality owing to their rigorous peer-review process [38]. This study focused exclusively on peer-reviewed journal articles indexed in reputable database such as Scopus to ensure the inclusion of high-quality, methodologically sound, and widely recognized research [32,39–43]. Conference papers and book chapters were excluded as they often undergo less rigorous peer review, offer limited methodological transparency, and may not consistently meet the inclusion standards required for systematic academic analysis [13,44,45]. Furthermore, inclusion and exclusion criteria were applied. The inclusion criteria focused on peer-reviewed journal articles that directly addressed the intersection of digital technologies and sustainability in the construction sector. Exclusion criteria involved eliminating articles that were not written in English, did not fall under the subject field of engineering, did not expressly discuss green buildings and digital technologies, lacked full-text access, and did not provide clear implications for digital adoption or sustainable practices. A total of 420 articles were identified for additional abstract screening. Abstracts of these articles were appraised in a concise manner. If the abstracts were insufficient in providing necessary information, the contents of the chosen papers were meticulously scrutinized. After applying the screening techniques, a total of 135 articles were identified as suitable for additional analysis. Fig. 1 shows an overview of the research methodology.

The Fig. 1 illustrates the methodological framework used in this study, which consists of three main phases: data collection, bibliometric analysis, and qualitative systematic analysis. During the data collection phase, a detailed keyword search was performed in the Scopus database. During the bibliometric analysis phase, VOSviewer software was used to perform a variety of analyses, including annual publication trends, keyword co-occurrence, journal contributions, and co-authorship visualization by country. These analyses provided insights into the evolution of the field, core research clusters, and influential sources and networks. In final phase, qualitative systematic analysis, involved in-depth discussions to extract qualitative insights, identify knowledge gaps and future research directions, and outline theoretical and practical implications.

3.1.1. Bibliometric analysis

Multiple bibliometric analysis tools are accessible, including Gephi, CiteSpace, and VOSviewer. In this study, VOSviewer was used because it enables researchers to generate visual depictions of bibliometric networks, including networks that show co-authorship, co-citation, and keyword co-occurrence. These visualizations offer valuable insights into the organization and connections within a research subject, making it easier to access and analyze knowledge [46]. In addition, VOSviewer can be used to analyze bibliometric networks and effectively discover developing research trends, key topics and prominent areas of interest within a specific discipline. VOSviewer was used to analyze the bibliometric indicators such as keywords co-occurrence analysis, prominent journals and co-authorship. This can assist researchers in remaining informed about the most recent advancements and determining which topics to target for additional exploration. Moreover, previous studies also adopted VOSviewer for bibliometrics analysis [47]. In bibliometric analysis, setting a minimum citation threshold is essential to ensure that

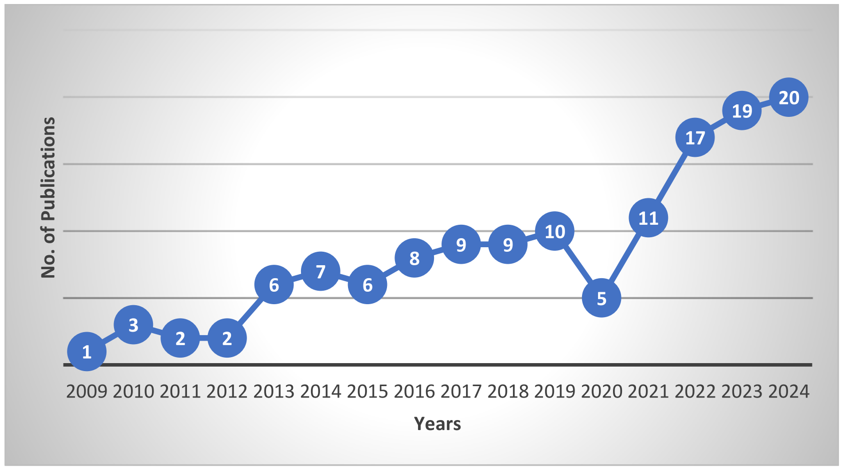

Fig. 2. Number of publications.

only the most influential or frequently occurring item such as keywords, authors, or publications are included in the visualization. This threshold filters out less significant data and improving clarity. For instance, a threshold of five citations means only documents or terms cited at least five times are visualized, helping focus the analysis on well-established or widely recognized contributions within the field. This approach enhances the reliability and interpretability of the network by highlighting meaningful relationships among key research themes [48].

In addition, the clustering related items based on their co-occurrence or citation patterns. Each cluster typically represents a thematic area or research trend, visually distinguished by different colors. This allows researchers to identify and analyze major intellectual structures and emerging areas within the discipline. In tools like VOSviewer, this method is automatically applied, offering an intuitive, data-driven map of the research landscape that aids in understanding how topics are interconnected across a body of literature [49].

3.1.2. Qualitative systematic analysis

Furthermore, following the bibliometric analysis conducted in step 2, a qualitative study was carried out on a specific group of publications utilizing the qualitative analysis technique. While bibliometric analysis is valuable, but it is insufficient for a thorough understanding of the subject matter. In this study, a qualitative systematic analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. PRISMA provides a structured approach that enhances the transparency, rigor, and reproducibility of systematic reviews [50]. The review process began with the identification of 2,891 articles through comprehensive searches in major academic database such as Scopus. The initial pool was screened based on predefined inclusion and exclusion criteria, including relevance to digital technologies and sustainability, peer-reviewed journal publication, and empirical contributions, non-English articles, conference papers, and book chapters were removed during the screening phase. After assessing titles, abstracts, and full texts, 135 articles were deemed eligible for detailed qualitative analysis. Qualitative insights were extracted using thematic analysis, whereby each selected paper was systematically reviewed to identify recurring themes, patterns, and concepts related to the adoption of digital technologies and sustainability practices. Key information such as study objectives, methods, findings, and implications were coded manually and grouped under thematic categories to enable cross-comparison and synthesis. The PRISMA guidelines ensured a systematic approach to article selection, minimized bias, and allowed for a clear presentation of the review process [51]. This methodological rigor provides confidence in the findings and strengthens the value of the synthesized insights for researchers, practitioners, and policymakers aiming to foster digital technology adoption and sustainability in the construction sector. The systematic analysis is comprehensively discussed in Section 5.

4. Analysis and results

4.1. Annual publication trend

Fig. 2 illustrates the rapid expansion of the implementation of digital technologies in green buildings to promote sustainability in the built environment. In 2020, there was a decrease in the number of publications, which can be attributed to the potential impact of the Covid-19 pandemic. Nevertheless, the number of publications experienced a steady increase in 2021 and subsequent years. Fig. 2 demonstrates the increasing prominence of digital technologies in green buildings, which present significant opportunities for progress in the built environment. Moreover, it is crucial to mention that the overall quantity of publications in 2024 includes the period until July, when the literature searches were carried out. Even in the first few months of 2024, the number of publications on digital technologies and green buildings increased, most likely reflecting a combination of evolving goals and global trends. In the wake of international agreements such as the Paris Agreement, there is increasing pressure to reduce carbon emissions in all areas, including urban development and buildings [52]. To help reach these objectives, experts are focusing on green building strategies, which could explain the increase in relevant publications in 2024.

4.2. Main research areas: keywords co-occurrence analysis

Table 2 presents the top 40 keywords together with their co-occurrences and total link strengths. These findings indicate that these terms have attracted considerable interest and are closely associated with other keywords. The following keywords represent the predominant research fields that center around green buildings and digital technologies.

In Table 2, total link strength represents the aggregate strength of all connections a keyword has with other keywords inside the bibliometric network. In co-occurrence analysis, a connection is formed between two keywords when they appear together in the same publication. The greater the frequency of co-occurrence of two keywords across several papers, the stronger the association between them, resulting in an increased link strength. The present study calculates overall link strength using VOSviewer, based on the frequency of co-occurrences between a keyword and all other keywords in the dataset.

The bibliographic technique was employed to ascertain the main areas of study in the subject matter through keyword analysis. Author keywords are widely regarded as the most efficient means of finding the main research areas within a particular discipline [53]. The VOSviewer software was utilized to construct a network that represents

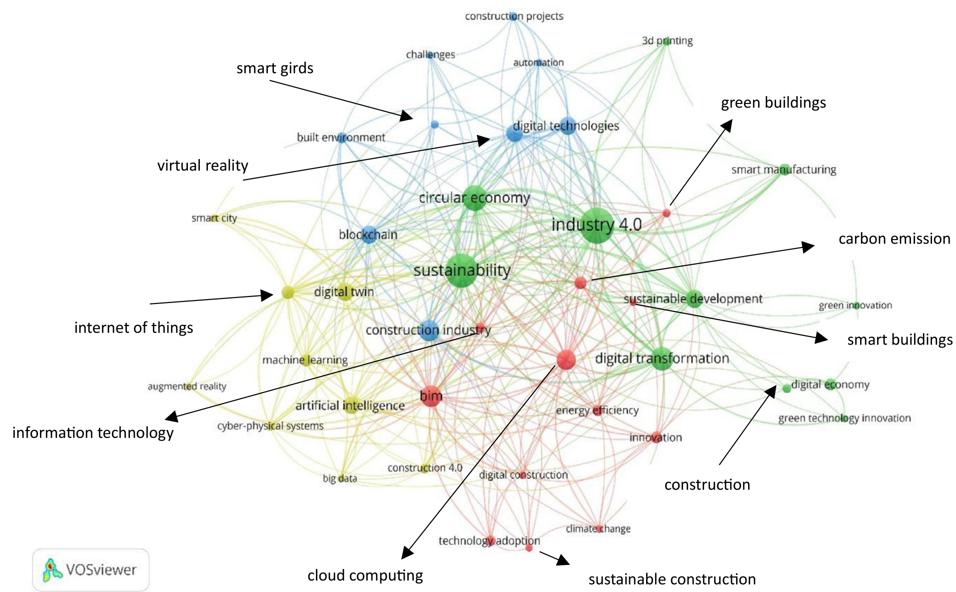

Fig. 3. Main research areas: keywords co-occurrence analysis.

Table 2
Top 40 primary research areas related to green buildings and digital technologies.

Keyword	Occurrence	Total link strength
Industry 4.0	143	25
Sustainability	109	31
BIM	88	23
Circular economy	59	27
Construction industry	56	20
Digital transformation	55	24
Construction	54	23
Cloud computing	51	25
Internet of things	50	19
Sustainable development	49	24
Blockchain	49	19
Digital twin	47	21
Artificial intelligence	44	22
Digital technologies	43	15
Built environment	39	20
Augmented reality	32	17
Machine learning	30	16
Construction 4.0	25	13
Cyber–physical systems	23	14
Sustainable construction	23	15
Smart manufacturing	23	10
Big data	20	15
Automation	20	12
Smart grids	19	11
Virtual reality	18	13
Innovation	18	13
Energy efficiency	18	13
Smart city	15	11
Digital construction	14	10
Smart buildings	14	11
Green buildings	12	09
Challenges	12	08
Climate change	11	09
3D Printing	10	08
Construction projects	10	06
Digital economy	09	05
Carbon emissions	08	05
Information technology	08	08
Green technology Innovation	07	04
Green innovation	05	05

the co-occurrence of keywords, with a focus on author keywords. The intensities or weights of the connections between network nodes can be determined by observing the thickness of the edges, which represent the interactions between keywords. The data presented in Fig. 3 demonstrates a clear association between the widths of nodes and the frequency of keywords usage in the literature. The proximity of the nodes implies a robust correlation between them.

As mentioned earlier, the subject of green buildings and digital technologies have been given limited consideration, as indicated by the Scopus search, which yielded just 135 pertinent papers. Given the increasing emphasis on decreasing energy consumption and addressing climate change, green construction approaches have become indispensable. Digital technologies provide novel methods to optimize energy use in buildings, in line with sustainability goals. The swift progress of digital technologies, has facilitated the creation of intelligent building solutions. These technologies offer novel possibilities for monitoring, regulating, and enhancing building systems to attain elevated levels of energy efficiency and sustainability. Fig. 3 displays the network that was produced. Based on the information provided in Fig. 3, four clusters have been identified. These clusters can be characterized as follows:

4.2.1. Industry 4.0 integrated cluster (green color)

In this cluster industry 4.0 is integrated with circular economy, sustainability, sustainable development, digital transformation, green innovation, digital economy, 3d printing, smart manufacturing, green technology innovation and construction. Industry 4.0, also known as the “Fourth Industrial Revolution” support the shift towards a circular economy by promoting resource efficiency, minimizing waste, and managing the entire lifecycle of buildings. Digital platforms have the capability to monitor and enhance the movement of materials, facilitate the process of remanufacturing and recycling building materials, and enable the implementation of collaborative consumption models [54]. Industry 4.0 fosters sustainability through the optimization of energy and resource utilization, the reduction of environmental impact, and the enhancement of operational efficiency. In addition, smart sensors, IoT devices, and data analytics facilitate the continuous monitoring and management of energy usage, emissions, and waste production in real-time [55]. Industry 4.0 promotes sustainable development through the stimulation of innovation, economic expansion, and social advancement, while simultaneously reducing adverse environmental impacts [56]. Moreover, digital technologies facilitate the implementation of sustainable practices in various industries, including renewable energy production, sustainable agriculture, and smart cities. Industry 4.0 signifies the digitization of manufacturing and other industries by using automation, AI, robotics, and data analytics. This change enhances productivity, flexibility, and competitiveness while facilitating the adoption of more sustainable and resilient building models [57].

Furthermore, industry 4.0 fosters ecological innovation by facilitating the creation of environmentally-friendly products, procedures, and services. Advanced manufacturing technologies, including 3D printing, additive manufacturing, and digital twins, facilitate eco-design, lightweighting, and materials innovation, hence minimizing the environmental footprint [58]. Industry 4.0 plays a crucial role in advancing the digital economy by generating fresh prospects for generating value, fostering entrepreneurship, and stimulating job expansion. Digital platforms, e-commerce, and online markets facilitate effective allocation of resources, collaboration, and innovation in the areas of green and circular economy [59]. Industry 4.0, such as 3D printing or additive manufacturing, transform conventional manufacturing methods by allowing for production as needed, customization, and minimizing waste. 3D printing facilitates the implementation of sustainable design principles, enhances material efficiency, and enables the use of dispersed manufacturing models [60]. In addition, industry 4.0 facilitates the rapid advancement of green technology innovation through the provision of sophisticated tools and methodologies for the purposes of research, development, and commercialization. Emerging technologies, such as renewable energy systems, energy storage, and smart grids, utilize digitalization and automation to improve efficiency and performance in building and construction sector [61].

4.2.2. Digital twin integrated cluster (yellow color)

Digital twin (DT) plays a crucial role in combining different advanced concepts and technologies in green buildings, such as smart cities, IoT, AI, ML, AR, cyber–physical systems, big data, and construction 4.0. DT offers a virtual duplicate of urban environments, enabling city planners and officials to simulate and optimize several areas of city operations, such as transportation, energy distribution, waste management, and public services. Cities may enhance efficiency, sustainability, and livability by incorporating IoT data and real-time analytics into digital twins, enabling data-driven decision-making [62]. In addition, IoT-enabled DT facilitate proactive maintenance, energy optimization, and improved services in smart cities and green buildings. On the other hand, AI and ML techniques are utilized to analyze DT data in order to detect patterns, forecast results, and enhance performance. AI-powered DT can optimize several aspects of the built environment, such as energy usage, building operations and performance, by analyzing large datasets from IoT sensors and other digital sources. In addition, AR enhances the visualization and interaction with DT by overlaying virtual information onto the physical environment [63]. Moreover, CPS-enabled DT facilitate real-time monitoring, control, and optimization of physical assets and processes by combining sensor data, control systems, and simulation building models.

Furthermore, DT is essential in construction 4.0 as it digitize the complete lifespan of construction projects, encompassing design, planning, construction, and operations. BIM models function as digital replicas of buildings and infrastructure, facilitating collaborative design, clash detection, prefabrication, and construction sequencing to improve efficiency and quality [64]. DT enhance the design, construction, and management of green buildings by optimizing energy efficiency, improving indoor air quality, and ensuring occupant satisfaction. Building energy models function as computer replicas that replicate energy consumption, natural illumination, and thermal satisfaction to guide design choices and operating approaches for green buildings [65,66]. In addition, by integrating DT with these cutting-edge ideas and technologies, construction industry can develop more intelligent, streamlined, and environmentally-friendly urban areas, structures, and infrastructure for the coming years to promote sustainability.

4.2.3. BIM integrated cluster (red color)

BIM is integrated with cloud computing, digital construction, technology adoption, climate change, innovation, energy efficiency, sustainable construction, smart buildings, carbon emission, green buildings and information technology. Smart or intelligent buildings have a greater focus on information technology (IT) rather than green buildings. Smart or intelligent buildings are characterized by the integration and automation of facilities and systems such as air conditioning, lighting, electricity, and stability. This integration and automation aim to enhance energy efficiency, comfort, and security within the building [67]. Smart buildings effectively integrate building management and IT technologies to dynamically enhance system performance and streamline facility operations. In addition, with the utilization of digital construction is essential in the progression of green buildings towards smart buildings as it facilitates efficiency, sustainability, and innovation over the whole lifespan of the building. BIM, a sort of digital construction technology, aids architects and engineers in developing environmentally friendly building designs that are both highly efficient and sustainable [68]. BIM facilitates the modeling of energy performance, daylighting, and thermal comfort, empowering designers to enhance building layouts, materials, and systems to achieve optimal energy efficiency and environmental sustainability [69]. Furthermore, with the utilization of digital construction technologies optimize the construction process, resulting in less waste, cost, and environmental footprint. Technological advancements like as 3D modeling, prefabrication, and robots enhance the precision, efficiency, and excellence of building, while simultaneously reducing material waste and resource usage. Digital construction improves the overall sustainability of building projects by optimizing construction operations and logistics [70].

Furthermore, integrated sensors, smart meters, and energy management systems collect and analyze data on energy consumption, indoor environmental conditions, and occupant behavior. This enables building operators to optimize system performance and configurations to achieve optimal efficiency and comfort. Digital construction forms the basis for incorporating intelligent building systems and technologies that improve sustainability and the experience of occupants. Smart sensors, IoT devices, and building automation systems establish connections between various building systems, facilitating the continuous monitoring, control, and optimization of energy consumption, lighting, HVAC, and other operations in real-time [71,72].

4.2.4. Construction industry integrated cluster (blue color)

In this cluster construction industry is integrated with blockchain, smart grids, VR, automation, digital technologies, construction projects, challenges and built environment. The integration of blockchain technology into several advancements in the construction industry establishes a dynamic ecosystem that tackles challenges and transforms the built environment. Blockchain technology improves transparency, security, and efficiency in the construction industry by offering a decentralized and tamper-proof ledger for recording transactions, contracts, and project data. It aids in the optimization of payment procedures, monitoring the origin of materials, and confirming project milestones, hence decreasing conflicts and enhancing confidence among those involved [73]. In addition, smart grid technology enhances the efficiency of energy distribution and usage in buildings by incorporating renewable energy sources, energy storage systems, and demand-side control technologies. On the other hand, VR technology facilitates the creation of immersive visualizations and simulations for building projects, providing stakeholders with the opportunity to engage with and explore virtual environments prior to the commencement of construction [74].

Furthermore, automation technologies, such as robotics, drones, and autonomous vehicles, improve efficiency, safety, and quality in building projects. Blockchain technology can enhance the security of supply chain transactions, streamline payment processing, and validate equipment maintenance records. This allows for the smooth integration of automation technologies into construction workflows [75,76]. The

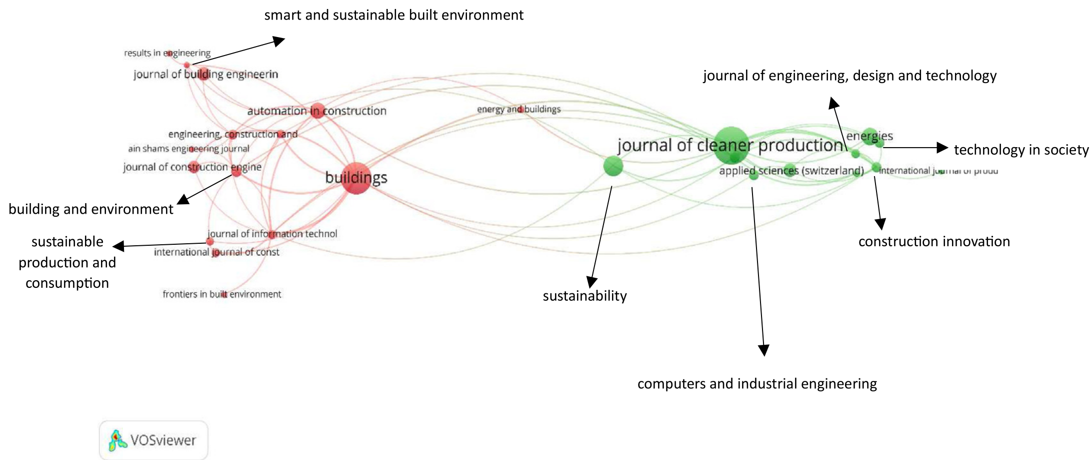

Fig. 4. Visualization of prominent journals for research in green buildings and digital technologies.

Table 3
Contribution of journals.

Source title	Number of studies	Total citations	Average year published
Journal of cleaner production	23	221	2023
Buildings	19	140	2019
Sustainability (Switzerland)	15	87	2022
Energies	13	72	2021
Automation in construction	11	50	2022

construction industry encounters a multitude of challenges, including cost overruns, timetable delays, and quality difficulties. Nevertheless, these challenges can be alleviated by integrating digital technologies to minimize hazards, enhance project transparency, and foster collaboration in building projects through the augmentation of transparency, responsibility, and confidence among project stakeholders. Furthermore, blockchain-based solutions facilitate the adoption of sustainable construction methods, energy-saving strategies, and intelligent urban development projects, resulting in the creation of healthier, more habitable, and eco-friendly urban environments [77].

4.3. Prominent journals

A notable publication is important since it serves as a platform for researchers, academics, and practitioners to share their findings, advancements, and viewpoints in the fields of green buildings and digital technologies. Dissemination of knowledge is crucial for the advancement and development of green buildings. Green buildings are essential in addressing environmental concerns such as climate change and resource depletion. A renowned research publication in this domain advocates for the dissemination of innovative strategies, technological advances, and best practices for the development, construction, and management of sustainable buildings. To aid researchers, academics, and practitioners in the field of green buildings in implementing digital technologies, the top five journals were identified. It is shown in Table 3 that *"Journal of cleaner production"* got the highest number of citations, followed by "*Buildings", "Sustainability (Switzerland)", "Energies", and "Automation in construction"*. This is because of the scope of *"Journal of cleaner production"* that covers a broad range of topics pertaining to sustainability, environmental management, and strategies that promote cleaner manufacturing.

Fig. 4 provides a visual representation of the important research journals in the field of green buildings and digital technologies. In order to conduct the analysis of source citations, a threshold of 4 was established as the minimum number of documents required for a source to be included on VOSviewer. Out of the 182 sources, 44 meet the threshold and are therefore included in the analysis. Out of the 44 sources, only 23 are connected, while the other 15 sources are strongly connected as shown in Fig. 4.

4.4. Geospatial collaboration of research articles

"Co-authorship" analysis is a method of analyzing documents to study collaboration in the field of geospatial. Fonseca et al. [78] state that scientific collaborative networks are a defining characteristic of modern academic research. It indicates that co-authorship analysis allows for the depiction of collaboration patterns among people and organizations. In order to categorize by country, a threshold was established for a minimum number of documents for a country, set at 2. Out of the total of 47 countries, 27 countries fulfilled this requirement. Upon conducting the analysis, it was found that out of the total of 27, only 17 are interconnected and are visually shown in Fig. 5. Table 4. depicts the overall link strength between countries based on co-authorship. The visualization implies that the geographical locations of the countries might influence their co-authorship. Specifically, authors who are in close proximity are more inclined to collaborate on writing projects. For instance, China, the United Kingdom, and Australia are geographically close to each other, as seen in Fig. 5.

The identification of countries with greater influence in the network was based on the average citations. Table 4 displays the five countries with the highest level of influence in the network. Table 4 reveals that China, the United Kingdom, Australia, US, and Malaysia are the five leading countries in this collaborative network. China has the most robust collaboration with three prominent contributors: the United Kingdom, Australia, US and Malaysia. Given that the majority of green building publications originate from China, it is anticipated that there would be a robust cooperation with other countries. In addition, China has intensified its research efforts on green buildings in recent years in response to the significant levels of carbon emissions [79]. In contrast, US seems to have minimal cooperation with other countries. It is recommended that collaborative digital platforms be implemented to improve information exchange and encourage the dissemination of best practices among stakeholders in the green building community. These platforms serve as hubs for sharing information, exchanging ideas, and boosting collaboration on sustainability initiatives, ultimately driving collective action towards a more environmentally friendly built environment.

Table 4
Top 5 countries collaborating in green buildings and digital technologies.

Country	Documents	Average citations	Total link strength	Average year published
China	35	120	27	2022
United Kingdom	24	92	14	2022
Australia	19	77	19	2021
United States	15	52	08	2022
Malaysia	11	30	10	2022

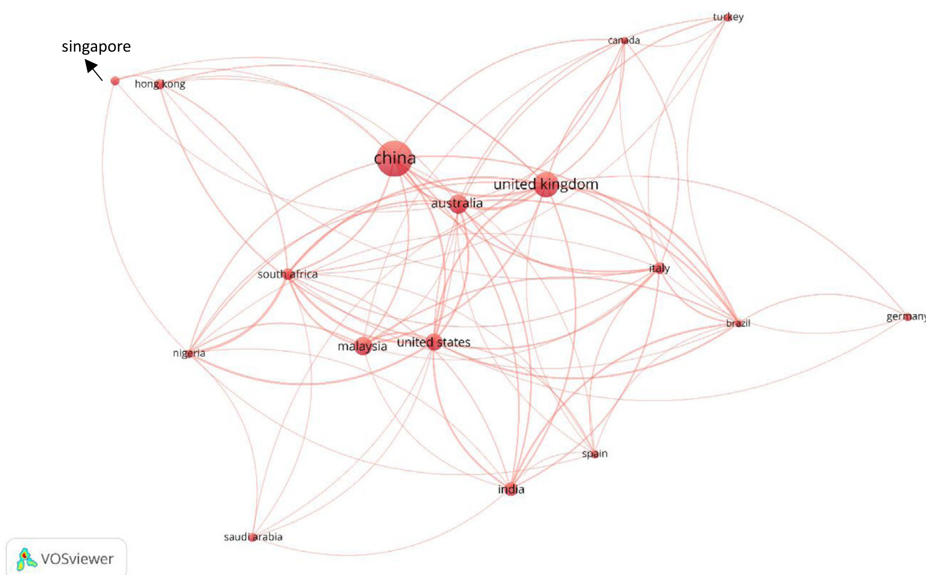

Fig. 5. Visualization of co-authorship by country.

5. Discussion

This section presents a qualitative systematic analysis of a chosen set of publications to offer an in-depth review of the nexus between green buildings and digital technologies. The subsections provide a detailed overview of how the integration of digital technologies can enhance sustainability of green buildings, the challenges and technological solutions in construction of green buildings. Additionally, this section highlights the key research techniques utilized to enhance sustainability in green buildings and digital technologies. The subsections also identify knowledge gaps and suggest future research directions for digital technologies in the context of green buildings. This part provides a comprehensive analysis of the significant discoveries, which could potentially illuminate the existing body of knowledge.

5.1. Overview of integration of digital technologies in context of sustainability of green buildings

Several digital technologies have been identified in the area of green buildings to enhance sustainability. BIM, DT, AI, ML, AR, VR, big data analytics, 3D printing, cloud computing, IoT, blockchain, cyber–physical systems, smart grids and robotics. To gain a deeper comprehension of the picture, it is crucial to examine the integration of digital technologies in green buildings individually.

(i) BIM in green buildings

BIM is of great importance in the realm of green buildings, since it provides a comprehensive approach to design, construction, and management that is well-aligned with sustainability goals. BIM facilitates the collaborative work of architects, engineers, and other stakeholders in a digital environment [12]. This integration enables the initial examination of building performance measures, such as energy usage, natural lighting, and thermal comfort, at an early stage. BIM facilitates the optimization of building performance over its entire lifespan by detecting and resolving sustainability concerns during the design phase [11,80]. In addition, BIM has the capability to incorporate life cycle assessment (LCA) techniques in order to examine the environmental impact of building materials and design choices across the full lifespan of a building [81]. It was found that BIM facilitates the choice of sustainable building materials and techniques by taking into account environmental consequences, as well as economic and performance considerations effects during the stages of extraction, manufacture, construction, operation and maintenance [8,82].

Furthermore, BIM software facilitates the utilization of simulation and analysis techniques to assess the energy efficiency of a building design [36]. Designers have the ability to experiment with many approaches to enhance energy efficiency, including optimizing the positioning of buildings, choosing suitable materials, and integrating renewable energy sources. BIM plays a crucial role in enhancing the energy efficiency of green buildings by precisely forecasting energy consumption and identifying areas for improvement [83,84].

(ii) Digital twin (DT) in green buildings

DT is a computer-generated model that replicates a physical building and is enhanced with up-to-date information collected from sensors and IoT devices. Within the realm of green buildings, this digital replica has the capability to consistently observe and track energy use, indoor air quality, inhabitant behavior, and various other environmental components. Through the analysis of this data, operators of buildings can find potential areas for improving energy efficiency, minimizing resource usage, and enhancing the comfort of occupants [85]. In addition, DT utilize sophisticated analytics and ML algorithms to predict future performance by analyzing past data and simulations. It was found that predictive analytics in green buildings can forecast energy usage, detect possible system malfunctions, and optimize building operations to reduce the environmental impact [86].

Furthermore, DT allow designers and operators to replicate various scenarios and assess their influence on the functioning of a buildings.

Within the realm of green buildings, this capability enables stakeholders to experiment with energy-conserving tactics, evaluate the practicality of incorporating renewable energy sources, and refine building systems to achieve optimal efficiency [87]. DT can facilitate the development of more environmentally friendly building environments by continuously improving design as well as operational factors. In addition, DT is essential for enhancing the sustainability of buildings through their ability to provide real-time monitoring, predictive analytics, simulation, lifecycle management, and user involvement. DT utilize data and technologies to enhance building performance and reduce the environmental impact at every stage of the building lifecycle [88].

(iii) Artificial intelligence (AI) in green buildings

AI is the field of study and engineering that focuses on creating computers and machines capable of adapting, learning, reasoning, and solving problems using artificial neural networks and algorithms that imitate human intellect. AI algorithms have the capability to analyze large quantities of data in order to enhance building designs for the purpose of energy efficiency, occupant comfort, and environmental sustainability [89]. In addition, AI-driven energy management systems have the capability to adapt building operations in real-time based on several factors, including occupancy patterns, weather forecasts, and energy prices. AI algorithms have the capability to forecast energy demand and provide suggestions for demand response and load shifting in order to decrease peak electricity use and decrease utility costs [90].

Furthermore, Yigitcanlar et al. [91] introduced the concept of "Green artificial intelligence" that has the capability to enhance indoor environmental quality by analyzing sensor data pertaining to temperature, humidity, air quality, and feedback from occupants. In addition, occupancy sensors driven by AI can enhance the efficiency of space utilization and HVAC operation by adapting to occupancy patterns, hence minimizing energy wastage in vacant areas. AI have the capability to optimize trash sorting and recycling procedures in environmentally-friendly buildings. AI-driven sorting systems have the ability to accurately detect and segregate recyclable elements from waste streams with greater efficiency compared to manual sorting techniques. This leads to higher recycling rates and a decrease in the amount of garbage sent to landfills. In addition, AI algorithms can optimize waste collection routes and schedules to minimize the usage of fuel and reduce greenhouse gas emissions related to waste management activities [92].

(iv) Machine learning (ML) in green buildings

ML is an area of AI that enables systems to learn from large amounts of data in order to create an analytical model. This model can then be used to solve issues, provide recommendations, make predictions, or other similar outcomes. Certain studies have specifically examined the characteristics of green building technologies, while also considering the relaxation of other factors such as human, technological, and specific requirements. The presence of significant uncertainty sometimes undermines the accuracy of green building cost projections, leading to a deleterious impact [93]. Furthermore, there has been a lack of initiative in developing analytical or ML-based models for predicting the costs of green construction. Several current models employ survey and questionnaire approaches to depict the practical scenario of green building costs. Additional quantitative and objective methods for estimating green construction costs are consistently required [94].

Furthermore, ML algorithms have the capability to examine data collected from sensors in building systems and equipment in order to identify irregularities and trends that may indicate possible malfunctions. ML models facilitate proactive maintenance strategies by continually monitoring equipment performance and accurately forecasting maintenance requirements [95]. This approach prevents expensive breakdowns and prolongs the lifespan of building assets. This not only decreases the amount of time that operations are halted and lowers the expenses related to maintenance, but it also lessens the negative effects on the environment caused by replacing equipment [96].

(v) Augmented reality and virtual reality in green buildings

AR and VR are crucial elements that will enhance the building and construction sectors and enable the introduction of novel productivity in the field. AR consists of real-world experiences, while VR offers a fully immersive experience that entirely isolates the user from the physical environment. AR and VR can be employed throughout the early stages of green building design to provide a visual representation of concepts and designs. These technologies can be utilized by architects and designers to generate immersive experiences, enabling stakeholders to gain a clearer comprehension of the proposed concepts [97]. This can result in making more knowledgeable choices about sustainability attributes such as daylighting, passive thermal regulation, and the incorporation of renewable energy. Furthermore, AR and VR have the capability to replicate and represent the movement of energy within buildings, assisting designers in enhancing energy efficiency [98]. Stakeholders can use visualization techniques to understand how sunlight will enter a building at different times of the day. This enables them to make design adjustments that optimize natural lighting and minimize heat gain [99].

AR enables the superimposition of real-time data onto physical building components, enabling remote monitoring of energy usage, HVAC operation, and other systems by maintenance staff. By utilizing this technology, it becomes possible to detect and address any inefficiencies or maintenance problems, so enhancing the overall efficiency of the building and minimizing energy usage [100]. On the other hand, VR technology may offer immersive virtual tours of environmentally-friendly buildings, highlighting its sustainable attributes such as green roofs, solar panels, rainwater harvesting systems, and energy-efficient appliances. This can enhance knowledge regarding sustainable construction approaches and motivate stakeholders to integrate comparable attributes into their projects [101]. AR and VR experiences can effectively involve the public in initiatives that promote sustainability by enabling them to interact with virtual representations of green buildings and acquire knowledge about their ecological advantages. This can promote community engagement in sustainable development initiatives and incentivize individuals to embrace environmentally conscious practices [102,103].

(vi) Big data analytics in green buildings

Big data analytics is the systematic analysis of vast and diverse data sets, sometimes referred to as "big data", with the aim of revealing concealed patterns, unexplored relationships, market trends, customer preferences, and other valuable insights. Data analytics encompasses the utilization of sophisticated analytical methodologies and instruments to quickly and efficiently handle, scrutinize, and interpret extensive quantities of data. The process of big data analytics commences by gathering data from diverse sources, such as sensors, gadgets, social media platforms, websites, transaction records, and other relevant sources [104]. Furthermore, big data analytics can enhance energy efficiency in buildings by gathering and examining data from sensors, meters, and other sources. Through the process of optimizing energy usage, buildings have the ability to decrease their impact on the environment and lower their operational expenses [105]. The utilization of big data analytics can enable the seamless integration of environmentally-friendly buildings with intelligent power networks. Through the examination of energy usage patterns and demand-response signals from the grid, buildings have the ability to promptly modify their energy consumption in order to optimize the utilization of renewable energy sources and reduce dependence on fossil fuels [106].

(vii) 3D printing in green buildings

3D printing, or additive manufacturing, has the capacity to transform the building and construction sectors, including environmentally friendly building methods. Construction techniques frequently lead to substantial material wastage. 3D printing enables accurate placement of materials, resulting in minimal waste and decreased environmental impacts related to buildings [107]. Certain 3D printing techniques allow for the utilization of recycled resources, such as recycled plastics or aggregates, in the field of construction. 3D printing can promote resource conservation and waste reduction by integrating recycled materials into the manufacturing process [108]. By optimizing the construction process, 3D printing has the potential to minimize the energy consumption typically connected with buildings. On-site printing of structures avoids the necessity of transporting pre-made components, hence reducing carbon emissions linked to transportation [109].

(viii) Cloud computing in green buildings

Buildings consume a significant quantity of energy throughout both the construction and operation phases. Cloud computing has been utilized to efficiently oversee energy management in different phases of building. In order to achieve the intended goal of green consumption, Li et al. [110] utilized a cloud computing platform to effectively handle construction performance assessment over the whole lifespan of a building. Despite the rapid emergence of cloud computing as a widely accepted computing paradigm, research in this field is still in its early stages. It was found that cloud computing has various tough scientific concerns including to security, software frameworks, quality of service, standardization, power consumption and effective energy management [111]. The fundamental components of a cloud computing system include SaaS (Software as a Service), PaaS (Platform as a Service), and IaaS (Infrastructure as a Service). SaaS applications are commonly included in data centers that are specifically designed to maximize energy efficiency. Users can access these applications remotely via the internet, eliminating the necessity for installing software on local devices, which can result in higher energy consumption [112]. PaaS providers offer platforms that facilitate the development, testing, and deployment of applications, typically making use of virtualization and technologies. By consolidating resources onto common platforms, resource utilization is enhanced and energy usage is reduced [113]. IaaS providers offer consumers the ability to access and utilize virtualized computing resources as required. This includes the ability to create and adjust the number of virtual machines as needed. Virtualization allows for more efficient use of resources by enabling numerous virtual machines to operate on a single physical server, resulting in reduced energy usage and hardware needs [114,115].

(ix) Internet of things (IoT) in green buildings

The IoT is transforming various industries, including green building development and management. IoT sensors have the capability to continuously track and analyze energy consumption in real-time, enabling more effective control and optimization of heating, cooling, lighting, and other operational systems [116]. Smart thermostats can automatically modify temperatures according to occupancy and weather conditions, hence minimizing energy wastage [20]. In addition, IoT devices can to monitor and record water consumption, identify any leaks, and enhance the efficiency of irrigation systems in green buildings, resulting in substantial water preservation [117]. This data can be utilized to enhance the efficiency of ventilation systems and guarantee the well-being and satisfaction of occupants. Moreover, the examination of data produced by the IoT can assist in identifying patterns, trends, and opportunities for enhancing the performance of green buildings. By harnessing data, this method enables continuous enhancement of building operations and environmental activities.

(x) Blockchain in green buildings

Blockchain enables transparent and secure peer-to-peer energy trading among building occupants or even between neighboring buildings. With blockchain-based smart contracts, energy producers (e.g., buildings with solar panels) can sell excess energy directly to consumers, fostering a decentralized energy market and promoting renewable energy adoption. Blockchain can be used to track and verify carbon credits and emissions reductions in green buildings. By recording carbon emissions data on a tamper-proof distributed ledger, stakeholders can ensure the accuracy and integrity of emissions reductions, facilitating carbon trading and incentivizing sustainable practices [118]. In addition, blockchain technology can enhance transparency and traceability in the supply chain of building materials and products. By recording every transaction and movement of materials on the blockchain, stakeholders can verify the origin, sustainability credentials, and ethical sourcing of construction materials, promoting green procurement practices [119].

Furthermore, smart contracts on blockchain platforms can automate the certification process for green buildings, such as LEED or BREEAM [120]. The immutable ledger of blockchain guarantees the integrity and permanence of environmental impact data, including energy usage, water consumption, and garbage generation. This facilitates the precise and reliable disclosure of sustainability measurements to regulatory bodies, investors, and the general public, promoting responsibility and trustworthiness [121].

(xi) Cyber–physical systems in green buildings

Cyber–physical systems (CPS) utilize a network of sensors to gather data on many building factors, including temperature, humidity, occupancy, energy usage, and indoor air quality. The sensors constantly observe environmental variables both within and outside the building, offering immediate information about its functionality. CPS employ sophisticated data analytics techniques to analyze the vast quantities of sensor data gathered from the building [122]. In addition, ML and AL techniques can detect patterns, anomalies, and chances for optimization. This allows for predictive maintenance, energy management, and adaptive control tactics. CPS enable seamless integration with smart grid infrastructure, allowing for two-way communication between green buildings and the electric grid. Buildings that are equipped with CPS can take part in demand response programs, modify their energy use according to grid conditions, and even produce and store renewable energy to maintain grid stability [123].

(xii) Smart grids in green buildings

Green buildings frequently integrate sustainable energy sources, such as solar panels, wind turbines, and micro-hydro systems, to produce environmentally friendly electricity on the premises. Smart grids facilitate the smooth incorporation of these dispersed energy resources into the building's energy infrastructure, optimizing their utilization and guaranteeing effective grid interaction. Smart grids facilitate demand response programs, enabling green buildings to modify their electricity usage in accordance with grid circumstances and pricing signals [124]. By implementing sophisticated metering, monitoring, and control systems, buildings can actively engage in load-shifting tactics, which effectively decrease peak demand and relieve strain on the power grid during periods of heightened electricity consumption. Smart grids enable the incorporation of energy storage equipment, such as batteries, thermal storage, and flywheels, into green buildings [125]. These Energy Storage Systems (ESSs) store surplus renewable energy produced during times of low demand and release it when necessary, offering backup power, load balancing, and system stabilization services. Green buildings that are outfitted with smart grid technology can interact with the utility system and react to signals from the grid immediately. By employing sophisticated control algorithms and automation systems, these buildings can efficiently manage their energy consumption, storage, and production in order to achieve grid stability and dependability goals [126,127].

(xiii) Robotics in green buildings

Robotics can mechanize repetitive maintenance duties, such as cleansing, examining, and fixing building elements. Automated cleaning devices integrated with advanced sensors and AI algorithms are capable of effectively cleaning various surfaces such as floors, windows, and facades. This technology minimizes the reliance on chemical cleaning agents and helps conserve water and energy resources. Robotics can optimize the construction process of green buildings, enhancing accuracy, velocity, and resource effectiveness [128]. Robotic construction technology, including 3D printers, drones, and automated bricklaying systems, can enhance material efficiency, reduce construction waste, and expedite project schedules, thereby promoting sustainable building methods [129]. In addition, robotics can aid indoor agriculture efforts in green buildings by enabling the growth of fruits, vegetables, and herbs in vertical farms or hydroponic systems. It was found that robots can contribute to the upkeep of green roofs by doing tasks like as irrigating plants, pruning vegetation, and monitoring soil conditions. Robotics can enhance monitoring and security measures in green buildings, hence improving safety and deterring unauthorized access or incursions. Autonomous security robots, outfitted with cameras, sensors, and AI algorithms, can patrol premises, identify abnormalities, and notify security staff of potential dangers or breaches [130,131].

5.2. Challenges and technological solutions in green building construction

Green building construction encounters multiple challenges, encompassing legislative hurdles and technological limitations. Nevertheless, technological breakthroughs provide encouraging options for overcoming these challenges. Below are several prevalent challenges encountered in green building construction, along with their associated technological solutions:

(i) *High Initial Costs* One of the primary challenges in the growth of green buildings is the notion of elevated initial expenses in comparison to conventional construction methods. Nevertheless, the progress in technology has resulted in the creation of affordable environmentally-friendly building materials and construction methods [132].

- *Technological Solution:* The affordability and accessibility of innovative materials, such as recycled steel, engineered wood, and sustainable concrete alternatives, are increasing. Prefabrication and modular construction methods decrease the duration of construction and decrease labor expenses, while enhancing quality control [133].

(ii) *Limited Availability of Sustainable Materials:* The limited availability of sustainable materials in green buildings construction is a significant challenge for the building sector. In recent years, there has been a rise in the demand for sustainable materials in construction. This is primarily driven by the increasing environmental consciousness and the implementation of rules that encourage the adoption of green building techniques. Nevertheless, the availability of these resources has not matched the rate of demand, resulting in scarcities and increased expenses [134].

- *Technological Solution:* Digital platforms and databases streamline the process of finding and acquiring sustainable products by offering detailed information on material properties, suppliers, certifications, and environmental impacts. Allocating resources towards technologies that facilitate the effective recycling and repurposing of construction waste helps mitigate the scarcity of sustainable materials. Advanced recycling techniques, such as the use of robots to sort waste, chemical recycling, and additive manufacturing can extract valuable resources from waste streams and transform them into construction materials of superior quality [135]. In addition, 3D printing and additive manufacturing technologies provide opportunities to produce intricate and personalized architectural components utilizing recycled materials [136]. Moreover, nanotechnology has the potential to create construction materials that are lightweight, long-lasting, and eco-friendly, while also improving their performance. Researchers can develop sustainable alternatives to conventional building materials by utilizing the distinctive characteristics of nanomaterials, such as carbon nanotubes, graphene, or nano-clay composites [137].

(iii) *Energy Inefficiency and Performance Variability:* The presence of energy inefficiency and performance variations presents notable challenges in green buildings, compromising their sustainability objectives and perhaps resulting in increased operational expenses. Insufficient design or construction defects can lead to energy inefficiencies and variations in performance. These concerns may encompass inadequate insulation, air infiltration, or inefficient HVAC systems [138].

- *Technological Solution:* The technological solution known as BIM software allows designers and engineers to generate intricate 3D models of buildings. This software also enables the simulation of energy performance, daylighting, and thermal comfort scenarios, all of which can be done prior to the commencement of construction. IoT sensors and smart building management systems constantly monitor and optimize energy use, HVAC functions, and lighting controls using up-to-date data and occupancy trends [139].

(iv) *Regulatory Compliance and Certification Requirements:* Green construction projects are required to adhere to strict regulatory norms and certification criteria, which can vary greatly depending on the specific region and jurisdiction [140].

- *Technological Solution:* The development of certification platforms and software tools simplifies the process of obtaining green building certifications like LEED or BREEAM. These platforms offer assistance, standardized document formats, and automated evaluation tools to guarantee adherence to regulatory and certification requirements [141].

(v) *Waste Management and Recycling:* Green buildings face specific challenges when it comes to waste management and recycling since they prioritize sustainability and environmental responsibility. Construction and demolition waste pose significant environmental issues due to their contribution to pollution and the depletion of resources in landfills [142].

- *Technological Solution:* Cutting-edge recycling technologies, including robotic sorting systems, concrete crushers, and mobile recycling units, provide the effective separation and processing of construction waste materials directly at the construction site. Utilizing digital tracking systems and blockchain platforms enables the transparent monitoring of supply chains and tracking of trash, thereby encouraging the concepts of a circular economy and the reuse of materials [121].

5.3. Key research techniques utilized to enhance sustainability in green buildings

(i) Simulation and Modeling

Simulation and modeling are essential in green building design and operation as they offer valuable insights into energy efficiency, environmental performance, and occupant comfort. Simulation tools, such as TRNSYS (Transient system simulation tool), EnergyPlus, eQUEST, and DesignBuilder, enable designers to forecast a building's energy usage and performance under various situations [153,154]. For instance, Lu et al. [155] utilized TRNSYS, a simulation tool for transient systems, which has the capability to establish contact with MATLAB through the communication object module interface. In addition, EnergyPlus is a comprehensive energy simulation software that accurately represents the energy use of a building by modeling its heating, cooling, lighting, ventilation, and other energy processes. The software is created by the U.S. Department of Energy and is utilized to evaluate the energy usage and effectiveness of buildings for different design and renovation situations. For instance, Dahanayake and Chow [156] carried out a study to integrates the mathematical model of Vertical Greenery Systems (VGS)

Table 5
Summary of Identified Knowledge Gaps in the Literature.

Knowledge gaps	Description	References
Digital technologies integration	Limited studies on applying digital technologies integration to retrofit existing buildings sustainably	[13,19,21,143,144]
Resilience and adaptability	Limited studies on digital technologies to enhance building resilience through real-time monitoring and predictive analytics for climate-related challenges	[145,146]
Regulatory and policy frameworks	Absence of standardized indicators to assess the sustainability impact of digital technologies	[147]
Interdisciplinary collaboration	Promoting interdisciplinary collaboration to develop holistic solutions that integrate technological, environmental, social, and economic dimensions of green buildings	[148]
Blockchain and sustainability	Limited studies in the application of blockchain and green buildings	[58,149,150]
Advanced building materials and technologies	Challenges related to integrate advanced materials and digital technologies like BIM enables sustainable design, efficient off-site construction, and optimized building performance	[69,151]
Economic models for green technology adoption	Future studies need to develop economic models and financial incentives that encourage the adoption of green building technologies	[152]

into the EnergyPlus simulation system. In addition, Dahanayake and Chow [157] conducted a study to estimate the annual reduction in cooling load for various buildings and scenarios in Hong Kong with the aid of EnergyPlus simulation tool.

Moreover, eQUEST is a software used for analyzing the energy use of buildings. It provides a user-friendly interface for the EnergyPlus software. Users can utilize this tool to conduct comprehensive energy analysis of buildings, which encompasses assessing adherence to different energy codes and regulations. For instance, a recent study conducted by Wagle et al. [158] to assess the impact of building design and retrofit characteristics on energy performance by utilizing eQUEST. On the other hand, DesignBuilder allows users to generate intricate 3D models of buildings and analyze their energy efficiency by employing dynamic simulation engines like EnergyPlus and DOE-2. This facilitates the prediction of energy use, the identification of energy-saving possibilities, and the optimization of building designs for enhanced efficiency [159]. For instance, Guo et al. [70] conducted study to focus on the assessment and improvement of green buildings utilizing BIM technology and BIM-related applications like DesignBuilder.

(ii) Decision-making techniques

Decision-making in green building projects frequently requires the careful consideration and weighing of multiple considerations, including environmental impact, cost-effectiveness, energy efficiency, and occupant health and comfort. For instance, Al-Atesh et al. [160] employed the Analytic Hierarchy Process (AHP) to choose between a steel building construction and a reinforced concrete building construction as an option for designing green buildings. A study was conducted in China to verify social sustainability metrics for green buildings using fuzzy Delphi technique [161]. According to this study, the key factors for social sustainability in green buildings are safety and durability. Furthermore, a recent study examined the implementation of blockchain technology in sustainable construction projects using an innovative combination of fuzzy decision-making trial and evaluation laboratory (fuzzy DEMATEL) and social network analysis (FDSNA) [162]. This study aimed to provide management and governmental agencies with a comprehensive understanding of the primary challenges to the successful implementation of blockchain technology. It is anticipated that this will facilitate the realization of advantages of these advanced technologies more quickly.

(iii) Surveys and interviews (qualitative and quantitative techniques)

Surveys and interviews are often employed study techniques in diverse disciplines, including the examination and assessment of green buildings. These techniques can be modified to gather both qualitative and quantitative data, depending on the objectives of the study. Integrating surveys and interviews can yield a comprehensive comprehension of green buildings. Surveys can measure the degree of satisfaction and the frequency of specific behaviors, whereas interviews can provide insight into the reasons behind occupants' behaviors and feelings. By employing a mixed-methods approach, it is possible to get more reliable and comprehensive conclusions and recommendations for enhancing the design, functionality, and user satisfaction of green buildings. For instance, Jaradat et al. [163] conducted a study to integrate green construction standards into the design and construction of buildings and projects through the use of survey and interview sessions. A recent study was conducted to investigate the barriers hindering the implementation of green retrofitting in existing residential buildings. The study employed a qualitative technique and involved conducting interviews with a carefully chosen sample of 16 construction experts, including architects, quantity surveyors, and engineers [164]. Additionally, a preliminary investigation was carried out to emphasize the challenges associated with the social and environmental aspects of green buildings using qualitative techniques. Raouf and Al-Ghamdi [165] conducted a study to develop a framework for assessing the quality performance of green building delivery during both the construction and operational stages by utilizing the qualitative technique. It was concluded that by integrating both quantitative and qualitative techniques in surveys and interviews, researchers and practitioners can obtain a thorough understanding of the various dimensions of green buildings. This includes not only technical performance measurements but also human perspectives and behaviors. These useful insights contribute significantly to the progress of sustainable construction practices and the promotion of a more environmentally friendly built environment [145].

5.4. Knowledge gaps and future research directions

The field of green buildings and digital technologies is dynamic and ever-changing. There are various knowledge gaps and domains that can be filled through future research to improve building sustainability and efficiency. These knowledge gaps were derived through a thematic synthesis of the selected 135 articles. Each article was examined to identify not only the contributions made but also the limitations and future research directions for further investigation. Table 5 elaborates the seven knowledge gaps, supported by representative references from the reviewed articles.

(i) Digital technologies integration

While there have been notable improvements in using digital technologies like BIM and sensor networks in green building design, further research is needed to increase their integration [9]. This entails developing advanced modeling tools that can accurately predict the environmental performance of buildings and exploring the potential of future technologies like AI to enhance design processes [79]. In addition, the primary and crucial knowledge gap that was emphasized is the integration of digital technologies to enhance sustainability. No study has discovered that integrated digital technologies enhance the sustainability of green buildings. In order to stay up-to-date with the latest advancements in the field, it is recommended to integrate BIM-Digital

Twin based sustainability model. This model will not only enhance sustainability but also help promote the notion of green buildings [144].

(ii) Resilience and adaptability

In light of the escalating occurrence and severity of extreme weather phenomena as a result of climate change, there is an emerging requirement to develop green buildings that possess resilience and adaptability [146]. It is recommended that potential future studies could investigate the utilization of digital technologies to improve the resilience of buildings. This could involve implementing real-time monitoring and predictive analytics to boost disaster response and recovery.

(iii) Regulatory and policy frameworks

Although there has been some advancement in the creation of green building rules and standards, further research is required to evaluate the efficacy of these policies and the methods used to enforce them. Furthermore, given the swift rate of technological advancement, authorities must clear instructions on how to modify current legislation to facilitate emerging digital technologies in green buildings [147]. It is recommended to implement green buildings standards codes and certification specifically for developing countries.

(iv) Interdisciplinary collaboration

Interdisciplinary collaboration is crucial for overcoming research gaps and generating innovation in the complex fields of green buildings and digital technologies. Future research endeavors should promote interdisciplinary collaboration among architects, engineers, computer scientists, social scientists, policymakers, and other relevant parties to create comprehensive solutions that take into account technological, environmental, social, and economic aspects [148].

(v) Blockchain and sustainability

Blockchain technology, the fundamental technology that underlies cryptocurrencies like Bitcoin, has the potential to significantly impact the construction sector. The current available literature indicates that the utilization of blockchain technology in the construction sector is extremely limited, however there is potential for significant expansion. The construction sector is well-known for its complex characteristics, which include the involvement of various stakeholders, long project durations, and significant financial transactions. Blockchain has the capacity to resolve persistent challenges in the industry, such as contractual disputes, supply chain management, and payment protocols [58]. To see the applications of blockchain in construction sector, it is recommended to implement the blockchain technology in building sector. For instance, to attain and sustain green building certifications, such as LEED, BREEAM, or Green Star, one must complete thorough paperwork and verification processes. Blockchain technology can securely store and handle this documentation, thereby enhancing the efficiency and transparency of the certification process. Additionally, it can aid in the surveillance of adherence to current sustainability mandates. Furthermore, the utilization of blockchain technology has the capacity to greatly influence the advancement, functioning, and administration of green buildings. Green buildings strive to mitigate their environmental impact by employing sustainable design, optimizing resource utilization, and minimizing carbon emissions. Blockchain can contribute to these objectives through several means, augmenting openness, accountability, and efficiency in green building initiatives [149].

Furthermore, blockchain technology can improve trust and transparency in the green buildings sector by creating an unchangeable record of transactions and information regarding building materials, energy consumption, emissions, and certifications [143]. Stakeholders can use this transparency to authenticate assertions on a building's sustainable attributes. Blockchain platforms can utilize smart contracts to automate energy management systems in green buildings, thereby optimizing energy consumption and minimizing waste. These contracts facilitate peer-to-peer energy trading, allowing surplus renewable energy produced by one building to be sold to nearby buildings, promoting a more efficient and decentralized energy environment [150].

(vi) Advanced building materials and technologies

BIM, a sort of digital technology, empowers architects and engineers to create and improve building designs by incorporating features that optimize energy efficiency, daylighting, and thermal performance. Through the incorporation of advanced materials into digital models, designers are able to assess the environmental impacts of various design alternatives and make well-informed choices to optimize sustainability [69]. In addition, digital technologies facilitate off-site construction techniques including prefabrication and modular construction, resulting in decreased on-site waste, reduced construction duration, and enhanced quality management. Off-site construction enhances the sustainability and efficiency of building projects by optimizing material utilization and expediting construction processes [151].

(vii) Economic models for green technology adoption

The adoption of green building technologies was found to be quite limited [152]. It is recommended to develop economic models and financial incentives that encourage the adoption of green building technologies, particularly in regions where cost is a significant challenge.

6. Conclusion

This review study aims to provide a bibliometric and qualitative systematic approaches of recent research on the intersection of green buildings and digital technologies for a sustainable future. In light of critical challenges such as climate change, resource depletion, and urbanization, the integration of green building techniques and advanced digital technologies is seen as a powerful approach for creating a more sustainable future. The three research questions were achieved with the utilization of bibliometric and qualitative systematic analysis. It was found that green buildings offer a pathway to reduce the environment footprint of the built environment through energy efficiency, water conservation, and sustainable materials. By using digital technologies, the ability to optimize building performance and improve occupant wellbeing is significantly amplified. It has been observed that the number of publications exhibited a consistent upward trend in 2021 and subsequent years. The keyword co-occurrence analysis revealed the primary research topics that have a significant connection to green buildings and digital technologies. Furthermore, it was discovered that China emerged as the primary contributor to research on green buildings and digital technologies, followed by the United Kingdom, Australia, United States, and Malaysia.

The following seven knowledge gaps were highlighted: (i) digital technologies integration, (ii) resilience and adaptability, (iii) regulatory and policy frameworks, (iv) interdisciplinary collaboration, (v) blockchain and sustainability, (vi) advanced building materials and technologies and (vii) economic models for green technology adoption. Thus, the study provides researchers with valuable guidance for future directions and the potential to investigate new domains. As we think about the future, it is crucial for governments, industry leaders, and consumers to play a vital role in creating an environment that supports the successful coexistence of green buildings and digital technologies. It is recommended to allocate resources towards education, research, and incentives can expedite the implementation of these practices, resulting in extensive advantages for the economy, society, and the environment. In essence, the nexus between green buildings and digital technologies serve as a symbol of optimism for sustainable future. By embracing this collaboration, we may imagine a future in which sustainable living is not merely an abstract idea but a tangible existence, guaranteeing a healthier, more adaptable, and fairer environment for future generations.

While this study has provided interesting insights, it is crucial to recognize its limitations when assessing the results. The research exclusively utilized a solitary database (Scopus), which could potentially affect the inclusiveness of papers incorporated in the investigation. In addition, the research was restricted to journal papers. In order to improve this study, future research efforts could involve including more databases and document types. Furthermore, the literature search was conducted utilizing precise keywords, which may not offer a thorough presentation of the subject domains. Future research endeavors may involve a broader spectrum of keywords.

CRediT authorship contribution statement

Bilal Manzoor: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Maxwell Fordjour Antwi-Afari:** Writing – review & editing, Visualization, Software, Conceptualization. **Khalid Saqer Alotaibi:** Writing – review & editing, Methodology, Data curation.

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.

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