Cleaner Engineering and Technology 29 (2025) 101089

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

A comprehensive literature review on risk identification and assessment in green building construction projects

Abdul-Mugis Yussif [a], Ridwan Taiwo [a], Pshtiwan Shakor [b], Tong Han [c], Saeed Reza Mohandes [c,*], Maxwell Fordjour Antwi-Afari [d], Kamal Qazi [c], Atul Kumar Singh [e], Mary Subaja Christo [f], Mohd Asif Shah [g,h,i,**]

[a] *Department of Building and Real Estate, Faculty of Construction and Environment, Hong Kong Polytechnic University, Hung Hom, Hong Kong*
[b] *Technical College of Engineering, Sulaimani Polytechnic University, Sulaymaniyah, Iraq*
[c] *Department of Civil Engineering and Management, School of Engineering, The University of Manchester, Manchester, United Kingdom*
[d] *Department of Civil Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham, B4 7ET, United Kingdom*
[e] *NICMAR Institute of Construction Management and Research, Delhi-NCR, Bahadurgarh, 124507, India*
[f] *Department of Networking and Communications, School of Computing, SRM Institute of Science & Technology, Kattakulathur, Tamil Nadu, 603203, India*
[g] *Department of Economics, Kardan University, Parwane Du, 1001, Kabul, Afghanistan*
[h] *University Centre for Research & Development, Chandigarh University, Gharuan, Mohali, Punjab, 140413, India*
[i] *Division of Research and Development, Lovely Professional University, Phagwara, Punjab, 144001, India*

ARTICLE INFO

Keywords:
Construction projects
Green buildings
Scientometric analysis
Comprehensive literature review
Risk factors

ABSTRACT

Building green for sustainability cannot be over-emphasised, considering the current environmental crises. Green buildings minimise environmental degradation and reduce consumption of depletable resources while providing maximum occupancy satisfaction. Despite the numerous studies of risk assessment in Green Building Construction Projects (GBCPs), limited attention has been given to methodologies that enable risk evaluation from the projects' inception to the end of their service life. Secondly, the existing methods do not consider the accumulated knowledge and experience obtained from previous risk assessment models. Finally, existing studies fail to provide a detailed description of each risk, as they only list them, leading to ambiguity in the practical sense. A scientometric analysis was performed to reveal the current research trend of risk identification in GBCPs. This study systematically reviewed relevant literature from the last two decades until the end of 2024 to collate the most influential risks associated with GBCPs. From the systematic literature review, a total of forty-two (42) risks were identified and defined clearly before further grouping them into nine (9) mutually exclusive categories to ease targeted assessments. The knowledge-based approach was proposed for identifying and evaluating the risks due to its unique nature of enabling long-term analysis by tapping into the accumulated knowledge and experience from previous evaluation models. The knowledge-based approach emphasises establishing a strong foundation involving risk scope definition, identification, analysis, response planning, execution, and monitoring and control as a feedback system supporting risk evaluation throughout the service life of the project. After the analysis, it was found that the risk evaluation studies in GBCPs need to create assessment models that consider the post-construction variables and the accumulated knowledge of previous evaluations. Secondly, a clear description of each risk eases its categorisation for tailor-targeted assessment. The current limitations include limited collaboration between developing and developed countries and a scarcity of empirical research in developing nations. The study proposes future research opportunities in green building risk studies to promote research growth, highlights the need for holistic risk management frameworks, and fosters sustainable construction practices globally.

* Corresponding author.
** Corresponding author. Department of Economics, Kardan University, Parwane Du, 1001, Kabul, Afghanistan.
E-mail addresses: mugis.yussif@connect.polyu.hk (A.-M. Yussif), ridwan-a.taiwo@connect.polyu.hk (R. Taiwo), pshtiwan.shakor@spu.edu.iq (P. Shakor), tong.han-2@postgrad.manchester.ac.uk (T. Han), saeedreza.mohandes@manchester.ac.uk (S.R. Mohandes), m.antwiafari@aston.ac.uk (M.F. Antwi-Afari), kamal.qazi@manchester.ac.uk (K. Qazi), marysubaja@gmail.com (M.S. Christo), m.asif@kardan.edu.af (M.A. Shah).

https://doi.org/10.1016/j.clet.2025.101089
Received 30 November 2024; Received in revised form 1 September 2025; Accepted 1 October 2025
Available online 2 October 2025
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1. Introduction

Green building design is an environmentally responsible and resource-efficient practice toward achieving enhanced occupancy well-being, resource circularity, clean energy utilization, and general sustainability throughout the project's life cycle (Ding et al., 2018; Dwaikat and Ali, 2016; Solaimanian, 2025). The green building construction concept may be applied to minimise construction and demolition waste, as conventional methods generate more waste and increase environmental pollution over the building's lifetime (Li et al., 2016; Solaimanian, 2025; Yeheyis et al., 2013). For instance, traditional construction contributes to approximately 35 % of global waste generation, while green practices have been shown to reduce waste by up to 50 % during construction phases (World Green Building Council, 2022).

Numerous benefits have been highlighted in green building practices, including 30–50 % energy savings and 20–30 % water conservation during operation (Guan et al., 2020; Zhao et al., 2018). Additionally, green buildings enhance productivity, comfort, and overall occupancy satisfaction by up to 15 % (Devine and Kok, 2015; Halicioglu and Gurel, 2024). They are also known for promoting biodiversity (Amani, 2025; Wuni et al., 2019). These benefits cover social, economic, and environmental aspects of the environment (Iwuanyanwu et al., 2024). Green buildings embracing digital green value co-creation behaviour enable stakeholders to collaboratively share resources and innovate, which in turn optimizes energy efficiency, reduces environmental impacts, and enhances overall sustainable performance (Yin and Zhao, 2024a). In light of this, sustainable construction is considered from different angles, including minimizing the utilization of depletable materials, reducing degradation, and eliminating soil and land pollution (Dalirazar and Sabzi, 2022; Jaradat et al., 2024). Green

Despite the enumerated benefits, Green Building Construction Projects (GBCPs) face risks that cannot be overlooked (Komurlu et al., 2024), highlighting the pressing need to identify and develop tools to tackle them (Liu et al., 2024) efficiently. However, the importance of risk management in GBCPs and the overall development status in this area have not been adequately studied despite their critical role in ensuring the successful implementation of sustainable practices (Komurlu et al., 2024). Considering the risk of cost overruns, for instance, studies reveal that over 40 % of green building projects face delays and cost overruns due to unaddressed risks (Devine and Kok, 2015). Regarding regional analysis, 55 % of construction projects and 65 % of public construction projects have been recorded to experience cost overruns in Malaysia and Jordan, respectively (Dong et al., 2025). The most critical issue concerning cost overruns and delays in this field is their prevalence in both developed and developing economies (Abdelalim et al., 2025).

Generally, the construction industry is rife with unlimited uncertainties, creating barriers, challenges, and risks (Alamdari et al., 2023a; Okudan et al., 2021). As a result, managing the risks is a critical component undertaken during the construction process, and it transcends all the phases of the project, from planning to operation stages. Poor risk management inherently leads to undesirable project performance (Khodabakhshian et al., 2024). Since GBCPs are constantly gaining significant interest in the efforts to meet sustainable development goals (SDGs) and support sustainable construction (Abdulmaksoud and Beheiry, 2023; Adabre et al., 2021), risk management in GBCPs is more highlighted than ever. Therefore, effective risk management is essential for ensuring the success of green building construction projects through proactively identifying risks and developing responsive strategies.

The primary sources of risks in GBCPs change dynamically regularly. Incorporating innovative approaches and technologies, eco-friendly materials, and complicated designs in GBCPs introduces new risks (Hwang et al., 2017a; Yin and Zhao, 2024a). Similarly, the introduction of new standards and regulations for governing green building designs generates additional risks due to policy deficiencies and untested concepts. In addition to the typical risks to which the construction industry is prone, such as cost overruns, schedule delays, and quality issues, GBCPs encounter risks unique to their sustainable nature (Alamdari et al., 2023a; El-Sayegh et al., 2021). For instance, adopting sustainable-entrenched technologies in GBCPs introduces complexities in projects, increasing the risk of delays and budget overruns (Arogundade et al., 2024; Okoye et al., 2022). GBCPs also face significant risks from material logistics, as a sustainable material supply chain involves higher upfront costs, face supply chain limitations, and quality control concerns, posing financial and procurement risks (Gounder et al., 2023; Nguyen and Macchion, 2023).

Furthermore, GBCPs require professionals with specialised knowledge, experience, and expertise (Coskun et al., 2023). The scarcity of professionals with this expertise makes the projects prone to technical risks and risks relating to implementation and quality control (Alamdari et al., 2023a). Inadequate understanding or implementation of specific sustainability standards and regulations adds another layer of risk that can cause inadvertent non-compliance and potential legal and reputational consequences (Gurgun et al., 2016). Sustainable construction is not free from legislative roadblocks, awareness hindrances, and economic barriers (Gan et al., 2015; Komurlu et al., 2024), affecting the design, construction, and operation phases of the project. Similarly, lack of government incentives and enforcement and slow cultural transitions hinder the implementation of green building practices (Arogundade et al., 2024; Singh et al., 2023a; Yin and Zhao, 2024b). The elements discussed are some of the sources of the risks associated with GBCPs.

The risks involved in GBCPs have caused mixed feelings among investors and developers who are primarily concerned with the return on investment of their projects. Researchers and construction professionals must identify the most effective ways of tackling the risks and collaborate to promote investors' interest in these projects (Dalirazar and Sabzi, 2022). Moreover, governments have significant roles in facilitating the transition from conventional building designs to green practices (Singh et al., 2023a; Yin and Zhao, 2024b). Some governments have taken notable steps to promote green building projects, such as the Ten Point Plan for a Green Industrial Revolution in the UK, the Development of Building Energy Efficiency and Green Building in China, and the Green Transition of Slovenia (IEA, 2024). Government policies are effective because they are the principal authorities overseeing any country's lawmaking and enforcement.

Research on risks in GBCPs has observed heightened attention from academia and construction practitioners (Ahmad et al., 2019), giving opportunities for empirical applications. However, the studies remain limited due to the emergence of significant records of new risks with time, threatening the success of the existing risk identification and mitigation strategies (Nguyen and Macchion, 2023). The thought-provoking questions emanated from critically reviewing the existing research papers on risk management in GBCPs warranted this systematic review to identify and define risks related to GBCPs and devise approaches to assess them effectively.

Considering previous systematic reviews identifying risks associated with GBCPs, Elseknidy et al. (2025) provided a comprehensive list of risk categories that did not capture environmental, performance, operational, and planning risks. Zhao et al. (2016) identified several risk factors in the literature; however, they left out risks involving schedule, legal, regulatory, communication and awareness, and environmental risks. Building upon the previously mentioned, Wuni et al. (2023) theorised the multidimensional influence of risk in green building projects with a comprehensive categorisation of risk. While a profound work, it did not describe in detail the meaning of each risk or examine the collaboration among developing and developed countries. Similarly, in the same timeframe, Nguyen and Macchion (2023) compiled various risks identified from the literature in a phase-dependent manner, providing an easy way to keep a record of the risks at each construction phase. However, it did not consider schedule and planning risk in its categories, limiting the potential to tackle the threats associated with this important task influencing the cost and success of the project.

Furthermore, Maqbool et al. (2023) provided a qualitative approach to assessing risks associated with GBCPs and establishing the relationships of how they influence each other. Though a great qualitative work, it failed to provide a thematic grouping of the risks or describe each risk in detail. In addition to this, this work focused only on projects located in the UK. Singh et al. (2023a) identified and assessed the barriers hindering the adoption of blockchain technology in green building projects by conducting surveys and systematic reviews. Though an excellent work, the work did not define what each risk represents, and it was also focused only on the adoption of blockchain technology. Recently, Wang et al. (2024) conducted bibliometric and systematic reviews on risks involved with green building projects to evaluate the methods used for their identification and assessments. However, it did not provide a detailed description of each risk and also did not cover the risks associated with scheduling and delays.

None of the aforementioned reviews clearly defined any of the risks they have identified, which raises uncertainty about what exactly a particular risk means and why it may be grouped with another risk. Table 1 presents the previous reviews on green and sustainable building risk assessments, the review methods, contributions, and the limitations leading to the establishment of our research gaps (see Table 2).

This review has identified two major research gaps in the current literature: 1) The limited cross-country research in the field, causing geographically focused outcomes (Adeniyi et al., 2025; Arogundade et al., 2024; El-Sayegh et al., 2021; Maqbool et al., 2023; Okoye et al., 2022; Rodriguez et al., 2024; Wimalarathna, 2023) rather than providing generalisable insights, and 2) The lack of adoption of risk identification and assessment strategies that extend beyond the construction stage of GBCPs and utilises the accumulated knowledge of previous risk evaluation models (Yin and Yu, 2022). Consequently, this work systematically identifies and assesses risks in GBCPs from a global perspective, intending to enhance the effectiveness of integrated risk assessment methods and consequently structuring effective risk management strategies for project management. In doing so, this review paper aims to answer the following research question.

i. What are the key outlets, authors, and collaborative sources in GBCPs' research?
ii. How can each risk be described in detail to facilitate grouping for effective management in GBCPs?
iii. What risk identification and assessment method will provide a long-term risk evaluation that is relevant from the inception to post-construction of GBCPs?

While the above works contributed significantly to the existing body of knowledge in their ways, they have limitations in various aspects, as pointed out above. Moreover, the reason for the need to continuously study and accumulate the risks associated with GCBPs is presupposed by the constant rise of interest in adopting green practices. The novelty of this research is demonstrated in identifying and compiling forty-two (42) comprehensive risks in GBCPs from the literature, defining them, and categorising them into nine major groups based on the primary factors affecting the projects' success. Among the categories are the schedule and planning risks and performance and operational risks, which were not collectively covered in similar research works. Secondly, a scientometric analysis revealed an isolated inter-collaboration level between low-income and high-income countries, whereby intra-collaboration within the same economic level is high but cross-economic collaboration is very low. Finally, the knowledge-based approach is proposed with detailed steps for assessing risks in GBCPs.

Table 1
Previous risk identification methods, contributions, and limitations.

Authors	Methods	Contribution	What's missing
This study	Scientometric, systematic, and Knowledge-based approach	•Extend the risk assessment framework to six steps instead of the often-used three steps. •The knowledge-based framework enables risk assessment from the planning to the end of the project's service life. •Thematic risk categorisation •Comprehensive risk description •Scientometric analysis	–
Wang et al. (2024)	Survey, systematic, and bibliometric	•Bibliometric analysis •Content analysis •Thematic risk categorisation	•Lack risk descriptions •No consideration of risk monitoring during the operation
Nguyen and Macchion (2023)	Systematic review	•Limited thematic risk categorisation •Bibliometric analysis •Content analysis	•Lack risk descriptions •No consideration of risk monitoring during the operation
Maqbool et al. (2023)	Surveys, interviews, and systematic review	•Content analysis •A qualitative measure of sustainable practice barriers	•Lack risk descriptions •No consideration of risk monitoring during the operation •No thematic risk categorisation
Singh et al. (2023a)	Survey, systematic review, and quantitative analysis	•Roadmap for tackling blockchain adoption in sustainable construction •Thematic risk categorisation •Quantitative and statistical analysis of risk categories	•Lack risk descriptions •No consideration of risk monitoring during the operation •Focused on only blockchain technology adoption
Wuni et al. (2023)	Systematic review, bibliometric review, and Pareto analysis	•Comprehensive risk analyses •Qualitative indicators for risk influences •Identified the most vital risks with Pareto analysis	•No consideration of risk monitoring during the operation
Li et al. (2022)	Scientometric review	•Macro-level visual analysis of stakeholder-related green building risks.	•Lack of comprehensive assessment of the risk •No consideration of risk monitoring during the operation
Chen et al. (2022)	Bibliometric and systematic reviews and surveys.	•Thematic risk categorisation •Qualitative measurement of risk influences	•Lack of risk assessment criteria •Lack of risk descriptions
Darko and Chan (2017)	Systematic review	•Identification of the general risks in green buildings	•Lack of risk assessment criteria

2. Scientometric analysis

Studying published works quantitatively to unearth relevant patterns that shed light on existing research trends is helpful, as it provides ample

Table 2
Filters were applied to retrieve the relevant literature.

Search parameter	Filter parameter
Language	English
Publication time	January 1993–2024
Documents inclusion	Article, Conference Paper, Conference Review, and Review
Search keywords	"green construction" OR "sustainable construction" OR "green building" OR "eco-friendly materials" AND "risks" OR "barriers" OR "challenges" OR "practices" OR "certifications".
Complete search string	(TITLE-ABS-KEY ("green construction") OR TITLE-ABS-KEY ("sustainable construction") OR TITLE-ABS-KEY ("green building") OR TITLE-ABS-KEY ("eco-friendly materials") AND TITLE-ABS-KEY (risks) OR TITLE-ABS-KEY (barriers) OR TITLE-ABS-KEY (challenges) OR TITLE-ABS-KEY ("practices") OR TITLE-ABS-KEY ("certifications")) AND PUBYEAR >1997 AND PUBYEAR <2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "cr")) AND (LIMIT-TO (SUBJAREA, "ENGI") AND (LIMIT-TO (LANGUAGE, "English"))

resources to guide future research opportunities (Chen, 2013). Here, the research fields and evolutions are investigated through the lenses of different indexes (Taiwo et al., 2023). This research used the VOSviewer software to investigate journal contributions, co-word analysis, co-authorship by country, and co-authorship networks. On the other hand, the CiteSpace software was used for co-citation timeline, co-occurrence, citation burst, and institutional collaboration analyses. Although both VOSviewer and CiteSpace offer some overlapping functionalities, they complement each other through their unique strengths. VOSviewer excels in generating clear, intuitive visualizations of bibliometric networks and is particularly effective for co-word analysis and visualizing co-authorship relationships at the country level, offering an accessible approach to understanding the structure of academic networks (Arruda et al., 2022). In contrast, CiteSpace is well-suited for more complex analyses, such as co-citation timelines, citation bursts, and the detection of emerging trends, providing insights into the temporal evolution of research and institutional collaborations (Chen, 2014). By combining both tools, this study achieved a more comprehensive exploration of the research landscape, capturing both static network structures and dynamic, time-based research trends. This approach allowed for a nuanced understanding of the field's development and the identification of future research opportunities.

2.1. Search string and material retrieval

A bibliometric search is the primary way to retrieve the records of relevant publications for the Scientometric analysis (Chiang et al., 2023). The keywords, databases, and publication years were carefully selected to ensure the most useful documents were obtained for the required analyses. The search strings, sources, inclusion and exclusion criteria, and filtering techniques adopted are discussed in the next subsection.

2.1.1. Sources and initial inclusion criteria

The search for relevant literature was conducted in the Scopus database due to its compilation of other databases such as Science Direct, Emerald Insight, and Springer Link (Szalkowski and Johansen, 2023). Secondly, it is known for its extensive coverage of green building articles, serving as one of the most comprehensive databases in this field (Wuni et al., 2019). The search was limited to formal research literature published in English from 1993 to the present, as there was no recency limit set. Moreover, to increase the focus and relevancy of the results to our research objectives, the subject area inclusion was limited to Engineering and Business, Management, and Accounting. The following structured steps were followed to compile the relevant documents for the review.

1. **Keyword searching:** this step involves using specific words and phrases that encapsulate the main concepts related to risk studies in green construction. This search was done using the search string without filters, i.e., ("green construction" OR "sustainable construction" OR "green building" OR "eco-friendly materials" AND "risks" OR "barriers" OR "challenges" OR "practices" OR "certifications"). This step yielded 6878 records.
2. **Application of search filters:** the initial search yielded 6878 documents, which included many irrelevant articles to the specific objectives of this research. Therefore, an advanced refinement was necessary to select the most appropriate papers given the substantial volume of data collected. Table 1 shows the search parameters and filters applied to retrieve the documents in Scopus search, reducing the retrieved documents to 4054. Here, only documents related to engineering were included, given the field's relevance and that it has already produced more than 4000 records. We also considered only research articles, conference papers, and review journal and conference papers due to the need to maintain reliability.
3. **Scanning through titles, abstracts, and keywords:** Despite applying filters, the refined outcome still comprised many irrelevant studies. A detailed examination of the retrieved studies' titles and abstracts was conducted to address this shortcoming. This rapid screening procedure identified 165 studies with potential relevance.
4. **Snowballing:** Forward and backward snowballing techniques were employed to expand the sample size and ensure comprehensive coverage of the research articles pertinent to the study, as the results retrieved by the search string may not always be perfect (Taiwo et al., 2023). Twenty (20) more relevant articles emerged from the snowballing to be included in the final database for analysis.
5. **Finalising the database:** The selection of 185 publications for scientometric analysis was based on a systematic search process and specific inclusion criteria designed to ensure relevance and quality. The publications were chosen for their alignment with the study's objectives, covering key topics and trends in green building risk management from 2002 to the end of 2024. This curated selection reflects the scope and focus of the research, ensuring that only the most pertinent and influential works were included. By focusing on this set of high-quality, relevant publications, the analysis provided meaningful insights while avoiding the challenges of analysing an excessively large dataset. This approach enabled a thorough examination of the field, capturing both foundational studies and recent advancements and facilitating the identification of emerging trends and future research directions.

Fig. 1 shows the document retrieval, finalisation, and scientometric review process of the study.

2.2. Findings from the scientometric analysis

2.2.1. Publication trend

The number of research articles published annually related to risk management in Green Building Construction Projects (GBCPs) has achieved general growth in the last decade. Notably, steady growth was witnessed from 2017 onwards, despite a few dips until 2020. This phenomenon can be attributed to the formulation of the SDGs in 2015, which piqued researchers' and practitioners' interest in engaging in sustainable construction practices, as sustainable practices were petitioned for all industries (Abdulmaksoud and Beheiry, 2023; Adabre et al., 2021). The trend shows promising growth in interest in the future, as the highest number of publications per year is witnessed in 2024. Overall, the findings from the publication trends strongly imply that the topic of "Risks in GBCPs" is an emerging issue gaining momentum. Fig. 2 illustrates the number of published documents per year from 2002 to 2024 to assess the research tendency.

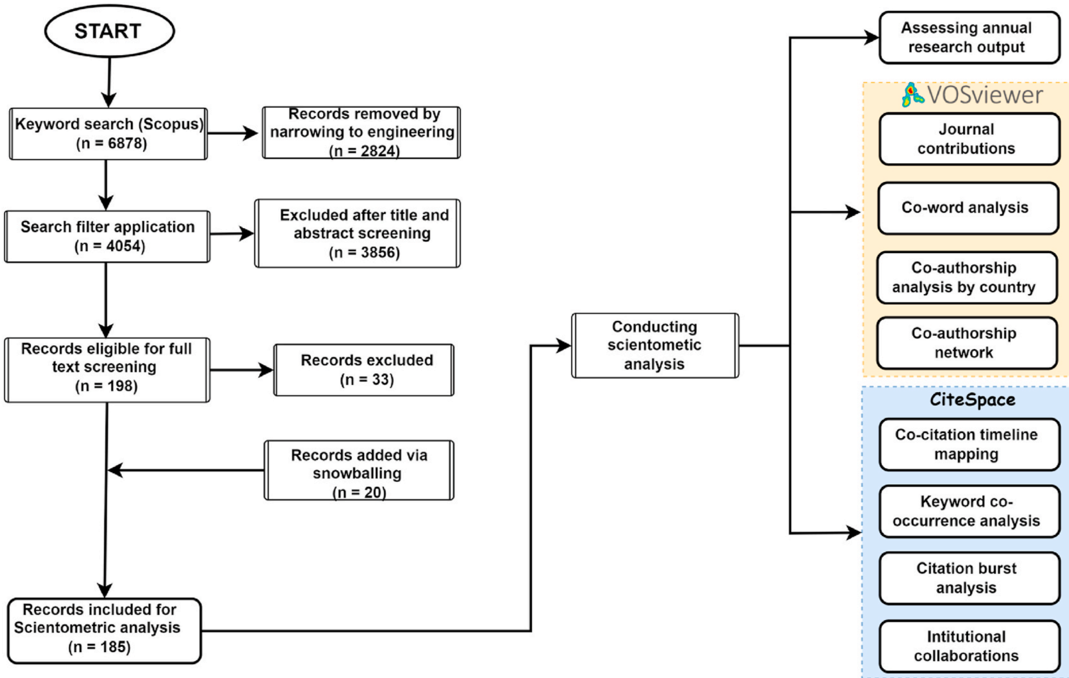


Fig. 1. The methodological framework of the review process.

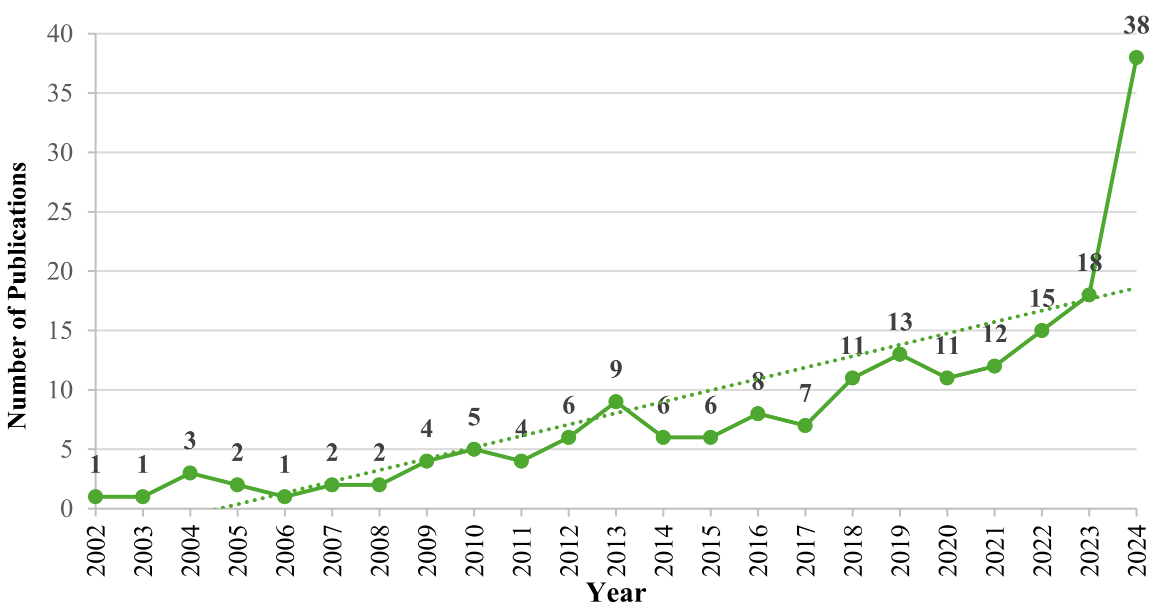


Fig. 2. Number of annual publications.

2.2.2. *Journal contributions*

Analysing the outlets of scholarly articles provides researchers and other focused audiences with reliable journals to source relevant content. The prominent journals publishing risk studies in GBCPs are identified based on direct citation outcomes of the 185 synthesised papers. As shown in Fig. 3, 27 journals met the criteria, forming a network of interconnected coloured clusters and nodes. The clusters distinguish between relationships of research disciplines and co-citation frequency. The network is also distance-dependent, indicating stronger citation links, cohesive citation patterns, and interconnected research themes between closely positioned research outlets (Owolabi et al., 2022). The node sizes in the clusters show the impact of the research outlet compared to the others. For instance, the Journal of Cleaner Productions, Smart and Sustainable Built Environment, IOP Conference Series: Materials Science and Engineering, and Journal of Engineering, Design, and Technology have larger node sizes and exhibit relatively larger nodes, signifying their higher impact in research publications compared to other outlets. Furthermore, thicker lines between nodes demonstrate the strength of citation relationships between those journals. An example is the Journal of Cleaner Production and Architectural Engineering and Design Management. These interactions are essential to guiding researchers in identifying the best outlets to increase the visibility and impact of their works and benefit large audiences.

2.2.3. *Co-word analysis*

Co-word analysis was performed to study the keyword co-occurrence

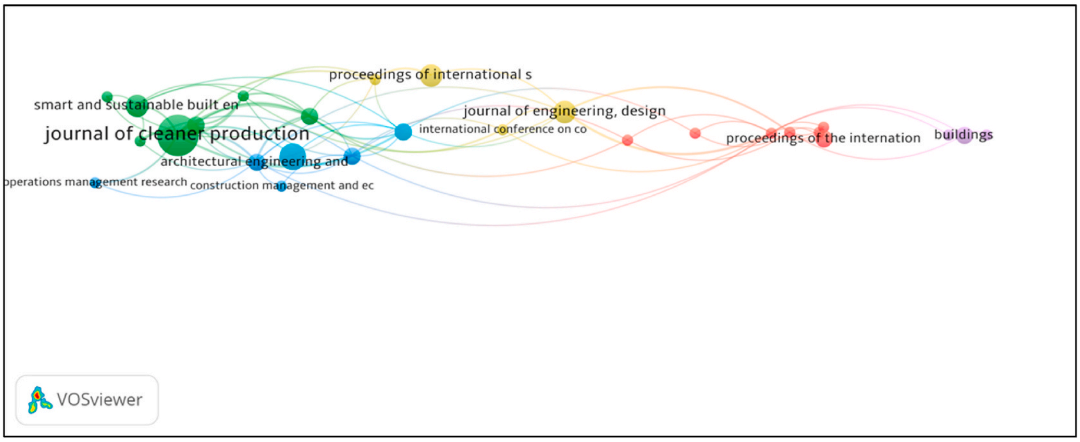


Fig. 3. Analysis of journal contributions.

from the selected articles and identify the relationships between concepts and the evolution of research topics. The minimum occurrence threshold was set to 5, resulting in 29 out of 475 keywords meeting the criteria. Similarly, the distance between nodes demonstrates the level of closeness (Owolabi et al., 2022). The colour bands indicate unique clusters and the years of the emergence of the various clusters. Larger node sizes show the frequency of their occurrence and importance. "Sustainable development", "sustainable construction", "construction industry", and "risk assessment" are the prominent keywords in the co-word analysis, as shown in Fig. 4. Thicker links are observed between "sustainable development," "sustainable construction," and "construction industry," signifying how closely they are often used despite "construction industry" emerging earlier than the other former two. Similarly, the phrase "green buildings" is often used with "sustainable development" and "risk assessment" with "sustainable construction." These phenomena can be attributed to the growing interest of researchers and practitioners in promoting sustainability in the construction industry by engaging in a substantial amount of GBCPs worldwide.

2.2.4. Co-authorship analysis by country

In this subsection, the geographical analysis of the research output is explored to establish the most active regions and encourage others to put more effort into GBCPs. The thresholds for the number of documents and citations from a country were set to 3 and 0, respectively. From 30 countries whose documents were analysed, 14 met the threshold, and 11 formed a network connection with four clusters. The node sizes also demonstrate the strength in terms of the number of documents and citations a country contributes to GBCP research. South Africa, the United Kingdom, and the United States produced larger nodes, denoting their significant contributions in the field. Countries form clusters with unique colours based on the strength of collaboration, co-citations, or similarities in research areas. For instance, South Africa, Nigeria, Malaysia, and India are developing countries with a collaborative cluster in red, as shown in Fig. 5, even though there are some interactions with other countries in different clusters. The clusters can help unearth regions that lack collaboration with each other.

2.2.5. Co-authorship networks

Following the country contribution analysis, the individual author

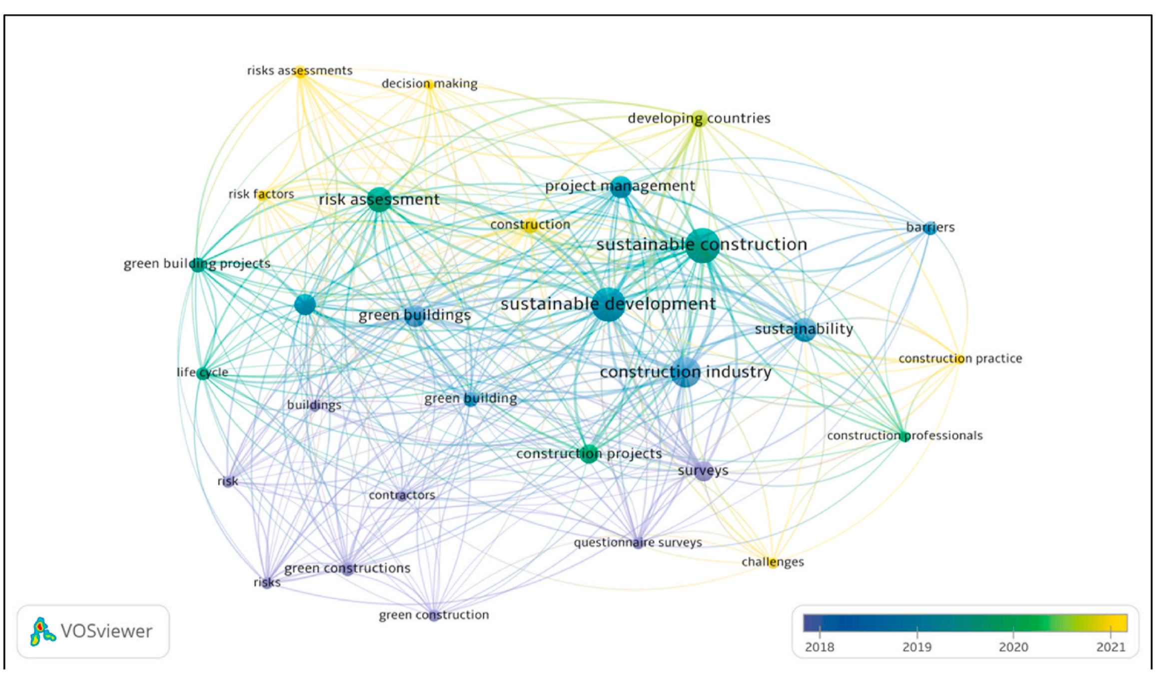


Fig. 4. Co-word analysis.

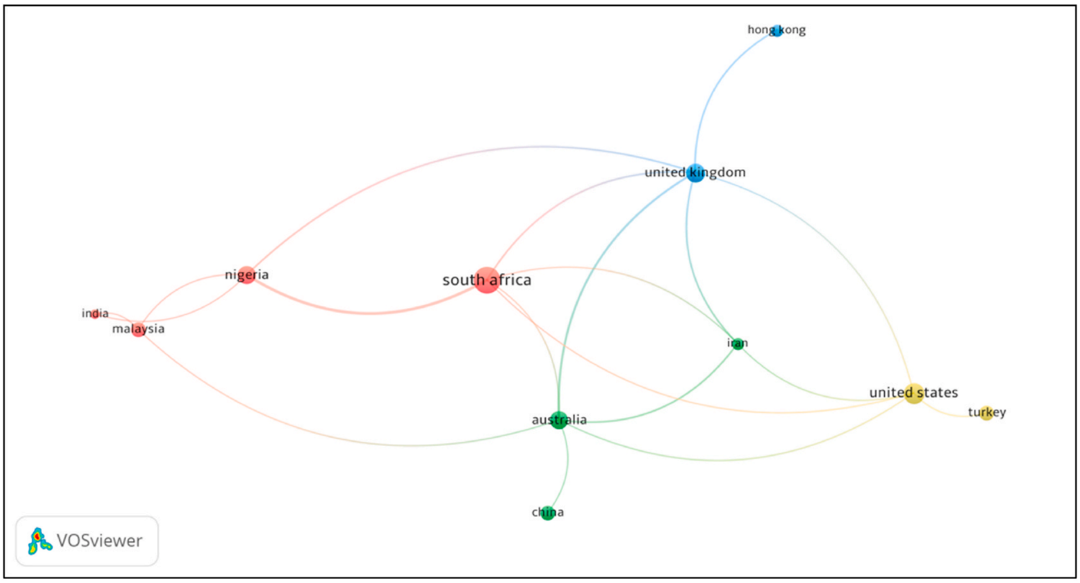


Fig. 5. Co-authorship analysis by country.

contributions are studied in this section. The collaborations were mapped to identify key researchers, research impacts, and dynamics in the GBCPs field. Among the 214 captured authors, nine formed the most extensive set of connected nodes and two comprehensive clusters in red and green, as shown in Fig. 6. The co-authorship social structure can aid policymakers and funding institutions in making informed research investments and decisions.

2.2.6. *Timeline co-citation map analysis of documents*

The co-citation relationships of risks in sustainable construction are explored to unveil the advancement of various studies over time. The research timeline based on a temporal-linear diagram is presented from 2015 to 2023, as shown in Fig. 7. Node size represents document importance, while proximity indicates high co-citation frequency (Azam et al., 2021). Individual studies (in circles) are connected to show citation or thematic relationships. There was a strong research output focusing on developing countries or from authors in developing countries during 2013–2018, where it halted and efforts diverted to potential barriers, drivers, and strategies in adopting green building technologies (GBTs). The coloured clusters inform readers about the evolution of research topics and the potential future research dynamics. The most prolific papers in terms of co-citation output are those related to GBTs in developing countries (Ametepey et al., 2015; Chan et al., 2018) and barriers, risks, and potential of adopting GBTs (Akadiri, 2015; E.E. & Davies, 2017).

2.2.7. *Co-occurrence analysis of keywords*

The co-occurrence analysis of keywords provides invaluable insights into the evolving landscape of hot research areas, analytical perspectives, and research methods in sustainable construction. In this research, the analysis was conducted over the period from 2002 to 2024, utilising a threshold value of K = 50, YearPerSlice set to "2," and applying the Pathfinder pruning method. The resultant keyword co-occurrence network depicts 323 high-frequency keywords interconnected by 1110 lines, as shown in Fig. 8. Keywords such as "sustainable construction," "sustainable development," "sustainability," "risk assessment," "green buildings," and "risk management" show thicker and denser circles, signifying their greater importance and co-occurrence frequencies. The font sizes of keywords also indicate their co-occurrence frequencies and prominence among the assessed papers, while connections indicate their relationships (Chen, 2013). The analysis of the period reveals that keywords like "sustainability," "sustainable construction," "sustainable development," and "construction industry" have shown enduring presence in the field. Concurrently, recent keywords such as "risks assessments," "multivariant analysis," "factor analysis," "building risk," and "systematic literature review" have surfaced, suggesting potential new

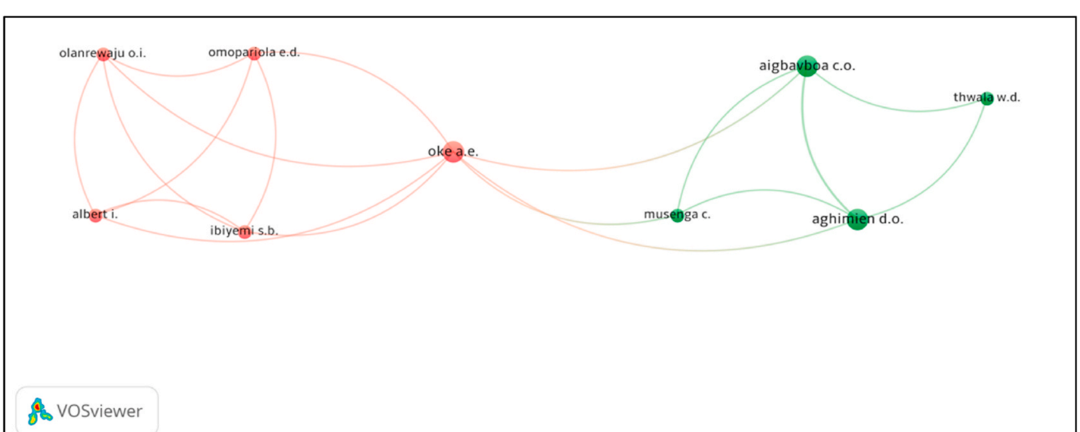


Fig. 6. Co-authorship networks of GBCP researchers.

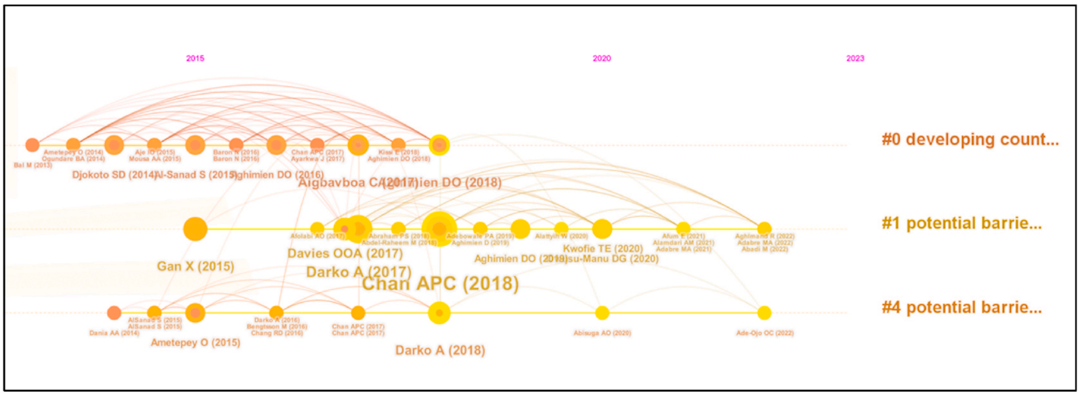


Fig. 7. Co-citation timeline of documents.

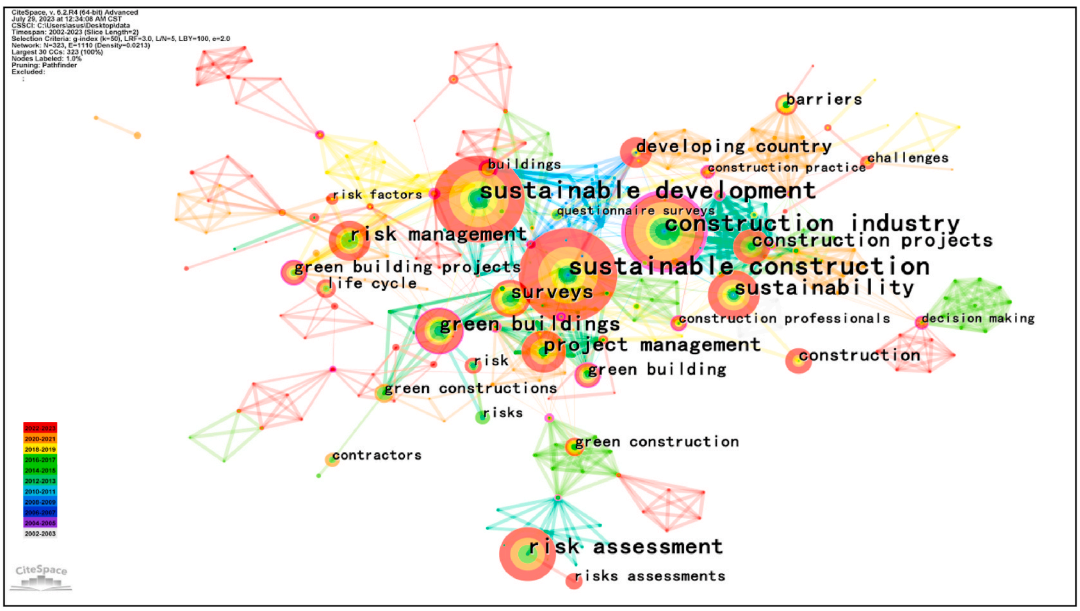


Fig. 8. The network of co-occurrence of keywords.

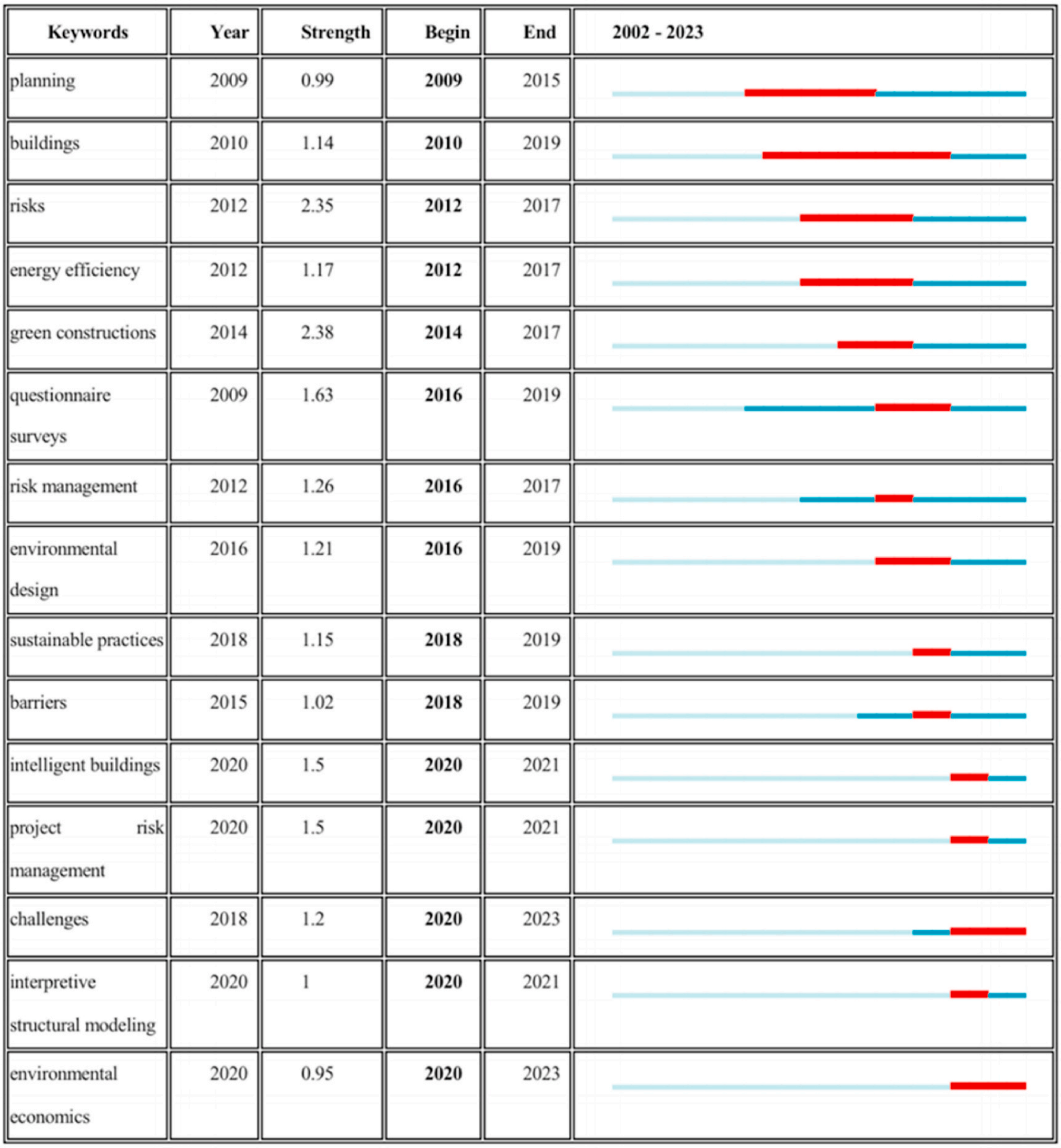
research directions in the sustainable construction domain. This observation highlights the dynamic nature of the research landscape and indicates opportunities for future exploration in sustainable construction studies.

2.2.8. *Citation bursts analysis*

Certain keywords have experienced a boom in appearance in GBCP studies over time due to their importance in communicating the relevant ideas and objectives of GBCPs and their developments. This phenomenon causes strong citation bursts during their active years, generating significant interest levels among researchers. Keywords and phrases like "Buildings," "planning," and "energy efficiency" have exhibited prolonged prominence as research hotspots over extended periods. Moreover, analysing the emergence strength of keywords reveals that "green constructions" (Strength = 2.38), "risks" (Strength = 2.35), "questionnaire surveys" (Strength = 1.63), and "risk management" (Strength = 1.26) have shown notable fluctuations in their appearance frequency. Fig. 9 shows the citation burst analysis of the top 15 keywords from the papers examined, where the red streak indicates the period of citation burst (Chen, 2013). In conclusion, the research content and hotspots in sustainable construction change over time, reflecting the progress of society and external environmental factors. This dynamic nature emphasises the importance of investigating risks in green buildings as a valuable and worthwhile research topic. Challenges related to implementing green building concepts are realised to influence current research works continuously, as is the environmental economics associated with GBCPs.

2.2.9. *Institutions collaboration*

The institutional collaboration network explores the relationships among research institutions in a specific field, offering an intuitive representation of their collaborations. The analysis covers "2002 to 2024″ in slices of "2″ years. With a parameter k of "100," the NodeTypes panel displays "Institution." Fig. 10 shows nodes sized by the number of journal papers published by each institution and connections reflecting collaboration strength. The Institution collaboration network produced 116 nodes and 108 connections, resulting in a network density of 0.0162. It presents a substantial number of research institutions, with dense connections among main institutions, implying significant collaboration. The University of Johannesburg, The Hong Kong Polytechnic University, and the American University of Sharjah appeared as the most prominent institutions in research output in this field. Similarly, the former two have the most extensive collaborations on the map. Various colour schemes representing nodes and links communicate the periods of activity, with most of the research collaborations and outputs showing significant recency. This behaviour signifies the continuous



Keywords	Year	Strength	Begin	End	2002 - 2023
planning	2009	0.99	**2009**	2015	
buildings	2010	1.14	**2010**	2019	
risks	2012	2.35	**2012**	2017	
energy efficiency	2012	1.17	**2012**	2017	
green constructions	2014	2.38	**2014**	2017	
questionnaire surveys	2009	1.63	**2016**	2019	
risk management	2012	1.26	**2016**	2017	
environmental design	2016	1.21	**2016**	2019	
sustainable practices	2018	1.15	**2018**	2019	
barriers	2015	1.02	**2018**	2019	
intelligent buildings	2020	1.5	**2020**	2021	
project risk management	2020	1.5	**2020**	2021	
challenges	2018	1.2	**2020**	2023	
interpretive structural modeling	2020	1	**2020**	2021	
environmental economics	2020	0.95	**2020**	2023	

Fig. 9. A citation analysis of GBCP literature.

interest and research dynamics in GBCPs over the coming years.

3. Key insights and discussions from in-depth literature analysis

3.1. Risk management in green building construction projects

Risk management is inherent to construction processes because it cannot be eliminated unless managed. Therefore, it is essential to employ the appropriate approaches, strategies, and actions to identify, analyse, and respond to the potential risks throughout the project's lifecycle to realise its successful completion within the allocated budget and timeline (Alhawari et al., 2012; Koc et al., 2023; Zayed et al., 2008). Risk management creates value for all stakeholders, adding economic, ecological, and social impacts to the project's sustainability goals. Thus, aside from safeguarding the project against potential losses, it explores new opportunities that align with the broader objectives of environmental stewardship and social responsibility (Testorelli et al., 2024). Risk management in GBCPs can be considered in two broad canopies based on the scope of the objectives: overall goals and hierarchical goals. The overall goal is to ensure adequate management processes are undertaken via risk identification, analysis, response, and monitoring for success throughout the lifecycle of the GBCP (Koc et al., 2023). The hierarchical goals, on the other hand, separate the output of individual risk management components into economic, environmental, and social goals for related analysis (Li, 2021). This hierarchical analysis is important when corporations and government agencies with significant sustainable targets interested in promoting specific sustainable development goals are involved.

3.2. Categories and detailed descriptions of risks in green building construction projects (GBCPs)

The study began with the risks identification process step to prepare suitable grounds for successful analyses and discussions. An effective risk identification would establish a solid basis to manage risks and ultimately determine the success of green building construction projects (Banaitiene and Banaitis, 2012). A thorough literature review was conducted to extract potential risk factors involved with GBCPs. Using

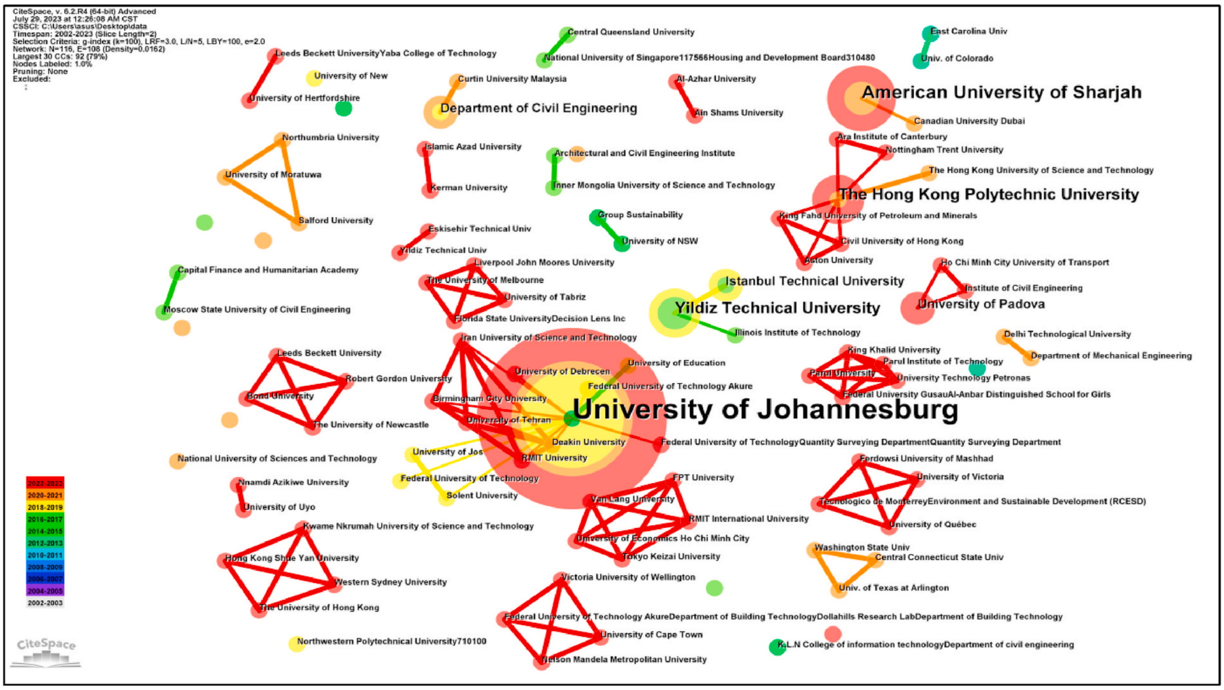


Fig. 10. Influence of institution in GBCPs.

the Scopus database, a total of 185 papers focusing on the analysis of risks associated with GBCPs were carefully selected, which provided valuable resources in creating the initial list of risk factors. From the selected papers, forty-two (42) most influential risk factors were identified and subsequently categorised into nine primary risk categories. These categories encompass technical risk, financial risk, material, equipment, and technology risk, design risk, schedule and planning risk, regulatory and legal risk, communication and awareness risk, performance and operational risk, and environmental risk.

3.2.1. Technical risks

Technical risks in GBCPs encompass numerous factors dictating the product's quality. They are part of the broader quality and technical issues category, forming challenges associated with design, construction, and assessment experiences. These risks are interconnected with various stakeholders, including contractors, subcontractors, project teams, and material and service providers, whose collective actions are required for the success of the projects (Yang et al., 2016). The risks could be expertise challenges, material availability, lack of high-end technique, unclear owner requirements, vague role allocations (Hwang et al., 2017b), and design and construction risks (Yang et al., 2016). The design and construction phase entails some of the primary technical challenges due to the intricacies of the various activities in this stage (Al-Bahar and Crandall, 1990; Wang et al., 2004). Table 3 presents the identified technical risks associated with GBCPs and their definitions.

3.2.2. Financial risks

Green building construction projects frequently require higher initial investments compared to traditional building projects owing to specialised materials, equipment, and technologies (Gashaw et al., 2023; Maqbool et al., 2023). Additional skilled labour and expertise in sustainable construction practices are needed for these projects, increasing the emergence of financial risks in the industry (Chan et al., 2017; Javed et al., 2019; Qin et al., 2016). Moreover, factors such as insufficient client funding and resources, inflation, and inaccurate estimation of return on investment (ROI) or payback period can further contribute to financial risks (De Beer, 2023; Koc et al., 2023). They are also influenced by high-cost transportation and storage. (El-Sayegh et al., 2021; Rodriguez et al., 2024; Wuni et al., 2023). The identified risks under the financial category are described in Table 4.

3.2.3. Material, equipment, and technology risks

The availability and choice of environmentally friendly materials are critical in green building projects (Gurgun et al., 2018). Similar concerns are associated with obtaining and operating green equipment and technologies, as a mishap can cause risks associated with materials, equipment, and technology, leading to project delays and cost overruns. These risks primarily revolve around the shortage, quality, specifications, and performance of the green materials, equipment, and technologies implemented in the GBCPs (Al-Hajj and Hamani, 2011; Alattyih et al., 2020; Gurgun et al., 2016; Ismael and Shealy, 2018; Polat et al., 2017). Material-related risks can be caused by the lack of standardized definitions and regulations, varying material quality, long approval processes, and the need for special storage facilities (Gounder et al., 2023). Equipment risks may be due to untested new equipment, lack of experience with the equipment, and inherent flaws within the equipment itself. The evolution of new technologies, such as BIM (Al-Raqeb et al., 2024; aAhmed F Kineber et al., 2023), digital twin (bAhmed Farouk Kineber et al., 2023), blockchain (Singh et al., 2023a, 2023b) demands constant worker skill upgrades as they inject unfamiliarity into the workflow. The individual risks are detailed in Table 4.

3.2.4. Design risks

Design risk in green building construction projects refers to the potential challenges and uncertainties related to the design process. It encompasses factors such as inaccurate and insufficient design information, repetitive design alterations, and insufficient incorporation of sustainability concepts into the design of green buildings (Nguyen and Macchion, 2022; Okoye et al., 2022; Wuni et al., 2023). Insufficient innovation, low creativity in green building designs, lack of full assessment of the constructability of the designs, and change-resistant cultures due to fears and uncertainties are typical factors causing design risks (Polat et al., 2017; Waqar et al., 2023; Yin and Zhao, 2024a). The individual risks are detailed in Table 5.

Table 3
List and definition of risks under the technical category.

Category of risk	Risk	Description	Reference
Technical	Restricted accessibility and reliability of green building subcontractors	It highlights the risk of scarcity and unreliable performance of subcontractors specialised in green construction, potentially causing delays, quality issues, and disruptions in the project.	(El-Sayegh, 2008; Hlaing et al., 2008; Kartam and Kartam, 2001; Zhao et al., 2016; Zhi, 1995; Zou et al., 2007)
	Absence of skilled and experienced project team	It denotes the risk of not having a project team with sufficient expertise and experience in GBCPs, potentially leading to implementation challenges, quality issues, and compromised sustainability goals.	(El-Sayegh et al., 2021; Ismael and Shealy, 2018; Krechowicz, 2017; Ofori-Boadu et al., 2012; Polat et al., 2017; Qin et al., 2016; Zhi, 1995)
	Technical complexity of design and construction of green buildings	It refers to the risk arising from the intricate and specialised nature of designing and constructing green buildings, which can introduce complexities, technical challenges, and potential errors.	(Al-Bahar and Crandall, 1990; Arogundade et al., 2024; El-Sayegh, 2008; Eybpoosh et al., 2011; Panthi et al., 2009; Wuni et al., 2023; Zhao et al., 2016; Zhi, 1995)
	Insufficient availability of suppliers of eco-friendly materials and products	It refers to the risk of insufficient availability of suppliers offering high-quality green materials and products, potentially impacting the project's procurement process, cost, and sustainability objectives.	(El-Sayegh et al., 2021; Lam et al., 2009; Wuni et al., 2023)

3.2.5. Schedule and planning risks

Schedule and planning risks provide the basis for determining difficulties and matching mitigation measures to enhance the schedule performance of projects (M. Li et al., 2017). They are often caused by unreasonably tight project schedules, logistic challenges, and labour shortages resulting from the limited availability of green materials and reliable green subcontractors and the inflation of material prices (El-Sayegh et al., 2021; Herath et al., 2023; Szymański, 2017; Yang et al., 2016). Delays are prevalent in construction projects, not excluding GBCPs (Hwang et al., 2017b). Additionally, inadequate scope definition and uncertainties about green building activities significantly contribute to schedule and planning risks (Alattyih et al., 2020; Winston, 2010). Supply chain management problems and contractual issues also complicate these risks (Al-Saffar et al., 2024). The individual description of each risk under schedule and planning is detailed in Table 6.

3.2.6. Legal and regulatory risks

A significant number of contractual laws and regulations control construction projects. These legal procedures are influenced by the sheer quantities of risks involved in the construction industry, as all green building projects. Regulations are reasonable due to the existence of unforeseen events, such as unexpected inflation of material and services, payment defaults, and conflicts of interest (Coskun et al., 2023; Maqbool et al., 2023). Conflicts may arise when the standard form construction contracts do not adequately address the green building concepts and

Table 4
List and definition of risks under the financial category.

Category of risk	Risk	Description	Reference
Financial	Shortage of client's funding and resources	Risk of inadequate financial resources allocated by the client, potentially limiting the scope, quality, and effectiveness of green building initiatives.	(El-Sayegh et al., 2021; Koc et al., 2023; Wuni et al., 2023; Zou et al., 2007)
	Inflation and price fluctuations of green construction materials and labour	Variations in the inflation rate will cause price changes for labourers and materials.	(Ahmad et al., 2019; El-Sayegh et al., 2021; Hwang et al., 2017a, 2017b; Rafindadi et al., 2014; Ranawaka and Mallawaarachchi, 2018; Zhao et al., 2016)
	Additional design and construction costs of green buildings	Risk of increased expenses associated with incorporating sustainable features and technologies into the design and construction process, potentially impacting the project budget and profitability.	(Alattyih et al., 2020; Wuni et al., 2023; Patrick and Couani, 2012)
	High cost of green materials and equipment	It refers to the risk of elevated expenses for procuring environmentally friendly materials and equipment, contributing to higher construction costs and financial strain on the project.	(Chan et al., 2017; El-Sayegh et al., 2021; Hwang et al., 2017a, 2017b; Hwang and Ng, 2013; Qin et al., 2016; Zhao et al., 2015)
	Additional expenses of green product and material certification and re-evaluation	It refers to the risk of additional expenses incurred for obtaining green certifications or conducting re-testing, potentially impacting the project budget and timelines.	(Gashaw et al., 2023; Gurgun et al., 2016; Koc et al., 2023; Wuni et al., 2023)
	Incorrect projection of project return on investment (ROI) or payback period	It refers to the risk of inaccurately forecasting the financial returns and payback period of green building investments, potentially leading to misaligned expectations and reduced confidence in the project's economic viability.	(Gurgun et al., 2016; Hwang et al., 2017b; C. Z. Li et al., 2017; Menassa, 2011; Qin et al., 2016; Ulubeyli and Kazanci, 2018)
	Lack of market demand	It is the risk of insufficient market interest or demand for green buildings, potentially impacting the project's marketability, sales, ROI, and long-term viability.	(Ashuri and Durmus-pedini, 2010; De Beer, 2023; Kasapoğlu, 2018; Maqbool et al., 2023; Okoye et al., 2022)

risks. Moreover, too many regulations and laws sometimes emerge from governmental bureaucracy, leading to confusion and risks (Adekunle et al., 2023; Kasapoğlu, 2018; Qin et al., 2016; Patrick and Couani, 2012). Labour disputes are another potential source of legal disputes in GBCPs (Tao and Xiang-Yuan, 2018). The individual description of each

Table 5
List and definition of risks under the material, equipment, and technology category.

Category of risk	Risk	Description	Reference
Material, equipment, and technology	Scarcity and insufficiency of authorised green materials, equipment, and technologies	It denotes the risk of insufficient supply of certified green materials, equipment, and technologies, potentially causing delays, cost overruns, or compromises in the project's sustainability features.	(El-Sayegh et al., 2021; Hwang et al., 2017a; Ismael and Shealy, 2018; Okoye et al., 2022; Rodriguez et al., 2024; Patrick and Couani, 2012)
	Unverified quality of new green products, materials, equipment, and technologies	It refers to the risks associated with using newly introduced or innovative green products, materials, equipment, and technologies whose performance and reliability have not been extensively validated, potentially leading to unexpected failures or subpar performance.	(Alattyih et al., 2020; Wuni et al., 2023)
	Inaccurate or insufficient green specifications of new green products, materials, equipment, and technologies	It emphasises the potential consequences of insufficiently detailed specifications for green products, materials, equipment, and technology. Such inadequacies may lead to mistakes during the project construction process.	(Al-Hajj and Hamani, 2011; El-Sayegh et al., 2021; Gounder et al., 2023)
	Poor performance of green materials, equipment, and technologies	It indicates the potential for green materials, equipment, and technologies to underperform, hence hindering the achievement of sustainability objectives, necessitating increased maintenance efforts, and diminishing the overall efficacy of the project.	(El-Sayegh et al., 2021; Gurgun et al., 2016; Hwang et al., 2017a)

risk is detailed in Table 7.

3.2.7. Communication and awareness risks

Communication and awareness risk encompasses the potential for ineffective communication, strained stakeholder relationships, unclear stakeholder responsibilities, and limited public awareness regarding the significance of green building, which can result in diminished project performance, conflicts, and disputes (Nguyen and Macchion, 2022, 2023; Okoye et al., 2022; Wuni et al., 2023). Each risk identified under the communication and awareness risks is detailed in Table 8.

Table 6
List and definition of risks under the design category.

Category of risk	Risk	Description	Reference
Design	Inaccurate and insufficient design information	It indicates the risks associated with deficient or erroneous design information, specifically, the absence of necessary data or requirements, resulting in additional work and construction delays.	(El-Sayegh et al., 2021; El-Sayegh, 2008; Okoye et al., 2022; Qin et al., 2016; Zhao et al., 2016)
	Frequent design changes and variations	It underlines the possible hazards associated with frequent revisions and alterations to the green building design, which may result in interruptions, escalated expenses, and project schedule delays.	(Hwang et al., 2017a; Ismael and Shealy, 2018; Nguyen and Macchion, 2022; Okoye et al., 2022; Ranawaka and Mallawaarachchi, 2018; Zhao et al., 2016)
	Insufficient incorporation of sustainability into the green building design	Risk of failing to fully incorporate sustainable design principles and features into the overall design of green buildings, potentially resulting in suboptimal performance, missed opportunities for energy efficiency, reduced environmental benefits, and low confidence.	(Alamdari et al., 2023b; Wuni et al., 2023)

3.2.8. Performance and operational risks

Performance and operational risk concern the operation efficiency, maintenance, labour productivity, equipment, and technology in green building construction projects (Ahmad et al., 2019; Alattyih et al., 2020; Wuni et al., 2023). Failure to meet sustainable construction certification requirements and incidents during construction significantly contribute to performance and operational risk (Adekunle et al., 2023; Krechowicz, 2017; Qazi et al., 2021). Performance and operational risks may emanate from increased equipment cost and faulty equipment issues. These risks are also influenced by the level of expertise in operating the equipment and executing various tasks within the project (Mokhtar Azizi, 2010; Al-Saffar et al., 2024). The failure and lack of tools to measure sustainable practices targets like embodied carbon during green building construction threaten its success (Cramer, 2023). Each risk associated with the performance and operational class is discussed in detail in Table 9.

3.2.9. Environmental risks

Environmental risk refers to potential uncertainties related to the green building construction site and weather conditions. It encompasses factors such as unforeseen adverse site conditions, challenges in land acquisition, and the influence of extreme weather events, all of which can contribute to environmental risks. Some of these events are uncontrollable and emerge from natural occurrences, natural conditions, and human-induced events. For instance, earthquakes can trigger liquefaction, causing severe environmental risks to green building projects (Afshari et al., 2016; Ahmad et al., 2019; Duong et al., 2023;

Table 7
List and definition of risks under the schedule and planning category.

Category of risk	Risk	Description	Reference
Schedule and planning	Delays caused by the green construction process	It refers to the potential setbacks and extensions in the project timeline that may occur.	(Chan et al., 2017; Ismael and Shealy, 2018; Nguyen and Macchion, 2022; Okoye et al., 2022; Ranawaka and Mallawaarachchi, 2018; Szymański, 2017; Yin et al., 2018)
	Unreasonable tight schedule for sustainable construction	It denotes the risk of imposing excessively tight deadlines or timelines for completing green building projects, potentially leading to rushed work, compromised quality, and increased safety hazards.	(El-Sayegh et al., 2021; Okoye et al., 2022; Szymański, 2017)
	Failure to acquire materials/ equipment within the designated timeframe/stage	It refers to the risk of experiencing delays or non-availability of materials and equipment at the specified time or construction phase, potentially causing disruptions, rework, and schedule delays.	(Aktas and Ozorhon, 2015; Hwang et al., 2017a, 2017b; Krechowicz, 2017; Nguyen et al., 2017; Ranawaka and Mallawaarachchi, 2018; Yang et al., 2016)
	Poor scope definition and unclear allocation of roles in sustainable construction	It highlights the risk of inadequate clarity and understanding of the project scope and its feasibility and improper assignment of responsibilities among stakeholders, leading to confusion, inefficiencies, and potential conflicts.	(Alattyih et al., 2020; El-Sayegh et al., 2021; Gurgun et al., 2016; Okoye et al., 2022; Qin et al., 2016; Yang et al., 2016)

Table 8
List and definition of risks under legal and regulatory category.

Category of risk	Risk	Description	Reference
Legal and regulatory	Intricate approval procedures, codes, and regulations for green buildings	It highlights the risk of encountering intricate and time-consuming approval processes, building codes, and regulations specific to green buildings, potentially causing delays, increased costs, and compliance challenges.	(Gurgun et al., 2016; Hwang et al., 2017a; Polat et al., 2017; Qin et al., 2016; Zhao et al., 2016; Patrick and Couani, 2012)
	Change in local regulations/ governmental policies	It underlines the risk of experiencing alterations in local regulations and governmental policies related to green buildings, potentially requiring adjustments, additional compliance efforts, and impacts on project feasibility.	(Ahmad et al., 2019; Hwang et al., 2017b; Ismael and Shealy, 2018; Tao and Xiang-Yuan, 2018; Yang et al., 2016; Zhao et al., 2015; Patrick and Couani, 2012)
	Evolving procedures and policies for green building certification	It refers to the risk of modifications or updates in the procedures and policies of sustainable building certifications, potentially necessitating adjustments, re-evaluations, and additional efforts to meet the revised requirements.	(Bashir et al., 2024; El-Sayegh et al., 2021; Nutter, 2011; Okoye et al., 2022; Qin et al., 2016)
	Inadequate definition of project parties' contractual roles and responsibilities	It denotes the risk of unclearly defined contractual obligations among project parties, leading to misunderstandings, disputes, and potential delays or disruptions in green building projects.	(Coskun et al., 2023; Gurgun et al., 2016, 2018)
	Unclear contract clauses and conditions for green building	It highlights the risk of uncertain conditions for disputes, claims, and litigation resolution in contracts of green building construction, resulting in contractual disputes, disagreements, and difficulties in ensuring compliance with sustainability objectives.	(Gurgun et al., 2016; Qin et al., 2016; Rafindadi et al., 2014; Yang et al., 2016; Zhao et al., 2015; Patrick and Couani, 2012)
	Litigation, legal actions, and prosecutions during construction for not achieving client expectations	It denotes the risk of legal disputes, lawsuits, or prosecutions arising from the failure to meet client expectations in green building projects, potentially leading to significant financial and reputational consequences.	(Ametepey et al., 2015; Kasapoğlu, 2018; Okoye et al., 2022; Qin et al., 2016; Tollin, 2011)

Williams and Dair, 2007). The individual risks under the environmental category are detailed in Table 10.

3.3. Knowledge-based risk management process in GBCPs

Assessing risks in construction projects is often considered in three steps, namely: risk identification, risk assessment, and risk response (Zayed et al., 2008), and the same steps have been applied to GBCPs (Duong et al., 2023; Li, 2021) (see Table 11). However, studying it from the knowledge-based risk management approach may provide a deeper understanding of better applications for risk mitigations throughout the project's lifecycle. The knowledge-based risk management approach entails the following six primary components: establishing the scope, identifying the risk, analysing the risk, planning a response to the risk, educating stakeholders about the risk, and ensuring continuous monitoring of the effects of the risk. It has received success in other areas of the construction industry research (Goh &Chong, 2024; Sadeghi &Zhang, 2024), including assessing the performance of green buildings (Nilashi et al., 2015). This process is summarised in Fig. 11. The next subsections discuss each component in detail.

3.3.1. Risk scope establishment

This stage specifies the level of entities and bodies to be considered within the concerned group for constructing the full risk coverage. The targeted stakeholders, objectives, extent of the risk management activities, duration, and processes are defined in this stage. Establishing the scope requires a systematic identification of the physical and operational boundaries of the projects and the resources involved (Alhawari et al., 2012). Further, the operational authorisation limits are delineated to set clear lines of authority and decision-making protocols and minimise project conflicts, and the responsible support personnel is clearly stated. Stakeholders are required to make informed decisions based on the essential information about design details, materials, equipment, labour, etc., provided under the scope of the risks (Le et al., 2009). The outcome of this stage in GBCPs is to ensure that all stakeholders maintain a common understanding of the risk management constituents, objectives, and parameters within which the risk will be managed. It's a foundational step that sets the stage for all subsequent risk management activities, such as risk identification, analysis, and response planning.

3.3.2. Risk identification

A well-structured and comprehensive risk identification lays the

Table 9
List and definitions of risks under the communication and awareness category.

Category of risk	Risk	Description	Reference
Communication and Awareness	Inadequate communication, collaboration, and information exchange among project team members	It refers to the risk of ineffective communication, collaboration, and sharing of vital information among the project team members, leading to misunderstandings, errors, and hindered progress in green building projects.	(Hwang et al., 2017b; Le et al., 2009; Nguyen and Macchion, 2022; Shooshtarian et al., 2023; Tang et al., 2007; Zhao et al., 2016)
	Weak connections among the client, project team, and supply chain partners	It highlights the risk of ineffective relationships and communication channels among stakeholders, resulting in conflicts, delays, compromised quality, and increased project costs.	(Okoye et al., 2022; Qin et al., 2016; Wuni et al., 2023; Zhao et al., 2016; Patrick and Couani, 2012)
	Complex stakeholder composition and requirements	These refer to risks emanating from challenges, such as potential conflicts and disagreements arising from the diverse stakeholders involved in green building projects, each with unique objectives and demands.	(Alamdari et al., 2023b; Wuni et al., 2023)
	Ambiguous responsibility of stakeholders in attaining green certification	It denotes the risk of ambiguity or lack of clarity regarding stakeholders' specific roles, responsibilities, and obligations in achieving the green certification requirements, potentially leading to confusion, inefficiencies, and non-compliance with the certification standards.	(Nguyen and Macchion, 2022; Qin et al., 2016)
	Insufficient public awareness and knowledge	It highlights the risk of limited awareness among the public regarding the importance of green building, potentially leading to resistance, scepticism, or reduced support for green building initiatives.	(Gashaw et al., 2023; Ismael and Shealy, 2018; Okoye et al., 2022)

foundation for subsequent processes and guarantees the effectiveness of risk management (Banaitiene &Banaitis, 2012). The risk identification phase is crucial for effective risk management as the remaining stages depend on it to establish the right call for mitigation. The sources of risk and potential consequences must be identified before mitigation processes can be applied (Al-Bahar and Crandall, 1990; Project Management Institute, 2021; Wang et al., 2004). Notwithstanding, the risk identification process facilitates the project to comprehensively investigate all prospective risk drivers and corresponding impacts, thereby minimizing the posed detrimental consequences (Siraj and Fayek, 2019; Zayed et al., 2008). The knowledge-based risk management process leverages the knowledge and experience from previous lessons, reports, and events to provide a reliable expert-based problem-solving platform (Alhawari et al., 2012; Herath et al., 2023).

Table 10
List and definitions of risk under the performance and operational category.

Category of risk	Risk	Description	Reference
Performance and operational	Low labour and equipment productivity	It refers to the risk of decreased efficiency and output from workers and equipment involved in green building projects, potentially leading to project delays and increased costs.	(Wuni et al., 2023; Al-Saffar et al., 2024)
	Lack of adequate GB maintenance	It denotes the risk of insufficient maintenance practices for green buildings, resulting in reduced performance, increased energy consumption, and diminished sustainability benefits over time.	(Ahmad et al., 2019; Nguyen and Macchion, 2022; Qin et al., 2016)
	Difficulties in operating green solutions	It highlights the risks in effectively utilising and managing the sustainable technologies and systems implemented in green buildings, leading to suboptimal performance and limited realisation of the intended environmental benefits.	(Ismael and Shealy, 2018; Nguyen and Macchion, 2022)
	Failure to meet sustainable construction certification requirements	It refers to the risk of not achieving the specified criteria and standards set by green building certification programs, which may result in the loss of desired certifications, reputational damage, and missed opportunities for demonstrating sustainability achievements.	(El-Sayegh et al., 2021; Gurgun et al., 2016; Okoye et al., 2022; Qazi et al., 2021)
	Injuries and accidents during construction	It refers to labour injuries resulting from excessive exertion, contact with dangerous substances, equipment malfunctions, and certain environmental incidents such as air, water, or soil pollution.	(Afshari et al., 2016; Guan et al., 2020; Ismael and Shealy, 2018; Krechowicz, 2017; Rafindadi et al., 2014; Tao and Xiang-Yuan, 2018; Zhao et al., 2016)

The techniques and tools used to identify risks are diverse. Some techniques adopted in risk management research include brainstorming, taxonomies, questionnaires, interviews, simulations, SWOT analysis,

Table 11
List and definitions of risks under the environmental category.

Category of risk	Risk	Description	Reference
Environmental	Inadequate investigation of the construction site and unanticipated adverse site conditions	It highlights the threats of insufficient evaluation of the construction site's qualities and obstacles, which can result in unanticipated complications, project delays, and escalated costs.	(Ahmad et al., 2019; Nguyen and Macchion, 2022; Qin et al., 2016; Tao and Xiang-Yuan, 2018; Wuni et al., 2023)
	High demand for safeguarding the work environment at green building sites	The potential consequences of heightened requirements aimed at guaranteeing a secure and healthful work atmosphere inside green building construction sites. Such measures may negatively affect project timelines, financial outlays, and available resources.	(Ahmad et al., 2019; Hwang et al., 2017a; Nguyen and Macchion, 2022; Qin et al., 2016; Yang et al., 2016)
	Uncertainty in land acquisition	It refers to the risk of encountering difficulties or delays in acquiring suitable land for green building projects, affecting project timelines and feasibility.	(Afshari et al., 2016; Guan et al., 2020; Williams and Dair, 2007)
	Variations in weather conditions	It denotes the potential unforeseen or severe weather conditions throughout the construction of green buildings, which can result in incidents and delays.	(Afshari et al., 2016; Guan et al., 2020; Hwang et al., 2017a; Ismael and Shealy, 2018; Rafindadi et al., 2014; Williams and Dair, 2007)

fault tree analysis, and the Delphi method (Bahamid and Doh, 2017; Fang and Marle, 2012; Li, 2021; Rostami, 2016). New risks discovered within the ongoing project are easily transferred and applied to future projects through the knowledge-based risk management network. The output of this stage is a complete documentation of the risks and their potential consequences in the GBCP environment.

3.3.3. Risk analysis

Risk analysis involves systematically studying potential threats and their impacts (Neto et al., 2021) on the GBCPs. Identified risks are converted into units for easy decision-making based on three components: 1) the probability of risk occurrence, 2) the consequences of the risk, and 3) the degree of expected loss from the risks. These ratings are obtained from the experience and intuition of stakeholders. The probability of each risk is evaluated while stakeholders take the necessary steps to decide which risk should be tackled via qualitative or quantitative approaches (Alhawari et al., 2012). Here, decision-making is propelled by reusing risk-related knowledge, capturing and codifying knowledge, sharing, developing the risk repository, and applying the knowledge to enhance the effectiveness of the risk management processes. The risk analysis stage is essential as it helps reduce biases and eliminate redundancies when assessing the risks. Since members may inherently rate risks within their expertise higher than other risks, the assessment steps are repeated (Becker, 2004; Talet et al., 2018). The product of this stage is the risk repository detailing the validity, extent, impact, priority, and probability.

3.3.4. Risk response planning

The risk portfolio from the previous stages is implemented to create management plans, actions, and judgments (Alhawari et al., 2012). Risk response planning is a process supported by a quantitative framework that assists designated members in allocating resources effectively to manage interdependent risks during GBCPs (Fang et al., 2013). Various tools and techniques have been applied to model risk interactions and predict the global effects of mitigation actions. Examples are the analytical hierarchy process, analytical network process, artificial neural networks, design structure matrix, genetic algorithm, and Monte Carlo simulation (Al-Saffar et al., 2024). This stage proposes the suitable risk treatment actions required in the subsequent phases of the project's risk management process. Therefore, the proper security control measures must be taken to minimise the probability of the risk occurrence, the imminent loss extent, and the repercussions of the risk (Alhawari et al., 2012; Becker, 2004; delCaño & dela Cruz, 2002). The planning stage presents a platform for brainstorming into all the alternative measures members recommend as a course of action (Coskun et al., 2023). It is necessary to ensure that the stakeholders planning and reevaluating the risk response possess experience from similar projects to build the recommended strategies on concrete knowledge.

3.3.5. Risk execution

What is the proposed course of action recommended at the risk

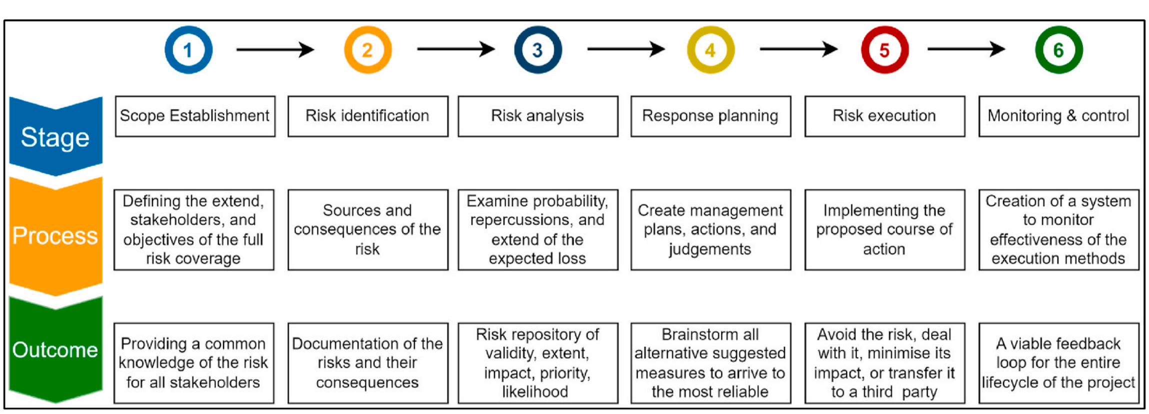


Fig. 11. The summary of the risk management process in GBCPs.

response planning stage? The recommended responses to the imminent risks are executed at this stage to mitigate their effects. Primarily, project managers can react to risk in four ways. The first is risk avoidance, where stakeholders avoid undertaking activities that could lead to risk. They thereby adopt a different approach to achieve the needed goals and thus eliminate the risk (Becker, 2004; Bundeh et al., 2024; Goh &Abdul-Rahman, 2013). The second is risk acceptance, which involves maintaining the risk and preparing to deal with its consequences when it happens. This method is particularly feasible with low-impact risks, resulting in minimum losses (Bai et al., 2024; Becker, 2004). The third is risk reduction, which entails implementing risk control measures to mitigate the probability of the identified risks or minimise their impact when they occur. The last method is risk transfer, where the risk is passed on to a third party willing to accept it through a contract (e.g., insurance), outsourcing, or hedging (Alhawari et al., 2012; Bai et al., 2024).

3.3.6. *Risk monitoring and control*

The risk management system for the GBCP needs a feedback process, which is what the risk monitoring stage does. It provides the platform to determine the viability of a response strategy and its effectiveness as the project progresses. Three essential steps are taken to monitor the risk performance at this stage. The risk is observed throughout the project lifecycle to recognise changes in its present state and record them in the risk profile of the project. Secondly, the effectiveness of the risk control measures is assessed periodically, and finally, the risk management system is continuously monitored to detect the emergence of futuristic risks across its entire lifespan (Alhawari et al., 2012; Becker, 2004; Salehi &Fontana, 2025). When the recommended responses prove ineffective, the risk will be reanalysed to determine a better way of mitigating it. It can also be checked off the list when there is the certainty that its occurrence has become historical and will not reappear. However, the records must be maintained for future projects to derive inferences. The project must be subjected to risk monitoring throughout its lifecycle (Tah &Carr, 2001).

4. Discussion

Properly understanding risks and risk assessment strategies enhances green building practices, certification, and insurance evaluation (Leskinen et al., 2020). As revealed in this research, the existing risk identification models do not define the risks presented to ease interpretation (Maqbool et al., 2023; Nguyen and Macchion, 2023; Singh et al., 2023a; Wang et al., 2024). However, this study found that the detailed description of each risk is a fundamental step towards providing focused and preferential treatments via grouping risks into their appropriate niches. The presented work enables industries to effectively identify the expertise required to perform a specific professional task. Thus, who to hire and how to group each department based on their expertise and the group of risks they can effectively tackle can adequately be guided through the findings established in this work.

Considering the research growth in this field, it is deduced that research on green building risks will continue to attract research in the coming years. Moreover, this is supported by the emergence of new risk groups, such as the scheduling and planning risks and material, equipment, and technology risks. Thus, risk management techniques such as knowledge-based methods are key to evaluating the emerging risks in this field, as they capitalise on the compounded experiences from existing attempts. Moreover, unlike other risk management strategies that do not account for the post-construction risks, the knowledge-based method provides a further step in monitoring and controlling the risks throughout the project's service life. The risk monitoring stage enables risk managers to continue documenting observations and new risks emerging during the operational life of the project.

4.1. *Effects of geographical locations on green building policies*

Generalising risk management strategies for GBCPs across all regions will be impractical due to varying climatic conditions, resource availability, cultural diversity, and regulatory frameworks. Thus, a number of green building assessment systems operate in different regions. These include LEED in the US, BREEAM in the UK, Green Mark in Singapore, BEAM Plus in Hong Kong, and GBI in Malaysia (Nguyen and Macchion, 2023). Thus, each of these assessment systems strives to reflect the unique environmental conditions, practices, and regulatory landscape of their respective geographical locations. For instance, when considering performance and operational risks - as categorised in this study- BREEAM in the UK focuses its design on insulation and energy consumption models on heating efficiency suitable for temperate regions. On the contrary, Hong Kong (BEAM Plus) and Singapore (Green Mark) prioritise energy efficiency and air-conditioning performance appropriate for tropical climates (Siva et al., 2017).

Moreover, it is necessary to acknowledge that existing assessment frameworks attach different weights to various elements, including energy, water, materials, etc. (Norouzi, 2020). Regions with similar conditions can adopt practices from each other or integrate missing concepts to tailor-make the suitable approach for their specific conditions (Kibert, 2022). Due to these differences, this research explored the works on risks involved with GBCPs from different regions across Africa, Asia, Australia, Europe, and North America. Through the comprehensive description and exclusive categorisation of the various risks, each risk can be deeply known and streamlined to promote international collaborations. The knowledge-based approach emphasises a careful and extensive study of the risk management process from planning to the end of the service life of the project. The accumulated knowledge allows for flexibility within the core frameworks of the assessment systems to accommodate local conditions, resources, and practices (Goh and Chong, 2024; Nilashi et al., 2015; Sadeghi and Zhang, 2024).

4.2. *AI in green building risk identification*

Artificial intelligence (AI) plays a significant role in unearthing useful facets of research and applications in the architecture, engineering, and construction (AEC) sector (Debrah et al., 2022). This phenomenon is observed due to the acquisition of large amounts of data that cannot be analysed by statistical methods due to their volumes and dimensionality. For instance, long-term commercial building cooling data across different weather conditions to provide reliable insights into designing automatic optimal building control systems (Liao et al., 2024). Similarly, various machine learning models have been implemented to assess green buildings in promoting blockchain, robotics, and digital twin applications (Debrah et al., 2022). For risk classification and examination in green buildings, Singh et al. (2023b) implemented a deep learning approach integrated with PLS-SEM to identify a list of primary barriers that influence blockchain adoption for sustainable buildings. Waqar et al. (2023) conducted a comprehensive study into the risks impeding the ease of adoption of cloud computing in small-scale sustainable construction projects. The study identified numerous barriers that can be applied to optimising decision-making procedures to achieve the long-term operation of cloud computing in sustainable projects.

Text mining techniques and large language models (LLMs) are essential for document analysis in retrieving useful corpus for risk clustering and construction of green building risk recommendation systems. Clustering techniques are efficient machine learning algorithms that can easily draw insights and patterns from the text and automatically group them based on some similarity indexes (Afoudi et al., 2021). Other techniques, such as deep neural networks integrated with support vector regression, have been applied to predict uncertainties regarding financing and scheduling GBCPs with high accuracies to eliminate the problems of cost overruns (Darko et al., 2023). The risks involved with construction delays and cost overruns have been predicted with decision trees, artificial neural networks, extreme gradient boosting, and linear regression (Khodabakhshian et al., 2024). However, the use of AI, especially text mining, LLMs, and recommendation systems, still requires further studies, given that risks are best presented as descriptive elements.

4.3. Observations, research gaps, and research opportunities

1. From Sections 2.2.4, 2.2.5, and 2.2.9, it is observed that significant research output on risk assessments in GBCPs emerges from developing and developed countries alike. This phenomenon indicates the widespread interest in green building developments and practices in the light of meeting the 2030 sustainable development goals. However, there seems to be a gap between the research output and practice in developing countries, as the overconcentration of concept theorisation is observed rather than empirical outcomes. Considering the establishment of green building standards, even though the concept of green building is still in its development stage, the existing well-known standards such as LEED (the US), Green Star (Australia), BREAM (the UK), BEAM Plus (Hong Kong), and Greenmark (Singapore) are primarily from developed nations (Nguyen and Macchion, 2023). This circumstance might suggest low funding and derive for empirical research relating to green buildings or the scarcity of these projects in developing nations. It is important to glean knowledge from cross-references using the developed standards, but acknowledging the significant differences between various markets, regions, and countries will help customise green building standards to suit each location's practice. Otherwise, there will be a high likelihood of the proliferation of theoretical research and ideas that might not be entirely accurate and, therefore, become obstacles to field applications.
2. A limited cross-country collaboration between developing and developed countries is observed throughout the results of the reviewed articles. In Fig. 5, it is observed that South Africa is the only country to have significant collaboration links with developed nations such as Australia, the UK, and the US. Thus, researchers in developing countries are seen collaborating separately with each other, while developed countries also collaborate exclusively among themselves. This behaviour might cause knowledge segregation and prevent the open sharing of knowledge, experience, and research findings from different markets. Tapping from the challenges and solutions experienced by the countries with significant accomplishments in managing GBCPs' risks will provide new markets ample time to focus on new risks emanating in the future. A cross-reference platform for professionals to share and discuss impending risks appearing or existing in the market is also a great place to start and promote collaborations.
3. Managing risks for green building construction megaprojects requires complex systems to cater to all the challenges in the various phases of the project. Even if they are uncommon in the meantime, the trend of adopting green construction practices for sustainability indicates a significant amount of their proliferation in the future. It is incumbent to begin developing strategies to tackle potential risks in these projects through careful knowledge transfer. Machine learning approaches are developing in this research (Khodabakhshian et al., 2024) area, but have not reached their full potential due to limited and sparse data. Creating an open-source repository for data sharing will aid in building reliable machine-learning models for assessing risks in GBCPs. Open-access databases provide opportunities to develop benchmark models upon which new models can rely to become more accurate. Moreover, since qualitative and quantitative methods are common among the approaches to assessing risks in GBCPs, the evolution of large language models (LLMs) presents great opportunities for deriving significant insights into identifying and managing risks in this field (Taiwo et al., 2025). In general, machine learning has the potential to leverage the available corpus of metadata compiled on risk management to automatically learn and adapt to different projects given the right context.

The repositories should include diverse categories of data that align with the nine risk categories identified in this study. Essential data types would encompass project characteristics such as building size, type, certification targets, and geographical location, financial data including project costs, budget variations, and cost overrun patterns, schedule performance records documenting construction timelines and delay incidents, environmental performance data covering energy consumption and material usage efficiency, technology adoption records detailing green technology implementation and equipment performance, annotated case studies documenting successful risk mitigation strategies and lessons learned, and stakeholder survey data capturing satisfaction levels and performance evaluations. When these standardized datasets are made available through open-access platforms, they can significantly aid researchers and practitioners in developing, testing, and validating machine learning models for automated risk identification and management in GBCPs, enabling cross-project comparisons and the development of predictive models that adapt to different geographical and regulatory contexts.

4. Cultural risks represent a critical yet underexplored dimension in GBCP implementation that can significantly impact project outcomes across all phases of the project lifecycle. Cultural understanding becomes particularly critical when projects involve stakeholders from diverse origins and backgrounds, as different cultural frameworks can create substantial barriers to effective collaboration and risk management (Alamdari et al., 2023b). These cultural misalignments manifest in several ways that directly affect GBCP success. Communication barriers arising from different cultural approaches to directness, feedback delivery, and conflict resolution can lead to misunderstandings about green building requirements, delayed decision-making processes, and ineffective risk reporting mechanisms. For instance, misalignment in project objectives and risk prioritization among stakeholders like contractors and clients from different cultural backgrounds can create conflicting expectations about sustainability targets and implementation timelines. Cultural differences in hierarchical versus collaborative decision-making styles can result in some stakeholders preferring group consensus while others practice top-down authority, potentially slowing critical decisions about green technology adoption and environmental compliance measures. Resistance to change, often rooted in cultural conservatism, can limit the adoption of innovative green technologies and cause the underutilization of sustainable construction methods, particularly in regions where traditional construction practices are deeply embedded in cultural identity. Cultural attitudes toward innovation and risk-taking directly affect stakeholder willingness to invest in unproven green technologies or sustainable materials, with risk-averse cultures potentially compromising environmental performance targets. Additionally, GBCPs may fail to meet social sustainability objectives in cultures where public participation in decision-making is limited, reducing community acceptance and support for green building initiatives. Power distance variations across cultures significantly impact risk communication effectiveness, as junior and mid-level managers may hesitate to raise concerns about project practices or environmental compliance issues in high-power distance cultures, causing delayed identification of project risks and subsequent cost overruns. The varying emphasis on individual versus collective responsibility also affects accountability structures for environmental performance, making it challenging to establish clear ownership of sustainability outcomes. Despite these significant impacts, cultural risk management in GBCPs are often considered only at the technological implementation level rather than throughout the entire project lifecycle, though cultural risks can emerge as early as the planning and stakeholder engagement phases.

5. Conclusion

Risk management plays a fundamental role in addressing the challenges associated with green building construction projects (GBCPs). This study has highlighted the critical need for systematic approaches to identify, forecast, and manage risks to facilitate the industry's transition from conventional to sustainable practices. By conducting a scientometric analysis of 185 articles from 2002 to the end of 2024, this research has compiled and analysed relevant risk factors associated with GBCPs, offering significant contributions to the field.

The study conducted a systematic literature review to identify 42 well-defined risks. By clearly defining them, it further categorised them into nine primary risk groups to promote targeted approach to assessing them. The nine (9) groups were: 1) technical, 2) financial, 3) material, equipment, and technology, 4) design, 5) schedule and planning, 6) legal and regulatory, 7) communication and awareness, 8) performance and operational, and 9) environmental risks. These categories ensure comprehensive coverage of risks from the planning stage to operation and throughout the lifecycle of green buildings. The study clearly described each risk to minimise vagueness in identifying any of these risks to enable easy targeted grouping and assessment, contributing immensely to the existing literature. Secondly, the current trend and influencing outlets of research on risks in GBCPs have been identified in this study to reveal areas with loopholes that need more attention. It was found that there is limited inter-collaboration between developing and developing countries but a high intra-collaboration strength within each group. Finally, the study proposed a knowledge-based risk management framework that emphasises continuous monitoring and feedback, addressing limitations in traditional methods that often neglect the importance of adaptive risk management over the lifecycle of green building projects. This approach equips researchers with the accumulated knowledge and experience from previous risk evaluation methods to facilitate the risk assessment process.

Despite an increased research output, the adoption of green building projects remains limited in developing nations, reflecting the need for targeted initiatives. The findings from scientometric analysis show a burgeoning interest of building industry researchers and practitioners in sustainable practices and green building research. However, the limited inter-collaboration between developing and developed countries leaves ample opportunities for policymakers and funding agencies to expand their objectives when initiating a research project. Strengthening collaborations between developed and developing regions is essential to facilitate knowledge transfer and enhance the global adoption of green building practices. Multidisciplinary research should be prioritized and supported by funding agencies to develop holistic risk management strategies.

Future research in GBCPs should focus on developing adaptive risk management frameworks with real-time feedback and monitoring mechanisms to address risks throughout a project's lifecycle. This emphasis is important because current risk assessment practices focus only on project risks within the construction phase. Regular re-evaluation and identification of emerging risks are necessary to address evolving challenges, guided by scientometric analyses of industry trends. Practical implementation and case-specific studies are vital to bridging the gap between theory and practice, especially in developing countries where green building adoption remains limited. Additionally, integrating supportive policies and regulations can further strengthen risk mitigation efforts and promote sustainable practices.

Despite the contributions of this research to the green building industry, the following limitations are associated with the methodology and results. The study did not use any statistical metrics to test the validity of the identified risks, as no survey or interview data was collected. Incorporating a survey to rate the identified risks using techniques such as the Linkert scale would provide sufficient data to empirically validate the results and evaluate the risks quantitatively with methods such as multi-criteria decision-making techniques or structural equation modelling. Discussions from industry practitioners will duly enrich the research's content and make it more pragmatic. Also, considering only the engineering field, some useful publications from the environmental science and business management domain may be ignored. These limitations will be addressed in our future research.

CRediT authorship contribution statement

Abdul-Mugis Yussif: Writing – original draft, Resources, Investigation, Formal analysis, Data curation. **Ridwan Taiwo:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Pshtiwan Shakor:** Writing – original draft, Validation, Resources, Methodology, Investigation, Conceptualization. **Tong Han:** Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Saeed Reza Mohandes:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Maxwell Fordjour Antwi-Afari:** Writing – review & editing, Validation, Supervision. **Kamal Qazi:** Writing – review & editing, Validation, Resources, Project administration, Methodology. **Atul Kumar Singh:** Writing – review & editing, Validation, Project administration. **Mary Subaja Christo:** Writing – review & editing, Validation, Software. **Mohd Asif Shah:** Writing – review & editing, Writing – original draft, Supervision, Project administration.

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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