

**Scientometric mapping of global research on green retrofitting of existing buildings (GREB): Pathway
towards a holistic GREB framework**

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Abstract

Green retrofitting of existing buildings (GREB) represents one of the best opportunities to reduce global energy consumption and carbon emissions, as well as improve people's health, well-being, and quality of life. It has thus received significant attention from researchers and practitioners over the years, with the proliferation of research works and publications. However, no study has attempted to *comprehensively* investigate the cumulative theoretical and practical value of this body of knowledge. This study aims to analyze the existing global research on GREB through the lens of a scientometric review technique and to provide pathways for future research. The scientometric mapping technique was utilized to systematically and quantitatively analyze 5,288 related bibliographic records retrieved from Scopus. Results showed that "energy efficiency" retrofitting has become the utmost research priority, while "occupant behaviour" and "indoor environmental quality" (comfort, satisfaction, air quality, etc.) are declining in importance in the current framework of GREB. Moreover, other concepts such as intelligent buildings, circular economy, and nearly Zero Energy Building (nZEB) are infusing into GREB. Based on the *status-quo* of practice, a holistic GREB framework involving two potential pathways – technology/approach-centred and human/physical-centred pathways – was proposed. The findings of this study not only contribute to the knowledge domain, but also act as a catalyst to spur the practice by revealing the research needs in this field.

Keywords: Green retrofitting, sustainable building upgrade, sustainable building renovation, building refurbishment, existing buildings, scientometric review

1. Introduction

Climate change is increasingly threatening humanity and nature today, and urgent actions are needed to tackle this pressing challenge. The built environment is a major player in both the cause of and solution to this challenge (Kelley, 2009; Filippín et al., 2018; Toufeili et al., 2022). Buildings are responsible for 37% of global greenhouse gas (GHG) emissions and 36% of the final energy consumption (United Nations Environment Programme, 2021). Meanwhile, the built environment also uses around 72% of electricity generated, produces 67% of solid waste, and depletes 13% of potable water (US Environmental Protection Agency, 2009). It is essential to mention that about 75% of those GHG emissions and energy consumption come from the operation and maintenance of the existing building stock, with embodied emissions and energy use from new buildings accounting for only the

remaining 25% (World Green Building Council, 2021). These values are during the life cycle of the building, while operations and maintenance happen during the service life of the building. Existing buildings, therefore, form the main bulk of the building stock. They are one of the world's biggest challenges in tackling climate change and sustainability (Aram et al. 2022). Green retrofitting of existing buildings (GREB) is the dominant, critical solution to transitioning to a low-carbon, climate-safe and healthy built environment (Onat et al., 2014; Jagarajan et al., 2017; World Economic Forum (WEF), 2022). The US Green Building Council (USGBC) defines GREB as:

"... any type of upgrade to an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, improve comfort and quality of space in terms of natural lighting, air quality, and noise, all done in a way that it is financially beneficial to the owner" (USGBC, 2003).

The above definition points out that GREB not only helps preserve the cultural heritage of buildings, but also brings about both tangible and intangible benefits to all stakeholders, including owners, occupiers, and the community. It also ensures a better-built environment for the future. These benefits broadly reflect the three pillars (i.e., environmental, society and economy) of sustainable development (Tan et al., 2018; He et al., 2019). Thus, GREB is not merely to fulfil the need to retrofit but to achieve sustainability in the built environment. It generally includes improving the performance of air-conditioning systems, lighting and controls upgrades, floor and ceiling insulation upgrades, façade replacement, and major plant replacement (Ma et al., 2012; Tan et al., 2021). The global commitment toward GREB implementation is growing rapidly, as many national and city governments worldwide have put significant effort into transforming aged existing buildings into green buildings. For example, the German government retrofitted over 900 aged (pre-1978) residential buildings by installing energy-efficient heating and cooling systems (Power, 2008). In the UK, the government has set policy targets to reduce the country's emissions from the existing housing stock by at least 68% by 2030 (Department for Business Energy and Industrial Strategy, 2020). In the US, the Department of Energy (DOE) awards \$32 million for next-generation building retrofits (DOE, 2022a). In Singapore, the Inter-Ministerial Committee on Sustainable Development (IMCSD) has set policy targets and timelines to green at least 80% of the existing building stock by 2030 (Building and Construction Authority, 2010). There are also several national and international programs to reduce carbon footprint to move towards a zero-carbon footprint future. They include but are not limited to the Kyoto protocol, EU Energy Performance of Building Directives (EPBD), and the European Emission Trading Scheme (EU-ETS) (Norouziasl et al., 2021). Today, the practice of GREB is no more an option. It is an absolute necessity.

Thus, GREB has received significant attention from researchers and practitioners, with the proliferation of research works and publications. This situation threatens research and practices improvement, making it challenging to uncover the critical GREB areas that need attention for researchers and practitioners' guidance. To solve this problem, it is crucial to comprehensively analyze the focuses, methods, and directions of GREB. Although previous studies have made significant contributions to determining the *status-quo* of GREB research (Ma et al. 2012; Jagarajan et al. 2017; Liu et al. 2020a; Lim et al. 2021; Ho et al. 2021), certain limitations exist. First, they are outputs of manual reviews largely criticized for high subjectivity and limited reliability (Yu and Liao, 2016; Markoulli et al. 2017; Darko et al. 2020). Second, while some studies are narrowed in perspective (focused on limited aspects of GREB), others are limited in capacity (lacking promising pathways for future studies). For example, Ma et al. (2012) focused on the approach to identifying and selecting the best retrofit measures for existing buildings. Liu et al. (2020a) focused on developing retrofit policies in China specifically. Ho et al. (2021) focused on performance indicators for GREB. Jagarajan et al. (2017) reviewed the body of knowledge on GREB. However, they did not address the core question of what more could be done? Jagarajan et al. (2017)'s study was limited to critical success factors, which is insufficient to convincingly benefit the world of practice. Researchers and practitioners are not only interested in what has already been done, but also in the significant areas of knowledge uncovered, where best to focus future research efforts, and the pathways for realizing them. Therefore, a study that provides a comprehensive landscape and understanding by revealing the insights and evolutionary progress of the GREB domain is still needed.

To address the above deficiency, this study is unique, arguably the first to conduct a comprehensive analysis of the global GREB literature through the lens of a quantitative approach – the science mapping technique. This study contributes significantly to the GREB body of knowledge by determining the scope and examining the current status of GREB, highlighting lapses and uncovering promising areas for future studies, and providing feasible and scientific recommendations for realizing the future directions. Practically, the findings are expected to act as a catalyst to spur GREB implementation and funding, by providing an up-to-the-minute reference point for advancing the knowledge base of decision-makers, policymakers, and practitioners.

2. GREB key terms and processes

Knowledge of the GREB process and strategies is essential for recognizing and discovering the key retrofit phases/activities and potential areas for further research and improvement. Therefore, before presenting the research methodology in the next section, a brief overview of the GREB process is given herein. This guides the discussion and future directions presented in Section 4. The overall GREB process can be divided into three main

phases: pre-retrofit phase, implementation and commissioning phase, and post-retrofit phase (Chidiac et al. 2011; Ma et al. 2012). The pre-retrofit phase, also referred to as the planning stage, is where a comprehensive examination is conducted to thoroughly understand buildings' operational problems, purposely identifying the best retrofit opportunities, measures, and technologies for existing buildings (Benzar et al. 2020). The evaluation generally focuses on the building energy end-use and its corresponding equipment inventory systems, as well as the so-called "*sick building syndrome*" related factors such as humidity, ventilation, and indoor air quality, among others. A large volume of scientific contributions exists to the methodologies for screening existing buildings and identifying appropriate retrofit actions/technologies (Li et al. 2013; Beccali et al. 2017; Chang et al. 2020). The phase where the selected retrofit actions/technologies will be implemented on-site and commissioned after prioritization (largely contingent on relevant energy-related and non-energy related factors) is the implementation and commissioning phase. This phase also has attracted much attention, as some retrofit actions may require considerable interruptions (Abdallah and El-Rayes, 2016; Vitiello et al. 2019). The post-retrofit phase is where regular monitoring and assessment of the operational data of building systems, including the well-being of occupants, is carried out periodically to ensure continuous and appropriate functional performance (Ma et al. 2012). The GREB knowledge structure is mainly in line with these key phases.

3. Research methodology

The science mapping technique was used to analyze the evolutionary progress of research on GREB. Science mapping provides a "systematic" method of domain analysis and visualization (Chen, 2017). It is purposely used to detect the intellectual landscape and research interests of a knowledge domain. As a quantitative technique that allows researchers to make discoveries from a large body of literature, it relies on large-scale bibliographic data to assess the research development of a particular domain via different quantitative indexes (Andriamamonjy et al., 2019). The research methodology followed a thematic content structure, covering data collection, bibliometric data extraction and critical analysis, modeling, visualization, and discussion and interpretation of results. The overall research process is shown in Fig. 1 below and described in detail next.

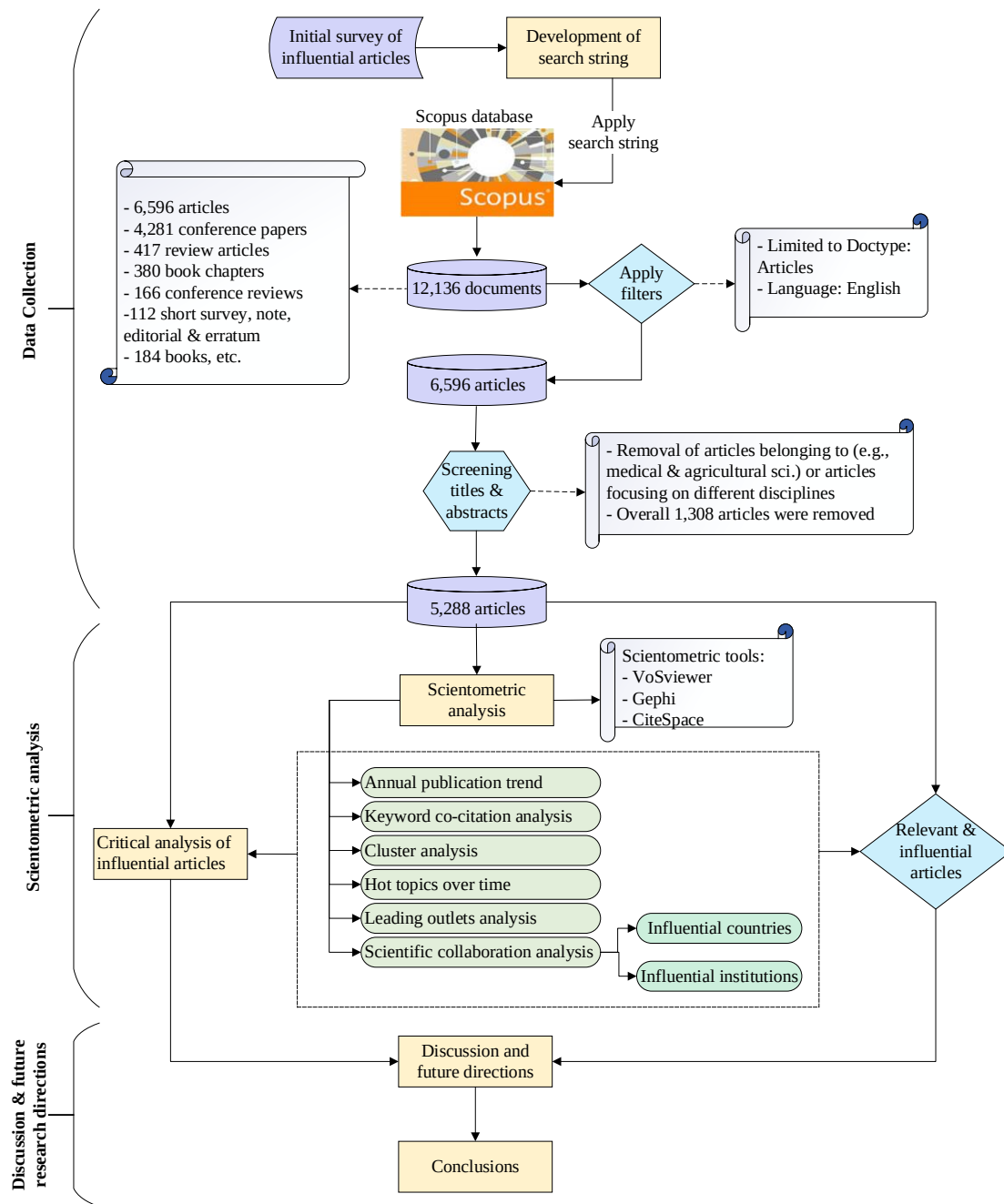


Fig. 1 Research methodology overview.

3.1. Data collection

This study analyzed bibliographic data retrieved from Scopus, the largest continuously updated academic database, rather than other databases such as the Web of Science, PubMed, and EBSCOhost. Thus, the possibility of collecting more recent publications is higher (Meho and Rogers, 2008). Moreover, Scopus has been widely employed in previous studies for similar purposes (Hosseini et al., 2018a; Darko et al., 2020). Due to the difficulty in checking and removing publication duplicates, given the large volume of datasets, the combination of different databases was not permissible in this study. Based on an initial survey of earlier review studies and influential

articles (Ma et al., 2012; Jagarajan et al., 2017; Liu et al. 2020a; Lim et al., 2021), the search string was developed as follows:

TITLE-ABS-KEY "Retrofit" OR "Building retrofit" OR "Sustainable building retrofit" OR "Sustainable building upgrade" OR "Green retrofit" OR "Green retrofitting" OR "Retrofitting of existing buildings" OR "Recommissioning" OR "Refurbishment" OR "Sustainable building renovation" AND "Existing buildings" OR "Existing infrastructure" OR "Buildings" OR "Infrastructure" OR "Construction project") AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")).

It is worth mentioning that retrofitting is used interchangeably with key terms such as "renovation", "refurbishment", and "recommissioning", all referred to as work required to upgrade aged or deteriorated existing buildings. The search was limited to only "article" under the "document type" with no "date range" set; non-English language publications were excluded. Note that journal articles are considered more influential and reputable for this kind of research (Santos et al., 2017). Besides, including all document types result in data imbalance, making data analysis and discussion challenging and costly (Hosseini et al., 2018a).

A total of 12,136 articles were initially identified, as of 7 March 2022. Upon sorting their "relevance" using Scopus, 5,288 articles were finally selected for the study. For example, articles belonging to medical, and agricultural science, or focusing on different disciplines rather than "buildings" or "infrastructure projects" were excluded. Note that focusing on an industry-specific study helps to comprehensively comprehend the *domain status-quo* and reveal more focused gaps and future directions. Besides, it helps to overcome the challenge of obtaining a workable number of relevant publications for the study (Darko and Chan, 2016; Tetteh and Chan, 2019). Moreover, the titles and abstracts of the articles were briefly reviewed to ensure that only publications meeting the scope and objective of this study were selected for the scientometric analysis. Afterward, all the bibliographic records for the retained articles (i.e., 5,288) were downloaded from Scopus, constituting the dataset for this study.

3.2. Scientometric analysis

The science mapping used in this study contains two main stages, following Cobo et al. (2011), Hosseini et al. (2018a), and Darko et al. (2020). Stage 1 involved creating networks through keyword co-occurrence analysis, document co-citation analysis, citation burst analysis, journals direct citation analysis, and co-authorship analysis. Stage 2 also involved generating maps for extracting useful information from the networks and presenting "the conceptual, intellectual, or social evolution of the research field, discovering patterns, trends, seasonality, and outliers". These goals were accomplished by combining multiple scientometric mapping tools. The reason being

that several scientometric tools exist with different capabilities and strengths, and a thorough analysis of any given field requires using several tools for different types of analyses (Cobo et al., 2011). To realize the entire intellectual landscape of the GREB domain, more powerful, open-source, and user-friendly tools, including VOSviewer®, CiteSpace®, and Gephi®, were employed (Gephi, 2010; Van Eck and Waltman, 2013; Chen, 2014). VOSviewer is a software tool specifically developed for creating and visualizing large bibliographic maps and supports special text mining features, including co-occurrence and co-citation analysis (Van Eck and Waltman, 2013). Citespace is a mapping tool with a built-in clustering algorithm, capable of detecting hidden connections between the different publications with unique visualization features that include but not limited to cluster visualization, timeline view, and timezone view (Chen, 2016). Gephi is a software tool for visualizing, exploring, filtering, and manipulating all kinds of graphs and networks and is suitable for generating in-depth information (statistics) on a specific graph and network (Bastian et al., 2009). For more information about the technical applications of VOSviewer, CiteSpace, and Gephi, readers can refer to Van Eck and Waltman (2013), Chen (2014), and Gephi (2010), respectively.

32.1 Critical analysis

To ensure sufficient coverage of the available data (i.e., 5,288 articles) and provide a comprehensive critical analysis of the knowledge domain, highly relevant and influential articles were identified with guidance from the results of the scientometric analysis – the generated networks, in particular the keyword co-occurrence analysis. Note that with this kind of study, there are no pre-specified criteria to settle on a defined number of articles for the critical analysis (*see, for instance*, Hosseini et al., 2018a; Luo et al., 2019; Darko et al., 2020; Yevu et al., 2021; Omrany et al., 2022). Regarding the results of the cluster analyses, research studies providing sufficient information about the key research interests were only considered. This was achieved after further thorough screening of the initially identified articles' title, abstract, and where necessary, the full content. It should also be mentioned that to allow for a more comprehensive discussion, other relevant books, reports, and articles from different disciplines, such as health science, were considered (Gou and Xie, 2017; Tetteh et al., 2019).

4. Analysis and results

4.1. Overview of GREB research publication trends

GREB research has been around since the late 1970s, when the National Science Foundation and the DOE co-funded a leading research group in the Center for Environmental Studies at the Princeton University to research energy conservation for space heating of townhouses in Twin River, New Jersey (Socolow, 1978). Fig. 2 shows the annual research publication trends and focuses in GREB from 1978 – 2022. Uncovering the general research

focus within each period (a decade) is of significant importance to researchers for analyzing and revealing more specific relevant gaps and future needs. To determine the research focus within each period, CiteSpace 5.8.R3 was used. For example, between the period 1978 – 1988, based on the largest cluster focus, the research outputs primarily focused on energy conservation actions – basically to learn how to model and modify energy use and savings in homes (Ross and Whalen, 1983; Wagner and Diamond, 1987). Progressively, there is a steady and growing momentum in interests in GREB research with coherent intents over the five periods (in decades). Considerable growth in the number of publications is evident from 2000 onward – *the 21st century* – with an average of 229 papers published yearly within this period. This is not surprising as many governments took bolder steps in aligning climate priorities with the requirement of an integrated urban ecosystem around that period (WEF, 2021). The period between 2016 to date, as of March 7, 2022, reveals ever-increasing devoted attention given to the importance of GREB (i.e., 3,203 papers). This growth is reasonable as many global leaders and organizations now see this period as a critical decade for real progress, following the Paris Agreement (United Nations (UN), 2015), by developing targets to transform the building sector towards sustainability goals. This growth will likely continue, as many countries/jurisdictions are progressively accelerating commitments to reduce energy consumption and carbon emissions from the buildings sector through GREB to transform them into green buildings.

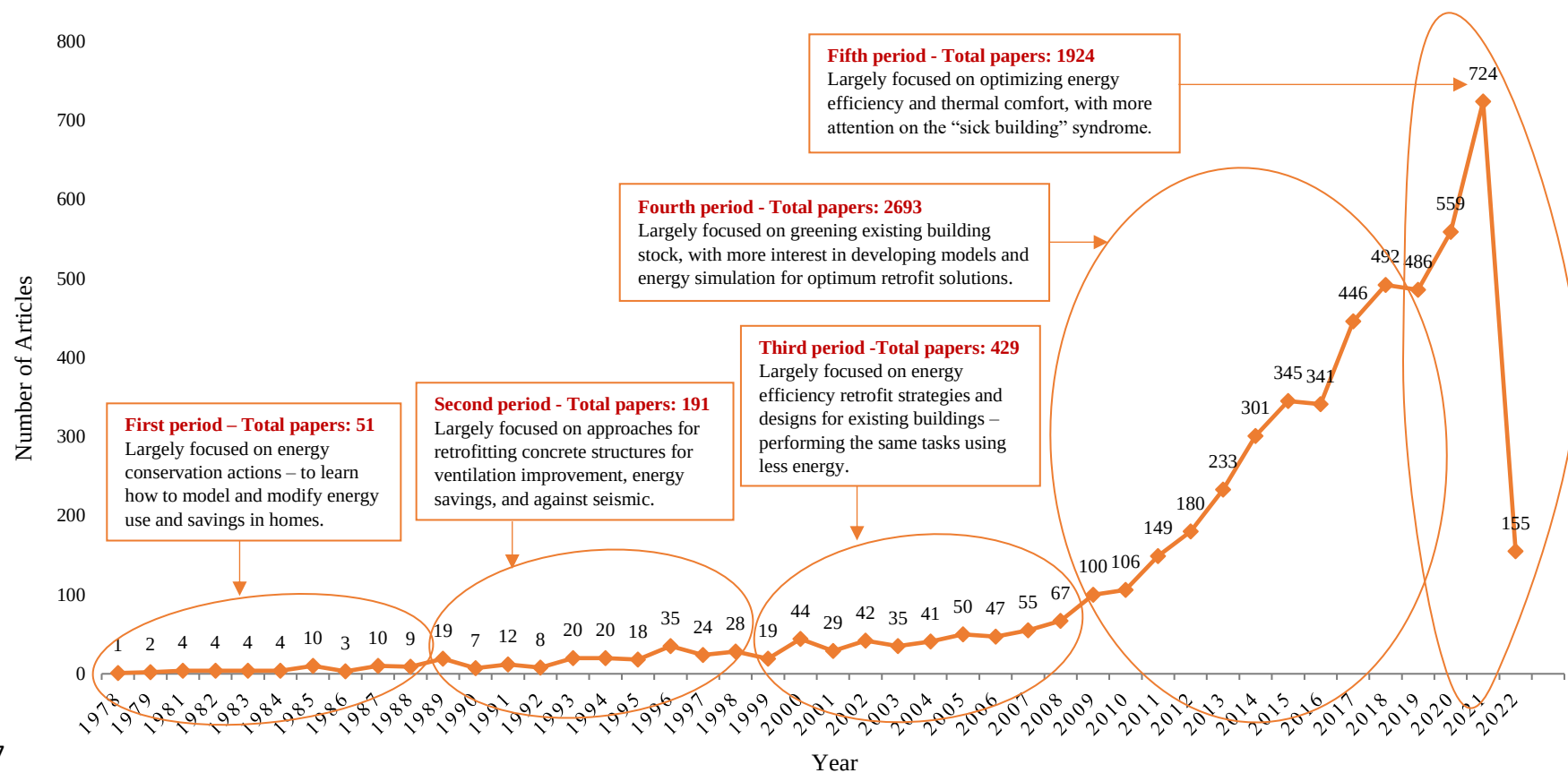


Fig. 2. Annual research publication trends and focus in GREB (1978 – March 2022). Note: the number of publications may increase at the end of 2022.

4.2. GREB knowledge structure

4.2.1. GREB research interests (keyword co-occurrence network analysis)

Analyzing keywords facilitates identifying and understanding the main research interests in any discipline (Sharifi, 2021). A visual knowledge map of the keywords network provides a holistic understanding of the main areas of investigation covered by studies and their interconnections. This study used VOSviewer 1.6.18.0 to produce the keyword co-occurrence network. The network comprises nodes and links denoting the keywords and correlations among sets of keywords, respectively. Whereas the sizes of nodes correspond to the frequency with which a keyword occurred in the literature, the thickness of the links indicates the strengths of weights of the relations (Van Eck and Waltman, 2013). The other developed networks in the succeeding sections, share similar descriptions, replacing keywords, for example with journals, institutions, countries, etc. To present a reproducible visualization of the keywords, “author keywords” was used instead of all keywords. In scientometric mapping studies, “author keywords” is highly preferred (Oraee et al., 2017; Darko et al., 2020). The “fractional counting” – an approach for reducing the impact of publications with many authors in co-authorship analysis (Van Eck and Waltman, 2013) – was used, resulting in a total of 28,469 keywords. To generate a more controllable and reproducible network of keywords, as evinced in previous studies, the “minimum number of occurrences” was set to 50, and the inclusion criterion met by 171 of the 28,469 keywords.

For comprehensiveness, similar keywords such as “residential”, “residential building”; “building energy retrofits”, “building energy retrofitting”; and “cost-benefit analysis”, “cost analysis” were merged as “residential buildings”, “building energy retrofit”, and “cost benefit analysis”, respectively. In addition, unrelated terms (e.g., China, United Kingdom, United States, etc.) were excluded. This resulted in a complex network consisting of 105 nodes and 10,080 links, as shown in Fig. 3, demonstrating the main research interests in the field of GREB. The data were further submitted to Gephi 0.9.2 for visualization of the network.

To determine critical research interests within the network, the degree of centrality, the most reliable approach to measure a node strength, was used. The research interests have been ranked in descending order based on their degree of centrality values. Where there is a tie, priority is given to the one with the highest betweenness centrality value. The betweenness centrality metric determines the shortest paths between all pairs of nodes in the network (Gephi, 2010). Table 1 shows the results of the research interests. The ranking and interconnections of the research interests, as displayed in this table and Fig. 3, respectively, reveal several insightful findings:

Table 1. GREB research interests and exploration relevance.

Research focus/interest	Degree centrality	Betweenness centrality	Exploration relevance
Retrofit	99	7797.26	1
Energy efficiency	88	337.87	2
Residential buildings	66	230.00	3
Buildings	66	170.51	4
Historic buildings	63	140.78	5
Building energy retrofit	62	174.45	6
Carbon emissions	62	149.60	7
Sustainability	56	119.11	8
Climate change	56	97.17	9
Energy savings	55	105.94	10
Thermal comfort	53	69.68	11
Building retrofit	51	97.07	12
Energy	50	88.00	13
Seismic retrofit	49	72.20	14
Energy consumption	45	131.27	15
Energy performance	43	50.72	16
Optimization	43	50.48	17
Office buildings	41	69.41	18
Building simulation	41	37.92	19
Rehabilitation	39	37.81	20
Environmental impact	38	37.31	21
Benchmarking	37	75.64	22
Building envelope	36	37.06	23
Multi-objective optimization	36	28.37	24
Social housing	35	40.06	25
EnergyPlus	35	30.97	26
Life cycle assessment	35	18.50	27
Energy conservation	34	31.68	28
Mediterranean climate	34	19.32	29
Building stock	32	31.32	30
Cultural heritage	32	17.97	31
Genetic algorithm	31	47.69	32
Indoor air quality	31	35.93	33
Unreinforced masonry	31	28.13	34
Energy simulation	31	24.35	35
Earthquake	31	16.98	36
Reinforced concrete	30	12.48	37
Adaptation	29	43.09	38
Building energy performance	29	41.56	39
Building energy simulation	28	17.34	40
Calibration	28	15.63	41
Resilience	28	13.37	42
Sensitivity analysis	27	34.25	43
Thermal insulation	27	25.43	44
Uncertainty	27	18.07	45
Retrofit strategies	27	17.06	46
Dynamic simulation	27	15.73	47
Modeling	27	13.17	48
Renewable energy	26	27.24	49
Vulnerability	26	16.76	50
Decision making	26	15.49	51
Energy demand	25	13.58	52
Existing buildings	25	13.41	53
BIM	25	12.57	54

Building performance	25	12.08	55
Energy policy	25	11.84	56
Conservation	25	10.29	57
Energy use	25	10.01	58
Life cycle cost	24	18.99	59
Mitigation	24	15.09	60
Occupant behaviour	24	15.01	61
Built environment	24	14.33	62
Energy efficiency measures	24	12.81	63
Insulation	24	12.07	64
Heating	23	16.22	65
School buildings	23	10.56	66
Ventilation	23	9.37	67
Energy audit	23	9.23	68
Strengthening	23	9.00	69
Embodied energy	22	20.85	70
Indoor environmental quality	22	14.31	71
Air conditioning	22	11.91	72
Cost-benefit analysis	22	8.14	73
District heating	22	5.36	74
Investments	22	5.18	75
Seismic risk	21	21.56	76
Cooling systems	21	6.52	77
Design	21	4.79	78
Heat pump	20	10.71	79
Infrastructure	20	4.51	80
Performance gap	20	2.85	81
Seismic	19	16.33	82
Sustainable development	19	7.89	83
Maintenance	19	6.56	84
Decision support systems	18	15.24	85
Building energy efficiency	18	10.28	86
Economic analysis	18	9.48	87
Monitoring	18	7.40	88
Base isolation	18	4.55	89
Intelligent buildings	18	3.66	90
Concrete	17	9.52	91
Seismic performance	16	2.77	92
Seismic vulnerability	15	2.54	93
Bridges	15	1.90	94
Ductility	14	7.29	95
Energy dissipation	13	7.47	96
Seismic assessment	13	4.18	97
Circular economy	13	3.37	98
FRP	12	4.10	99
Pushover analysis	12	3.90	100
Seismic isolation	12	3.77	101
Seismic design	12	3.23	102
Digital storage	11	2.59	103
Green infrastructure	9	1.02	104
nZEB	5	0.05	105

Note: BIM = Building Information Modeling; nZEB = nearly Zero Energy Building; FRP = Fiber-reinforced Plastic/Fiber-reinforced Polymer

- Some research interests have received increasing attention while others remain neglected or under-researched. Likewise, several research interests have faded away completely in recent years. Themes such as “energy efficiency”, “residential buildings”, “historic buildings”, “building energy retrofit”, and “carbon emissions” have received considerable attention in GREB, reinforced by their strong links (Fig. 3). The findings are consistent with Amirkhani et al. (2021). The high ranks of “energy efficiency” and “carbon emissions” could be explained by the current worldwide goal to achieve carbon neutrality by 2050. Improving “energy efficiency” in buildings through GREB is critical to “carbon emissions” reduction, which directly impacts carbon neutrality. “Energy efficiency” – reducing “energy demand” for building operations while maintaining the comfort and well-being of occupants (Ruparathna et al., 2016) – is primarily studied for “residential buildings” (Amirkhani et al., 2021; Omrany et al., 2022). This calls on practitioners and researchers to also focus more attention on the commercial sector, especially office, restaurant, and retail buildings, which are the biggest culprit in “energy consumption” and “carbon emissions” (DOE, 2022b), in order to achieve carbon neutrality. Energy efficiency upgrade of existing buildings is a vital move to minimize the “environmental impact” of the large existing “building stock” (Krarti and Dubey, 2018). Yet, among the concerns of practitioners and researchers, “building energy retrofit” is still mainly confined to a small cohort of the existing building stock. Future studies must focus on developing more appropriate intervention strategies to promote successful retrofit of existing building stock at scale to achieve the goal of carbon neutrality. The pathways for filling these gaps are fully presented and discussed in Section 5.
- GREB is an “optimization” problem. “Multi-objective optimization” techniques have been widely used to propose appropriate retrofit actions/technologies on a case-by-case basis (Hashempour et al., 2020). Several studies focused on optimizing “building envelope” and “heating”, “ventilation”, and “air conditioning” (HVAC) systems with or without considering occupants’ behaviour (Wu et al., 2017; Gunay et al., 2019). The process heavily relies on optimization technologies such as “genetic algorithm (GA)” (Rosso et al., 2020), “sensitivity analysis” (Gunay et al. 2019), and computational “building energy simulation” using “dynamic simulation” (Calise et al., 2020). “EnergyPlus” and “BIM – building information modeling” are building performance simulation tools frequently used to model the “building energy performance”. BIM has been considered a “decision-support system”, enabling more complex structures to be digitally modeled, prioritizing green retrofitting measures (Lim et al., 2021). To improve the level of automation in GREB

decision-making, the integration of optimization algorithms and visual programming tools with BIM has increased lately. Seghier et al. (2022), for example, integrated BIM with Dynamo (visual scripting) and a non-dominated sorting genetic algorithm (NSGA-II) customized in MATLAB® to support design decision-making during the retrofit process. Although GREB optimization studies have proliferated over the last few decades, most studies are case-based, confined to a specific building type and a single building block. It is in the remit of future studies to critically expand the scope by considering existing building stock at scale.

- Research interests that have remained neglected or under-researched include but are not limited to “green infrastructure”, “digital storage”, “fiber-reinforced plastic/fiber-reinforced polymer (FRP)”, “concrete”, “indoor environmental quality (IEQ)”, and “occupant behaviour”. While all of these fall below the highest-ranked research interests (Table 1), “IEQ” and “occupant behaviour” are declining in importance relative to energy, resources, and financial/cost components in the process and definition of GREB (Zhao et al., 2017; Hashempour et al. 2020). This surprising fact has also been noted in the unique domain of net zero energy building (Omrany et al., 2022). In GREB practice, building energy retrofit (the physical or operational modifications that reduce the amount of “energy use”) becomes the utmost priority. However, IEQ and occupant behaviour also has a strong influence on “energy consumption”, both through design-related decisions (e.g., passive and active design technologies, and renewable energy systems) (Suh and Kim, 2019; Liu et al., 2020b) and in the operation and control of the building (e.g., HVAC system) (Ruparathna et al., 2016). One of the possible reasons why IEQ and occupant behaviour do not match up with energy and cost elements in the holistic framework of GREB (as illustrated in Fig. 3/Table 1) could be because of the challenge of identifying simplified, cost-effective and standard-based methodology for their assessment (Yang et al., 2016; Zuhaib et al., 2018; Anand et al., 2019a; 2022). There are various standards and regulations to standardize and eventually codify IEQ and occupancy measurement. For example, the ASHRAE standard and the European standard EN15251 (Olesen, 2007). However, several studies have questioned the applicability and accuracy of some of the parameters of these standards (Nicol and Wilson, 2011; Marino et al., 2012; Azimi and O'Brien, 2022). This deters industry-wide acceptance globally to drive academic research. For example, Duarte et al. (2013) demonstrated that ASHRAE recommended occupancy schedule differed from the ground truth occupancy data (determined by passive infrared sensors data) by 46%. Recently, Esfandiari et al. (2021) assessed the quality of the indoor environment of Platinum-certified

office buildings in a tropical climate and found that occupants' responses on IEQ parameters such as relative humidity and illuminance level were outside the suggested range of the available standards. Accordingly, Heinzerling et al. (2013, p. 221) recommended that "standardized measurement protocols need to be established through long-term IEQ studies in order to create a benchmarking database of standard IEQ data." In another study, Al Horr et al. (2017) highlighted that research should be conducted to improve the robustness of global sustainability assessment systems for IEQ parameters and verify the efficacy of developed methods to increase occupant productivity. Occupancy information is not easy to gather and model because occupants' presence, both in time and in space, is often stochastic, not ignoring the number of occupants in a space, which is also a nontrivial aspect to characterize (Yang et al., 2016; Anand et al., 2021). Occupants' behaviour such as turning on/off lights or other devices when entering or leaving a space, operating windows/doors, etc. are complex behaviour and very difficult to predict. Yang et al. (2016) highlighted that the stochastic nature of the occupancy profile is one of the major causes of the gap between the actual and intended energy use for a building. Prior studies have used occupancy detection technologies such as motion sensors, vision sensors, radio frequency-based technology, electro-mechanical sensors, etc. and machine learning algorithms to define and model the occupant behaviour as close as possible to the real situation (Anand et al., 2019b; Zhou et al., 2021; Azimi and O'Brien, 2022). Yet, recent studies have highlighted that there is an urgent need for more standardized and cost-effective methodologies for occupancy data collection, considering real-time simulation of human-building interaction (Norouziasl et al., 2021; Anand et al., 2022). Therefore, research and organization should aim at standardizing methods of IEQ and occupant behaviour assessment to drive the development of more *advanced* models and systems to realize the all-inclusive content of GREB.

- Research interests such as "seismic retrofit", "seismic risk", "seismic performance", "seismic vulnerability", "seismic assessment", "seismic isolation", "seismic design", "earthquake", "unreinforced masonry", "reinforced concrete", "bridges", "strengthening", and "vulnerability" are blurring in relevance within the current GREB practice/literature. "Seismic retrofit", upgrading the performance of buildings with seismically poor redundancies, is mainly performed for buildings in earthquake-prone cities. In the past, as building structures were designed with no seismic prevention measures, promoting seismic retrofit was especially a mandatory task for saving human life and economic resources (Spence, 2007). Previous related studies

mainly focused on seismic retrofit interventions, performance, and cost for both “unreinforced masonry” and “reinforced concrete” structures (Bruneau, 1994; Dan, 2001). Seismic retrofit interventions adopted include “base isolation”, “fiber-reinforced plastic/polymer (FRP)”, “concrete”, and “energy dissipation”. While there are also studies addressing the environmental impact of these retrofit solutions (Vitiello et al., 2016; Belleri and Marini, 2016), only a handful of studies attempted to improve both the seismic and energy performance of existing buildings (Marini et al., 2017; Pertile et al., 2021). This invites further research to develop more innovative integrated retrofitting systems that address seismic, energy performance, and other green concepts such as “IEQ” and “occupant behaviour”.

- Research interests such as “intelligent buildings”, “circular economy” and “nZEB – nearly zero energy building” are now permeating the GREB space. Intelligent buildings “refer to buildings equipped with technology that allows monitoring of their occupants and/or facilities designed to automate and optimize control of appliances, in particular, lights, HVAC system, and home appliances, to save energy” (Nguyen and Aiello, 2013) and creating the desired indoor environment for occupants. Whereas a circular economy seeks to reduce waste and GHG emissions by incorporating recycled materials (Geissdoerfer et al., 2017), nZEB is a promising strategy for reducing the dependence on fossil fuels that cause GHG emissions (Omran et al., 2022). Within the network diagram in Fig. 3, these interests show weak links to a few retrofitting strategies, indicating that they are yet to see *full* integration and significant development in GREB practice. The realization of this goal will help to achieve energy independence (i.e., total cost savings from reduced energy use and bills) and carbon neutrality. This calls on funding agencies and researchers to pay more attention to exploring options and innovative ways to advance the application of these concepts in GREB practice/projects.
- While only those “main GREB research terms and interests” that met the inclusion criteria described in Section 4.2.1 are presented (see Fig. 3 and Table 1), there also are other relevant research interests directly linked to the GREB practice (e.g., occupant health, well-being, comfort and quality of life). Note that reducing the inclusion criteria may lead to introducing more research terms and interests, but compromising the research networks’ quality, readability and reproducibility. Previous studies have elaborated on how the condition of existing buildings is one of the most decisive influences on people’s health and their psychological and emotional wellbeing (Bonnefoy, 2007; Borsboom et al., 2016; Cincinelli and Martellini,

2017; Ortiz et al., 2019). For example, Ortiz et al. (2019) found that by improving the energy efficiency of 1.5 million existing buildings in Spain, the number of occupants with bad self-perceived health would be reduced by 100,000, and the number of people diagnosed with cardiovascular diseases by about 120,000. The most problematic housing condition is related to *bad* IEQ (including indoor air quality (IAQ), thermal, acoustical, and lighting quality) (Hormigos-Jimenez et al., 2018; Ortiz et al., 2019; 2020). It is estimated that people spend roughly 90% of their time or more indoors (Cincinelli and Martellini, 2017). Thus, these factors seriously threaten human health and quality of life in general. In a study on IAQ and health problems associated with damp floor covering in an existing office building in Finland, workers complained of several respiratory (increasing cases of asthma), conjunctival, and nasal symptoms (Tuomainen et al. 2004). Harmful emissions such as 2-ethyl-1-hexanol and 1-butanol were found in the indoor air and floor materials samples. With regards to lighting and health, studies have stressed that exposure to light pollution encourages the growth of cancer (Kloog et al., 2009), visibility issues (Berman and Clear, 2008), sleeping disorders and deprivation (Haus and Smolensky, 2006), and may have negative influences on several disorders such as diabetes, obesity, among others (Bass and Turek, 2005). Thus, studies such as the one conducted by Falchi et al. (2011) explore possible limiting measures for the impact of light pollution on human health, environment and stellar visibility. Several studies have also documented the direct and indirect effects of living in houses with indoor thermal discomfort (low or high temperatures) and/or under conditions of noise from installed systems (Babisch, 2002; Dear and McMichael, 2011; Fowler et al., 2015; Sweetnam et al., 2019). For instance, high noise levels from heating and ventilation systems can cause hearing loss and annoyance, leading to anxiety, depression, fatigue, and heart disease (Sweetnam et al., 2019). Overall, these factors (i.e., occupant health, well-being, comfort, and quality of life) have been seldomly explored and need to be incorporated into the research and development of retrofitting measures. This is also noted in the study by Ortiz et al. (2020). The authors, therefore, highlighted that there is a need for multidisciplinary approaches, in which buildings and HVAC systems, occupants, health and comfort, and IEQ are investigated as interacting elements and based on an integrated approach.

4.2.2. Clustering structure of GREB research (document co-citation analysis)

To better understand and appreciate the knowledge structure of GREB research, a document co-citation network was created using CiteSpace 5.8.R3. This helps to detect the main topics and knowledge hotspots of GREB research.

The software automatically generated a network with 12 clusters defined by cluster IDs (e.g., #0, and #1), as depicted in Fig. 4. Each cluster is represented by a line, specifying the fundamental topic explored within the study period (from 1978 to March 2022). The log-likelihood ratio (LLR), the text-mining algorithm in CiteSpace, was used for generating the cluster labels due to its clustering power (Chen, 2014). The network generated a considerable modularity Q value of 0.7969, demonstrating the accuracy of the established clusters, with dense connections between nodes within clusters and sparse connections between nodes in different clusters. Likewise, the high mean silhouette value of 0.8346 implies that each cluster is unique and homogenous (Chen, 2014). The results imply that GREB studies generally embody a network with dense connections that address a common issue. Table 2 presents the 12 clusters with their corresponding size (i.e. number of studies forming the cluster), silhouette values, and the mean year published (i.e. average period over which a cluster has been explored). The following observations are worth mentioning:

- As depicted in Table 2, all the silhouette values confirm the homogeneity of GREB research. This indicates that GREB research is primarily confined to only the knowledge within the cluster domains and does not benefit from adapting applicable theories or ideas from other relevant domains. Future studies should inculcate the attitude of adapting practical ideas or theories that would ensure deeper understanding and promote GREB implementation. The most significant clusters have been cluster “#0 building envelope”, “#1 data-driven approach”, and “#2 energy refurbishment”. The number of articles forming these clusters is 144, 136, and 125, respectively. In line with the earlier observations, retrofitting strategies aimed solely at building envelope improvement through energy refurbishment. Over the past decade, building envelope energy refurbishment strategies either focused on basic remodeling, replacement, performance optimization, or modifying existing elements (e.g., lighting upgrade, optimization of building operation and control, etc.). These strategies are known as *light retrofit* strategies, according to the UK Green Building Council (UKGBC) (2022). In other words, there are only a few studies that fall under the scope of *deep retrofit* – a considerable amount of work that results in partial modification to the building structure and/or service (e.g., insulation of floors, retaining walls, roof elements, façade, replacement of major plants, etc.) (Gupta and Gregg, 2016; Luddeni et al. 2018). One of the possible reasons could be that its implementation requires a comprehensive examination of the whole building and all the processes involved, including feasibility, compatibility, and associated benefits (Cascone et al., 2018; Luddeni et al., 2018). Meanwhile, limited practical or real case studies exist to steer its adoption (Zhai et al., 2011; Moser et al., 2012). For example, Cascone et al. (2018)

highlighted that it is worthwhile to conduct an in-depth analysis of green roof feasibility for retrofitting existing buildings by considering material characteristics, structural, thermal, economic and environmental compatibility. Future studies must provide more support for deep retrofit projects with a holistic and crystal-clear picture – not only of their implementation guide, but also the advantages of choosing deep retrofit versus light retrofit. Further, one of the possible scalable solutions to improve existing buildings’ energy performance has been the deployment of data, “data-driven approaches”. Building performance assessment depends on datasets to support and assist activities such as building energy benchmarking, energy profiling, and detail retrofit analysis (Wei et al. 2018). However, those datasets are mostly limited to individual buildings and in most cases, even missing or inaccurate. A critical challenge has been generating and deploying entire building stock data for accurate building performance analysis and cost-effective retrofit recommendations. This area also needs more research attention.

- One of the emerging clusters is “#13 supply-side management” with 18 publication records. In general, retrofitting technologies have been categorized into three: demand-side management, supply-side management, and human factors (Ma et al. 2012). Whereas the demand-side management and human factor focus on strategies for reducing building heating and cooling demands using energy-efficient equipment and changes in energy consumption patterns, respectively, supply-side management focuses on using renewable energy technologies such as hydropower, biomass, wind energy, solar photovoltaics, and geothermal energy, and building electrical system retrofit (Ma et al. 2012). In other words, supply-side management focuses on the provision of thermal energy for buildings by using alternative energy supply systems due to the increased awareness of environmental issues, wherein the concept of net-zero energy comes into play. Luo and Oyedele (2022), for example, developed a novel building retrofitting approach through the integration of life-cycle optimization and supply-side management – by incorporating passive retrofitting options (i.e., photovoltaic panel and solar thermal collector) and active retrofitting options (i.e., biomass boiler, heat storage, etc.). As mentioned earlier, the integration of this concept into GREB has yet to fully see significant development. However, the demand-side GREB should be prioritized as a more cost-effective option. If demand is not significantly reduced first, more supply of net-zero energy is required to meet the high demand, increasing the cost and financial burden on the government and public.

456 • The smallest clusters are #14, #15, and #40, respectively, denoting “automated energy performance
457 modeling”, “low carbon building energy design”, and “key performance strategies”. They recorded 17, 16,
458 and 6 articles, respectively, indicating that research conducted in these areas is insufficient and needs more
459 research attention. Section 4 discusses how these promising areas could be significantly improved.

Table 2. Summary of identified clusters.

Cluster ID	Name	Size	Silhouette	Mean (Year)
#0	Building envelope	144	0.732	2015
#1	Data-driven approach	136	0.824	2017
#2	Energy refurbishment	125	0.748	2012
#3	Homeowner refurbishment potential	45	0.970	2008
#4	Energy-demand saving	36	0.960	2010
#5	Thermal retrofit	36	0.924	2011
#9	Existing building	23	0.985	2017
#11	Domestic retrofit	21	0.927	2014
#13	Supply-side management	18	0.973	2018
#14	Automated energy performance modeling	17	0.958	2010
#15	Low carbon building energy design	16	0.975	2013
#40	Key performance strategies	6	1.000	2012

4.2.3. Hot topics over time (citation burst analysis)

Citation burst analysis tracks those keywords that have been cited most within the literature over a certain period, indicating topics that are fast-growing or having surges in citations (Chen, 2014). CiteSpace was used for conducting the citation burst analysis. A total of 289 keywords with citation bursts were identified. Fig. 5 shows the top 30 keywords with the strongest citation burst in the GREB literature. The reviewed literature year range is indicated by green lines, and the length of a citation burst event is by red lines.

As shown in Fig. 5, the mathematical model (burst strength, 37.2; year range, 1989–2008), earthquake resistance (35.45; 1989–2011), reinforced concrete (30.00; 1994–2012), concrete building (27.28; 2008–2011), computer simulation (23.85; 1994–2014), and seismic design (22.23; 2007–2012) had the strongest bursts in the literature. It is worth noting that some of the top keywords showed a strong influence in connection with other themes, as illustrated in Fig. 3/Table 1, although with slender description differences. For example, the seismic design was linked to areas such as bridges, unreinforced masonry, strengthening, etc. As mentioned earlier, although “computer simulation” did not appear in Fig. 3/Table 1, it can be defined as dynamic simulation, building simulation, energy simulation, etc., as they are performed by a computer. A careful observation of these bursts and periods confirms the attention of GREB research within the second and third periods, as depicted in Fig. 1.

The more recent hot topics (i.e., topics with a burst period from 2015 up until now, 2022) include geophysics, zero energy buildings, and retrofitting technologies. In GREB research, geophysics is connected to earthquakes/seismic and climate. Menna et al. (2022) highlighted that an improvement in seismic vulnerability is vital in reducing geophysical risks and hazards, a critical solution for mitigating the impacts of earthquakes. Moreover, while the relevance of converting existing buildings into zero-energy buildings is highlighted, retrofitting technologies (i.e.,

energy conservation measures used to promote building energy efficiency and sustainability) significantly contribute to improving the energy system performance of existing buildings. For example, traditional lighting systems in existing buildings could be replaced with passive infrared sensors (PIR) technologies to regulate the lighting system automatically. These reinforce the need for more research efforts going forward.

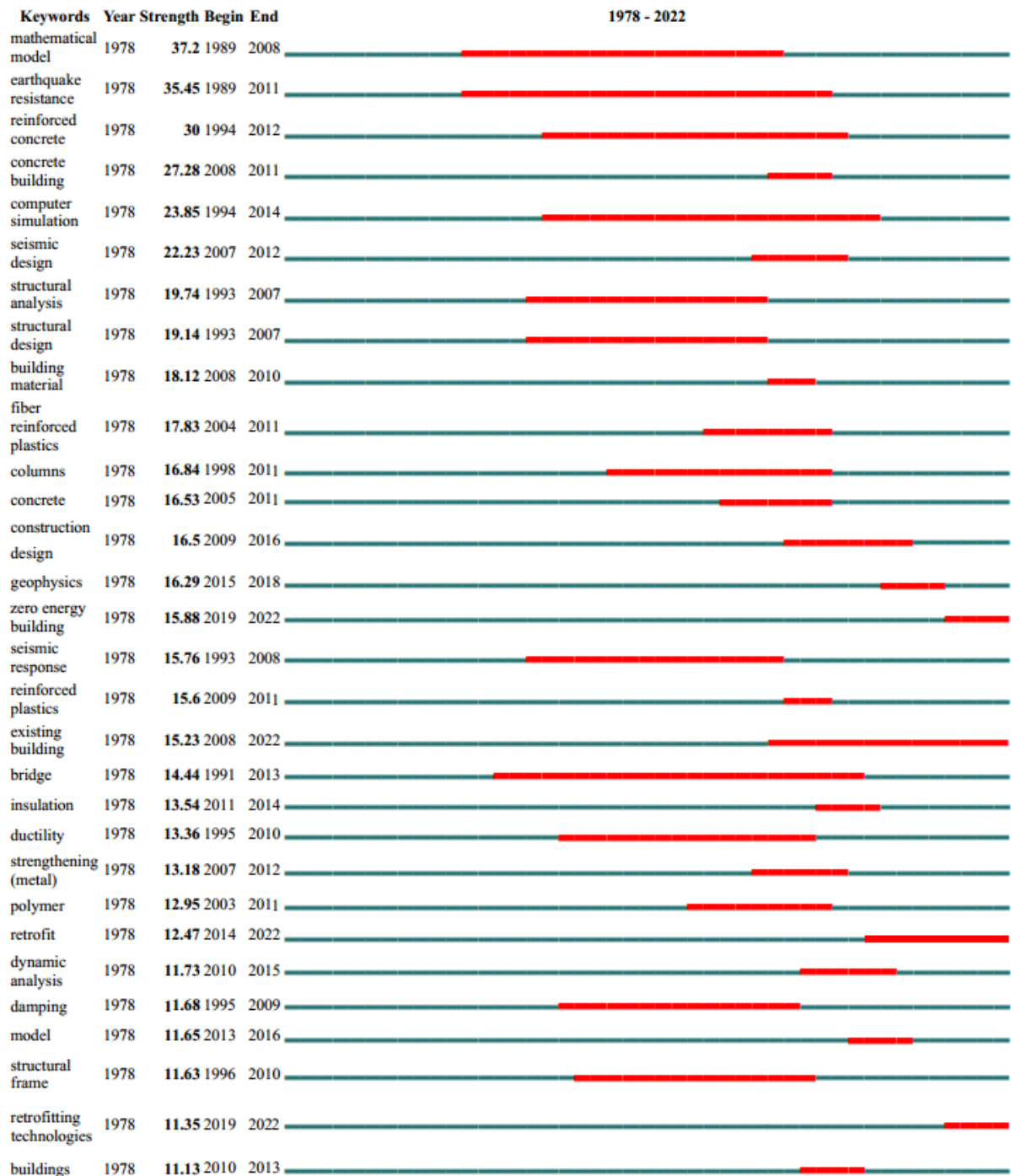
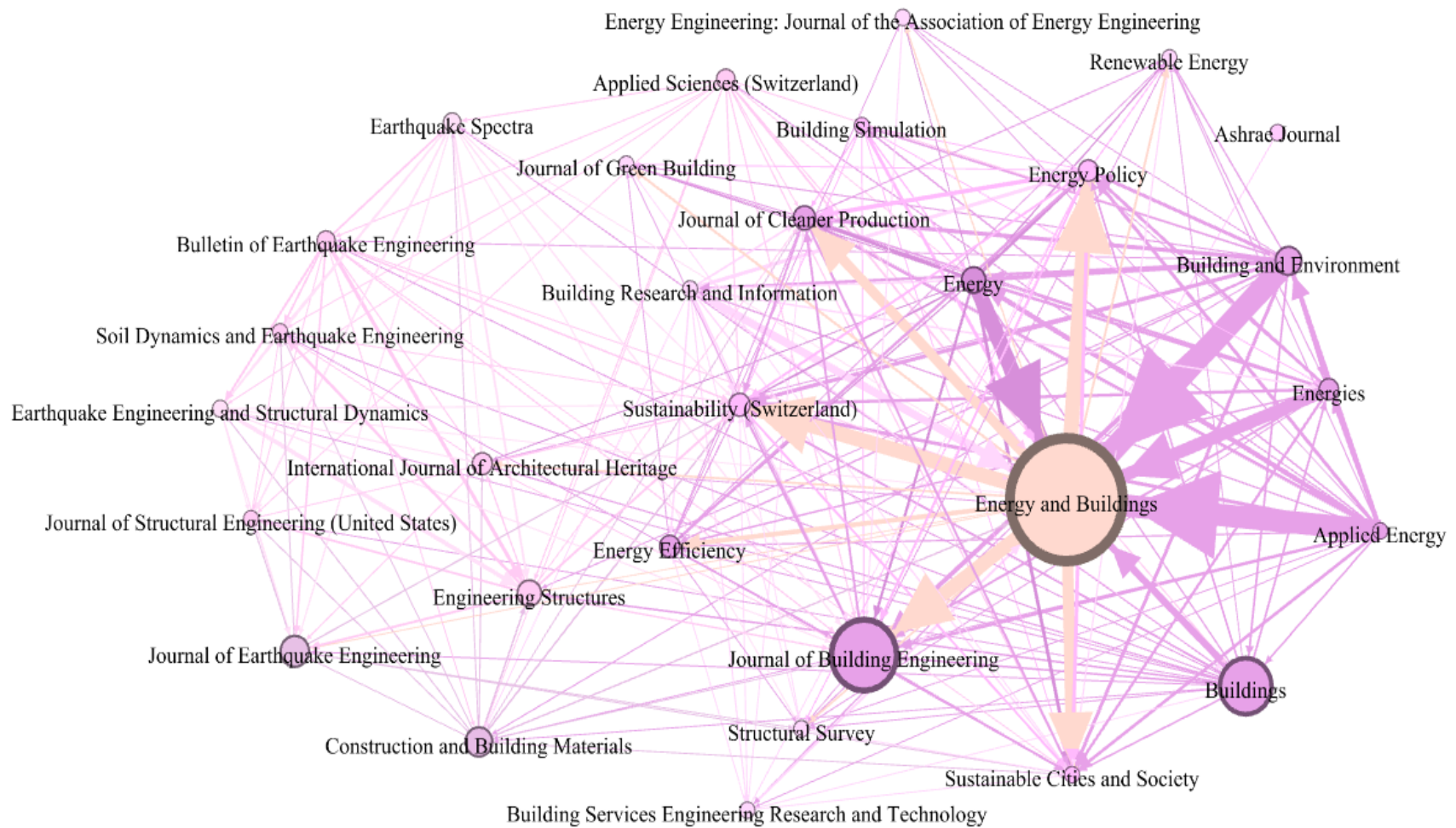


Fig. 5. Top 30 keywords with the strongest citation burst in the GREB literature.

4.2.4. Leading outlets for GREB research: direct citation analysis

Using VOSviewer, a direct citation analysis was performed to identify academic outlets that have contributed significantly to the maturity of GREB research. The discovery of prominent outlets in any scientific field is helpful to authors and readers in obtaining the best source of information and suitable publication outlets for their works. Equally, journal editors and institutions/libraries could adjust their journal goals and optimize resource investment (Hosseini et al. 2018b). The type of analysis was “citation”, and the unit of analysis was “source”. Further, to obtain the optimum network, the threshold for both the minimum number of documents and citations of a source was set to 30. Of 1,162 sources discovered, 30 met the threshold. Gephi was used to visualize the network (Fig. 6), comprising 30 nodes and 235 edges. Table 3 presents the top 20 prominent outlets for research on GREB, ranked based on weighted degree values. The weighted degree has been widely used to determine the influence of nodes in controlling the flow of information across networks (Prell, 2012). The nodes and edges were resized and recolored using the weighted degree values. The thickness of the edges is based on the number of citations (either inflow or outflow) between the nodes.

The results show that *Energy and Building* (weighted degree value of 2402) has been the most prominent outlet (i.e., the primary source of reference material for subsequent publications) for GREB research. There is a significant inflow of information (through citations) from *Building and Environment* (second prominent outlet), *Applied Energy* (third), *Energy* (five), *Energies* (ninth), and *Buildings* (twelfth) to *Energy and Building*, as depicted in Fig. 6. This is reasonable as these outlets address a common issue – reducing the energy needs of a building and improving indoor environmental quality. Conversely, there is a large outflow of information from *Energy and Building* to *Energy Policy*, *Sustainability*, *Journal of Building Engineering*, *Sustainable Cities and Society*, *Journal of Cleaner Production*, etc. These prominent outlets appear to advance building energy needs and mitigation of earthquake hazards. Overall, the outlets on the left side of Fig. 6 are mainly focusing on structural retrofit, while those on the right hand side is more related to energy and environment.



511

512 **Fig. 6.** Mapping of leading outlets in the GREB domain.

Table 3. Top 20 prominent outlets for research on GREB.

Rank ^a	Outlets	Number of documents ^b	Weighted Degree value
1	Energy and Buildings	622	2402
2	Building and Environment	144	792
3	Applied Energy	137	680
4	Energy Policy	92	582
5	Energy	102	549
6	Sustainability	188	518
7	Journal of Building Engineering	102	491
8	Sustainable Cities and Society	85	450
9	Energies	147	428
10	Journal of Cleaner Production	72	406
11	Building Research and Information	63	274
12	Buildings	77	259
13	Engineering Structures	173	235
14	Energy Efficiency	48	165
15	Bulletin of Earthquake Engineering	80	139
16	Earthquake Engineering and Structural Dynamics	67	112
17	Earthquake Spectra	81	97
18	Building Simulation	30	83
19	Journal of Earthquake Engineering	33	76
20	Soil Dynamics and Earthquake Engineering	39	74

^aRanking based on weighted degree values^bDuring the studied period (1978 – March 2022)

4.3. Scientific collaboration network in GREB research (co-authorship analysis)

Knowledge of the existing scientific collaboration network in any research discipline facilitates access to financial resources, expertise, and specialties, increases productivity, and limits research isolation (Hosseini et al. 2018b). Ultimately, this enhances scholarly communication and benefits scientific collaboration (Ding, 2011). Glänzel and Schubert (2005) highlighted that “almost every aspect of scientific collaboration networks can be reliably tracked by analyzing co-authorship networks.” They further argued that the lack of scientific collaboration in any research domain signifies lower research productivity. From this perspective, an analysis of the co-authorship network of institutions in GREB research is presented next.

4.3.1. Institutions

Identifying the collaboration network of institutions noted for high investment and interest in GREB research facilitates and assists long-lasting research partnerships and policy-making (Ding, 2011). The network was created using VOSviewer. The analysis type was “co-authorship”, the unit of analysis was “organization”, and the counting method was “fractional counting”. The “minimum number of documents of an organization” and the “minimum number of citations of an organization” were set to five to achieve the optimum network. Of 10,390 organizations found, 41 met the threshold. Gephi was used to visualize the network (Fig. 7), which comprised 41 nodes and 8 edges.

The nodes and edges were resized and recolored using the hyperlink-induced topic search in Gephi based on their hub scores in the network.

Fig. 7 shows that only a few institutions from the UK, Italy, Canada, New Zealand, and Mexico have established collaborative relationships in GREB research. Generally, the nature of collaboration in GREB research could be described as “*weak*” – as there is a noticeable weak institutional cross-linkages in the network – highlighting the lonely nature of GREB research. To obtain the highest standards of interventions and scholarships on GREB, strong collaborative relationships at the institutional level ought to be fostered across the entire network. An interesting finding is the inclusion of purely research institutes, including the National Renewable Energy Laboratory and Lawrence Berkeley National Laboratory in the US, and the National Center for Research on Earthquake Engineering in Taiwan, as influential actors in the network. This supports the assertion that the race to GREB needs a shift toward a partnership approach with a blurring of the conventional boundaries between academia and industry/investors.

4.3.2. Countries

To identify top influential countries, those countries actively involved in GREB research, and the collaboration among them, a collaboration network was created following a similar process explicated above. This exploration will generate insights about the most influential countries/jurisdictions that have actively explored GREB strategies and learn from those countries and respond with accelerating commitments as the climate rapidly deteriorates. The analysis type was “co-authorship”, the unit of analysis was “countries”, and the counting method was “fractional counting”. The “minimum number of documents of a country” and the “minimum number of citations of a country” were set to 15 to achieve the optimum network. Of 217 countries identified, 48 met the threshold. Gephi was used to visualize the network (Fig. 8), which comprised 48 nodes and 443 edges. The nodes and edges were resized and recolored using the weighted degree values, with bigger node sizes showing higher weighted degree values. The network (Fig. 8) reveals the following findings:

- Table 4 presents the top 20 influential countries/jurisdictions collaborating in GREB research based on the weighted degree values in the network. It is evident from the table/Fig. 7 that the US, UK, Italy, and China, ranking in the descending order, emerge as top-ranked countries/jurisdictions collaborating in GREB research. This indicates that these countries have contributed significantly to GREB research. Australia, Germany, and Canada appeared as fifth, sixth, and seventh influential countries, respectively. The links between them are weak. This reinforces the need for institutions in such countries to reformulate policies to

promote collaboration among themselves to further strengthen knowledge exchange and global collaboration in the GREB research field.

- In relation to the link's strength, the strongest links identified within the network were between the US–Italy, US–China, US–UK, Italy–UK, China–UK, and US–Canada. These strong links are very few (only six) compared with the network's total links (443). The possible reason could be because of limited cross-country and comparative studies in the existing GREB literature. Similarly, considering the existing strong links (mainly among a few developed countries), developing countries were inadequately represented in the network. This needs to be considered by these countries when refining their research policies as they are distantly away from the main collaboration network of GREB research. Therefore, there is a need for strategies that promote the exchange of knowledge and ideas on GREB research globally.



Fig. 7. Collaboration network of institutions in GREB research.

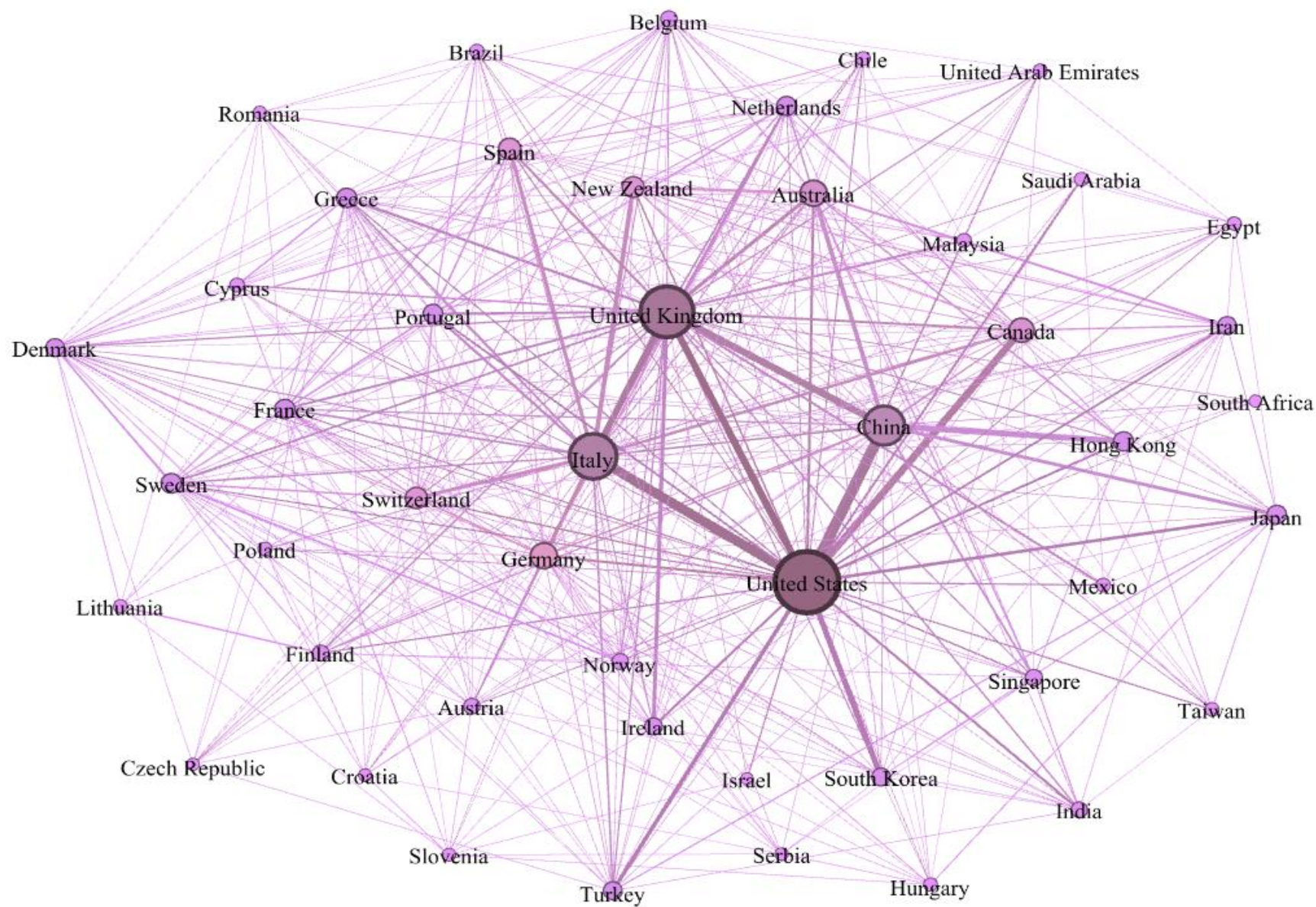


Fig. 8. Collaboration network of influential countries in GREB research.

Table 4. Top 20 influential countries/jurisdictions collaborating in GREB research.

Countries/Jurisdictions	Number of documents ^a	Weighted Degree Value	Exploration relevance
United States	1318	330	1
United Kingdom	753	261	2
Italy	962	223	3
China	341	183	4
Australia	198	95	5
Germany	223	94	6
Canada	280	83	7
Spain	233	66	8
Switzerland	120	65	9
New Zealand	120	62	10
Sweden	140	54	11
France	95	53	12
Greece	98	52	13
Netherlands	88	51	14
Hong Kong	103	50	15
Portugal	159	49	16
Japan	131	47	17
Turkey	119	45	18
Denmark	87	44	19
Iran	140	43	20

^aDuring the studied period (1978 – March 2022)

5. Discussion and future directions

This study has explored the *full* GREB scholarship, analyzing a large corpus of literature, through quantitative, text-mining approaches, in a systematic manner. The body of knowledge so far produced on GREB was assessed to identify the research themes, clusters, and collaboration networks of prominent outlets, institutions, and countries. The thematic evolutionary of GREB studies revealed a progressively steady growth and promising research focus, substantially consistent and more directed towards “energy efficiency”. This revelation, in general, is aligned with the keywords co-occurrence analysis. Other topics such as residential buildings, historic buildings, building energy retrofit, thermal comfort, etc. have also received significant attention in the GREB domain. Surprisingly, while occupant behaviour and IEQ are being largely neglected from the current frame of GREB definition/practice, topics including but not limited to seismic retrofit, seismic risk, and seismic performance do not equally integrate the all-inclusive goal of GREB. Besides, topics such as intelligent or smart buildings, circular economy, and nZEB are now being increasingly valued, although they are yet to see full integration in GREB practice. Future research should focus on achieving the comprehensive targets of GREB by integrating occupant behaviour, IEQ, and the current topics of intelligent buildings, circular economy, and nZEB into GREB. The established clusters have mainly been confined to only the knowledge within the cluster domains and self-referential, except for the importance of borrowing theories and ideas from other related fields. This is a generic issue affecting the innovative diversification of construction

management studies, as pointed out by Hosseini et al. (2018b). Another critical observation is the missing, weak, and loose collaboration links between institutions and countries. These problems are detrimental to the broader uptake of GREB and need to be solved. The borrowing of theories, ideas, models, and systems from fields such as computer science, manufacturing, automotive, etc., which have advanced both in research and practice, is recommended. It is also important that academic institutions, public and private research funding institutions, and countries/jurisdictions not only have to accelerate GREB implementation commitments but also must promote interdisciplinary, interinstitutional, and international collaboration, collectively in terms of standard practice, as the climate rapidly deteriorates. Furthermore, the network of outlets analysis revealed that *Energy and Building*, *Building and Environment*, *Applied Energy*, *Energy Policy*, *Energy*, *Sustainability*, *Journal of Building Engineering*, *Sustainable Cities and Society*, *Energies*, and *Journal of Cleaner Production* are the top 10 outlets in terms of serving as the key reference points for GREB publications. Based on the results, several gaps and pathways for future studies are discussed in the following sub-sections.

5.1. List of identified research gaps

The following research gaps were identified after summarizing and comprehensively analyzing the existing studies (note that these gaps, in general, are in connection with the network analyses):

- Most studies focused on energy efficiency retrofitting (EER) in residential buildings and mainly retrofitted on a case-by-case basis (i.e., confined to a single building block), but only a few studies exist on EER for the commercial sector, especially offices, restaurants, and retail buildings, and for large-scale building stocks;
- IEQ and occupant behaviour tend to be disregarded in comparison with energy and cost elements in the holistic framework of GREB, with both being seldom analyzed and predominantly assessed by simulation, limiting the wide adoption of such data to improve building operations and performance;
- While only a handful of studies have attempted to improve both the seismic and energy performance of existing buildings, innovative integrated retrofit approaches that address seismic, energy performance, and other green concepts such as environmental impact, IEQ and occupant behaviour have yet to be developed;
- A range of promising strategies and innovative concepts, such as intelligent buildings, circular economy and nZEB, that can be used for achieving energy independence and carbon neutrality has yet to be consolidated and *fully* developed in the GREB domain;

- Research interests such as occupant health, well-being, comfort, and quality of life have been seldomly explored and fall short of comprehensive evaluation and require *full* integration into the research and development of retrofitting measures;
- There is a lack of interdisciplinary approaches, wherein buildings and HVAC systems, occupants, health and comfort, and IEQ are examined as interacting components and based on an integrated approach;
- While there is much research on *light retrofit* strategies, few studies exist under the scope of *deep retrofit* with limited practical or real case studies to steer its implementation;
- A critical challenge has been *generating* and *deploying* entire building stock data for accurate building performance analysis and cost-effective retrofit recommendations;
- The integration of retrofitting technologies (i.e., demand-side management, supply-side management, and human factors) into GREB has yet to be *fully* developed;
- Limited studies exist in the area of automated energy performance modeling, low carbon building energy design and key performance strategies;
- There is a general lack of explicable theories to support GREB understanding and promotion, and limited studies exist, especially from the perspective of *developing countries*;
- There is a need for more practical promotion strategies (both general and context-specific) for GREB implementation globally;
- There is a lack of an *in-depth* exploration of the real challenges facing GREB implementation in each phase of the retrofit process (i.e., pre-retrofit phase, implementation and commissioning phase, and post-retrofit phase) and strategies to overcome them.

5.2. Pathways for future studies

Fig. 9 shows proposed promising future directions in GREB research. Both technology/approach-centered and human/physical-centered pathways are highlighted in each phase (i.e., pre-retrofit, implementation and commissioning, and post-retrofit phase) of the GREB process. Recall that each of these phases is briefly described in Section 1.1. Although the proposed promising future directions have few overlaps (yet different positions in each respective retrofit phase), each phase demands critical attention and examination to facilitate realizing the full potential of GREB.

5.2.1. Technology/approach-centred pathways

5.2.1.1. *Integrated digital technologies with occupant behaviour and IEQ modeling*

The integration and implementation of digital technologies, for example, BIM (identified as one of the research interests), for GREB is not new. However, their applications are still scarce and immature, especially for making decisions in the pre- and post-retrofit phases (Lim et al., 2021). These two phases are very complex (with a lot of uncertainty involved), time-consuming, and costly in terms of data acquisition and management. For example, in the pre-retrofit phase, significant time and effort are required in collecting the large amount of data needed for the assessments and finalizing optimal retrofit solutions and performance standards. Also, in the post-retrofit phase, data management and real-time building performance monitoring/analysis are challenging tasks for facilities managers and decision-makers (Schweigkofler et al. 2022). Previous studies have primarily integrated BIM and simulation software/tools for building energy and cost analysis (Lim et al., 2021), while occupant behaviour and IEQ are rarely considered in the GREB decision-making process. Occupant behaviour and IEQ have become increasingly important in the post-COVID-19 world (Li et al. 2021). Occupants not only have an impact on building energy consumption, but also on the IEQ. Occupants influence the indoor environment by generating heat, CO₂ concentration, light level, door status, binary motion as well as temperature (Yang et al., 2016). Anand et al. (2022) therefore highlighted that the post-COVID-19 era requires the consideration of novel sustainable strategies to create a synergy between occupant, IEQ and building energy efficiency. Occupant behaviour has a big impact on the performance of the retrofit measures, where even an efficient measure procured and installed can become inefficient depending on how occupants behave. Therefore, a more efficient digital approach that integrates factors with a high level of uncertainties (e.g., occupant behaviour and IEQ modeling) is urgently needed for GREB decision-making in the pre- and post-retrofit phases.

Accurate data acquisition is crucial for the successful implementation of digital technologies for GREB, especially for historic buildings with no digital model (structures without BIM model) (Sanhudo et al. 2018; Piselli et al. 2020). An alternative method is to generate as-is 3D models of the buildings using technologies such as 3D laser scanners, photogrammetry, and GIS. While there are several studies explaining the application of these tools (Nguyen et al. 2020; Alshawabkeh et al. 2021), studies that actually use BIM-3D laser scanning and/or photogrammetry (scan-to-BIM approach), or BIM-GIS integration for GREB are limited. Those few studies also have limitations that are worth addressing in future studies, in that they are confined largely to a small number of selected buildings (on a case-by-case basis). Moreover, those few studies that considered large-scale building stock by integrating BIM and GIS (Göçer

et al. 2016) or using GIS as a standalone method for GREB (Buffat et al. 2017) did not consider environmental conditions (e.g., temperature and airflow), IEQ, occupant behaviour, and socio-economic aspect, all of which are important for GREB decision-making. Future studies could address these limitations by integrating IoT – network of physical objects that are embedded with sensors, software, and other technologies for connecting and exchanging data – to monitor and capture environmental conditions and occupancy rates in real-time. Then, through BIM-IoT-life cycle cost assessment (LCCA) integration, the socio-economic aspect gap could be filled. The fostering of the paradigmatic digital trend in the GREB process requires the development of an all-in-one digital environment, in a more user-friendly, sustainable, and immediate manner, for complex decisions and cross management. Thus, further studies are needed for the development of a systematic framework with demonstrations of the scan-to-BIM-enabled LCCA-GIS-IoT integration. Taking a step further, especially in the post-retrofit phase, a more efficient and error-free method would be needed for the real-time monitoring and management of heterogeneous operational data. The concept of Digital Twin (DT) – virtual replica of the physical world, wherein components and processes can be aligned in real-time for greater efficiency and quicker decision-making actions – could also be introduced for real-time visualizing, planning, monitoring, and analyzing dynamic data. The scan-to-BIM-LCCA-GIS-IoT integration to apply the DT paradigm in GREB will provide a comprehensive view of the building status, thereby improving the user's experience and better decision-making opportunities. Again, useful information to monitor and maintain the building performance during the operation phase would be warranted, leading to more responsive building management. More recently, Schweigkofler et al. (2022) attempted to represent and visualize sensor data in BIM for energy management of existing buildings through BIM-IoT integration. The authors highlighted that it becomes difficult to manage and detect data anomalies, due to the progressively cumulative, dynamic, and heterogeneous data in real-time. Future studies should develop and integrate an AI-based anomaly prediction system into the BIM-IoT platform for predicting building facility anomalies. Further studies could also extend this workflow by developing automatic control feedbacks to receive anomaly warnings and remotely monitor and timely correct any defect. To realize this goal, it is crucial that future studies define or outline key performance systems as part of the monitoring process for tracking and notifying unacceptable thresholds of monitored parameters based on an alert system (Schweigkofler et al. 2022). This could lead to faster response and quick reactions to improve the buildings' operational performance post-retrofitting.

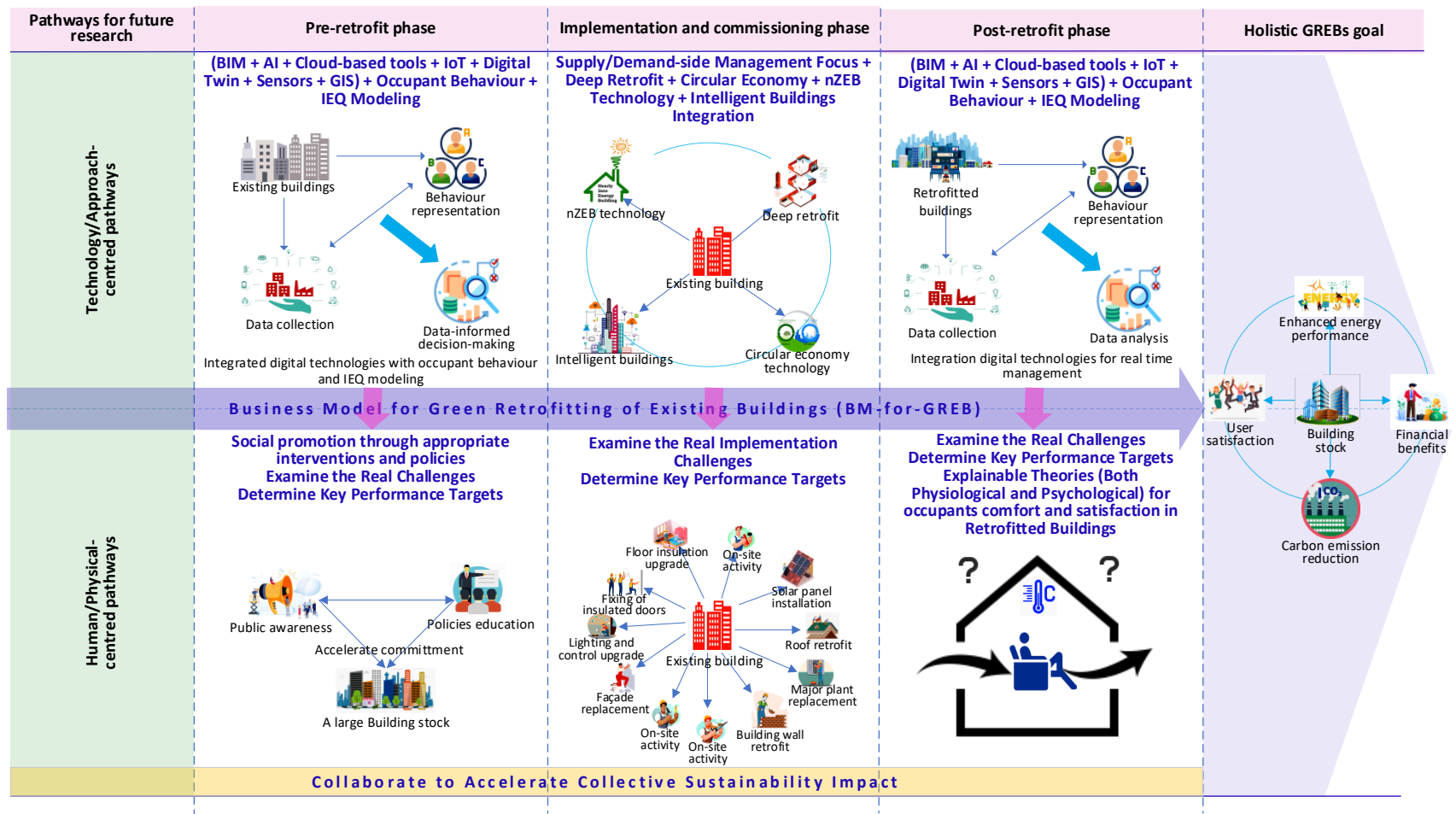


Fig. 9. Future research directions.

5.2.1.2. Integrated supply- and demand-side management strategies with deep retrofit, circular economy, nZEB technology and intelligent building approach

There is an important need to improve GREB practice via the use of advanced construction techniques and material choices to completely transform the built environment towards carbon neutrality (Gagliano et al. 2016; Tan et al. 2021). As discussed above, although supply-side management has a fundamental role in supporting GREB for net-zero carbon alignment, the need for adequate integration of demand-side management strategies, wherein low energy-efficient appliances and replacements (e.g., mechanical, electrical, and plumbing) are used, is highly recommended (Fan and Xia, 2018). Given the uniqueness of building types and distinctive local conditions, a solid understanding of these factors and the condition of the existing buildings is a primary step to making appropriate decisions on low carbon options to pursue (UKGBC, 2022). Future works should focus on developing an evaluation framework for prioritizing suitable packages of strategies needed for retrofit projects. This could further be aligned with the digital tools for efficient and effective implementation to cover the extensive content of GREB. Keeping this goal in mind, an assessment aptly designed based on the size and scale of retrofit is critical to identifying the specific focus of interests. With the goal to achieve complete energy savings and occupant well-being through deep retrofit, future studies should focus on establishing a priority list of retrofit strategies, informed by predictive energy modeling and life-cycle assessment. This will ensure that the needs of individual projects and primary concerns are provided for all retrofit types (e.g., by first giving priority to the highest energy reduction measures or focusing on less destructive changes). The need for further investment, in terms of research, in emerging methods such as circular economy, nZEB, and intelligent building into the GREB practice is key to establishing a complete low carbon asset. Promoting the circularity of construction materials, the reuse of waste building materials, is an effective method to reduce the carbon emission produced by new material production. Future research should focus on: (1) developing potential pathways, based on materials and circular thinking, to achieving circularity and net zero in GREB. Prior to that, it is crucial to identify priority impact areas via whole life carbon assessment and analysis of potential retrofit measures (UKGBC, 2022). In doing so, it is critical to not only focus on identifying low embodied carbon materials but also ensuring that the selected actions work together perfectly to make available the best possible strategy to realize net-zero carbon aspirations; (2) evaluating and comparing embodied carbon impacts against operational energy savings to identify the precise materials for the project; and (3) future disassembly and adaptability approaches of building components and materials to be built into the retrofit process to increase circularity in GREB practice. The nZEB has a fundamental

role in the development of intelligent buildings by tackling challenges relating to renewable energy production, energy efficiency, and energy management (Omran et al. 2022). Consequently, converting existing buildings into intelligent buildings play a crucial role in transitioning the built environment towards energy neutrality. As renewable energy production represents the core aspect of nZEB, future studies should focus on how to make those products intelligent or more responsive to occupancy data in existing buildings (e.g., adaptive solar façade, electrochromic glazing, etc.). This could be realized by embedding sensors into materials and equipment, together with wireless sensor networks, thereby resulting in a ubiquitous network providing extensive and valuable real-time data on performance. While advancing this goal, future research work could also focus on how to make existing buildings self-healing building skins to revolutionize the way in which the building façade and the materials used for equipment can be designed (Clements-Croome, 2011).

5.2.2. Business model for GREB (BM-for-GREB)

The continuing deterioration of ecological and social systems and attempts to reverse the trend to achieve sustainable development is redefining the overall conditions for business in the 21st century (Broman and Robèrt, 2017). Successful businesses have realized this by designing and building functional business models in this context (Boons and Lüdeke-Freund, 2013; França et al., 2017). A business model (BM) provides a means to put a strategy into practice and reflects the organization's realized strategy (Casadesus-Masanell and Ricart, 2010). The BM concept was proposed by Osterwalder and Pigneur (2010) through the BM "ontology," also known as "canvas" BM, and has become one de facto standard for BM development. The main rationale of BM is to deliver value to customers and catch profits. With the integration of sustainability strategy, its relevance extends far beyond financial gains to include social and environmental targets (Moschetti and Brattebø, 2016). Tantau and Maassen (2019) highlighted that a sustainable BM must be dynamic, embrace emerging dimensions of global sustainability, and be compatible with business strategy to create competitive advantages. Within the GREB framework, a BM that integrates holistic green concepts is key to helping accelerate the collective investments needed to achieve carbon neutrality (Tantau and Maassen, 2019). Thus, BM-for-GREB is an important tool for increasing existing buildings' performance and reducing energy and carbon intensity. It is useful to a large category of stakeholders such as building owners, tenants, facility managers, energy managers/auditors, developers, investors, materials and equipment suppliers and manufacturers, utility companies, government departments and authorities, energy-saving service departments, commissioning providers, and planning and design units. Lizana et al. (2016) highlighted that for BM to sufficiently

embrace the GREB practice, the different objectives of these stakeholders need to be fully understood. There is a need for better cooperation between these stakeholders in order to develop retrofitting projects. Hence, a BM-for-GREB that considers a wide range of drivers not only to show the need for the retrofit but also its potential benefits for all stakeholders, is crucial. Future studies should focus on developing a holistic BM-for-GREB and validating it through case studies to understand GREB investment decisions and assess outcomes in real projects. To accomplish this goal, it is important that future studies first explore business management theories such as the transaction cost theory, the resource-based theory, entrepreneurship theory, narrative theory, etc., to enrich an in-depth understanding of BM from the GREB perspective. Not only will the approach help to contextualize the BM-for-GREB, but also will enrich the GREB scholarship and address the endemic deficiency.

5.2.3 Human/physical-centred pathways

5.2.3.1. Social promotion of GREB through appropriate interventions and policies

Almost all existing studies on GREB are directed to the what-why-how questions (Jagarajan et al. 2017):

- What refers to the definition and scope of GREB,
- Why refers to the need for GREB, and
- How refers to the retrofit scenarios/actions and decision-making models.

Although there have been several macro policies or political interventions (e.g., economic incentives, regulations, and standards) to persuade homeowners to undertake retrofit, the take-up rate both in developed and developing regions is low (Guo et al., 2019; Bertoldi et al., 2021). It is frequently argued that the intentions of the public toward the GREB practice are still unclear, thereby leading to the poor effectiveness of the interventions of the macro policies (Kerr et al., 2018; He et al., 2019; Huang et al., 2021). This indicates that policy intervention strategies do not fit well with the sociocultural characteristics of the general public's retrofit decisions. Prior studies have attempted to understand the public decision's behaviour toward GREB implementation (Hwang et al., 2017; Tjørring and Gausset, 2019; He et al., 2019; Huang et al., 2021). For example, Hwang et al. (2017) investigated residents' perceptions of green retrofit programs in Singapore and explored their willingness to extend the retrofit into individual houses. He et al. (2019) explored the main factors that affect the intention of Chinese residents toward green retrofitting of existing residential buildings. Tjørring and Gausset (2019) investigated homeowners' drivers for retrofit from a sociocultural perspective in Denmark. Although these studies, at least in part, have contributed to improving retrofit policy design, they are limited to only a few populations (experts or specific groups of residents who had completed building retrofit)

and within a specific country. Thus, they lack a *holistic* and *heterogeneous* understanding of the general public's perceptions and global-wide sentiment orientation. In an integrative view, aggregated collection of diversified city-scale population sentiments toward housing renovation could derive greater benefits. Therefore, it is in the remit of future studies to fully evaluate and harness diversified population motivations for GREB, in particular sociocultural requirements, for optimizing macro policies for advancing its practice. Future studies should realize this goal through social media data, a huge data source yet to be fully leveraged in GREB research. Meanwhile, appropriate interventions and policies that seek to encourage general public participation must be established to facilitate a wider uptake of green retrofit. Moreover, educational policies regarding existing building retrofit can develop a social norm that “*everybody else is implementing it*” to encourage wider uptake.

5.2.3.2. Real challenges in GREB practice (considering pre-retrofit phase, implementation and commissioning phase, and post-retrofit phase)

Despite the numerous tangible and intangible benefits of GREB, the practice of GREB is still hindered by several challenges (Fylan et al. 2016). This could be one of the main reasons why the rate of GREB is still low (WEF, 2022). Although many studies have analyzed the challenges faced by building retrofitting (Davies and Osmani, 2011; Bjørneboe et al., 2018; Liu et al., 2020; Alabid et al. 2022), there is a lack of an *in-depth* exploration of them. For example, Davies and Osmani (2011) investigated the financial and business, environmental and cultural, technical and design, and legislative challenges for low carbon housing retrofitting in the UK. The study offers valuable insights, but these are architects-only “perceived” challenges, which might not sufficiently reflect the “real” challenges on the ground for a comprehensive set of key stakeholders. In Denmark, there exist information, financial, and process challenges that make the progress of energy retrofitting of single-family houses very slow (Bjørneboe et al., 2018). A lack of political will, capability, financing, misaligned incentives, and quality assurance challenge public building retrofit in Australia (Alam et al., 2019), though these findings are perceived and from only two focus groups. Until these challenges are better understood from a broader perspective and contexts and overcome, GREB may still be limited to only a few existing buildings. The identification of these challenges in each phase of the GREB process will help stakeholders (e.g., building owners, tenants, facility managers, energy managers/auditors, government departments and authorities, among others) address them as early as possible in the retrofit process. Future research works should comprehensively investigate the real technical, financial, institutional, social, environmental, and regulatory challenges for GREB. Achieving carbon neutrality is a global agenda. In fact, countries/jurisdictions and

their building retrofitting challenges differ, making “local context” matter (Liu et al. 2020). Hence, in every country/jurisdiction, making knowledge of the real challenges is imperative if the global sustainability of buildings is to be improved. To realize this goal, it is important that future studies investigate real case projects right from the pre-retrofit phase to the post-retrofit phase. Also, without a better understanding of the real challenges faced in GREB and how to overcome them, even those suggested technologies by the existing studies may never achieve large-scale uptake. For better comprehension of GREB needs and support for wider uptake of GREB, future studies should focus on providing strategies, recommendations, and policy packages that could be used to overcome the challenges.

5.2.3.3. Key performance targets for GREB throughout the entire retrofit process

To ensure GREB benefits are realized, a clearly defined set of upfront performance targets that provide clear benchmarks to track GREB project performance is crucial (UKGBC, 2022). In this study, key performance strategies appeared as the least cluster of GREB research, indicating that it is still less developed and, thus, likely to face many challenges. Kylili et al. (2016) conducted a systematic review of extant studies and found that no unanimous conclusion on key performance indicators’ (KPIs) sub-categories, nor a standardized approach or methodology, not even regulations or guidelines for the evaluation of each exist. Ho et al. (2021) highlighted that existing analytical methods and frameworks for evaluating the holistic performance of GREB are not applicable, meaning that KPIs, targets, or system boundaries are not clearly established. To realize the full potential of key performance strategies, future studies should focus on establishing a clear and applicable framework for setting performance targets at an organizational level with specific targets set to follow. The UKGBC (2022) emphasized that such a framework should consider factors including but not limited to operational and embodied carbon, health and well-being, and circular economy to ensure the most holistic approach. For instance, the comprehensive study by Lai and Man, (2017) points out that certain indicators such as health and safety still lack full consideration in terms of assessment. Ho et al. (2021) supported that the health and safety aspect could, to a large extent, determine the overall performance evaluation result of the concerned retrofit project, if accounted for and assigned with a higher weighting. With the entire GREB process in mind, future research should focus on defining KPIs for a full assessment of GREB, including the monitoring process to ensure building operations remain as intended at design, verified through the introduction of KPIs to the responsible stakeholders.

5.2.3.4. Explainable theories (both physiological and psychological) for occupants’ comfort and satisfaction in retrofitted buildings

Occupants' comfort, satisfaction, and well-being are among the important components of GREB decision-making. While these components are declining in importance, as noted earlier, previous studies have been largely focused on collecting occupant responses in real buildings to revise the traditional predicted mean votes (PMV) model (Barlow and Fiala, 2007). Yet, there is still a lack of an evidence-based parameterization of the concept of comfort and satisfaction expectation as well as well-being measures (De Dear et al. 2020). The understanding of the psychology and physiology behind occupant comfort and satisfaction is crucial to promoting natural ventilation and personal comfort system to lower the usage of central air-conditioning (Li et al. 2021). Therefore, future research should focus on providing a more convincing explanation of the psychology and physiology behind occupant well-being in retrofitted buildings. This research work is needed sooner than later, especially in commercial buildings where long-term air-conditioning has increased occupants' expectations for a comfortable temperature range leading to increased energy consumption (Li et al. 2021). This will also enrich the GREB scholarship and address the endemic deficiency in GREB research.

6. Conclusions

Existing buildings are one of the world's biggest challenges when it comes to tackling climate change and sustainability, due to their significant impact on energy consumption and carbon emissions. This challenge can be turned into a solution through a GREB revolution. Although several studies on GREB have been published over the years, they lack a comprehensive quantitative/objective review. This study analyzed the global research on GREB, using science mapping techniques, from its emergence in 1978 to the present. It provided a *full* picture of the landscape of the body of GREB knowledge, covering the largest corpus of literature (5,288 publications) and identified gaps from a holistic viewpoint. Different from other similar studies in the area, this study relied on quantitative analysis of the literature, effective in limiting subjectivity in the analysis, thus making the study findings more reliable and reproducible. This study uncovered 105 knowledge areas of GREB, a couple of them interrelated, largely limited to studies exploring "energy efficiency" options and optimization of the extensive content of GREB. In this context, several fundamental issues and useful future directions and pathways were discovered and put forward. The proposed framework for the future directions and pathways is believed to be punchy and set a pushy tone, offering remedial solutions to current drawbacks in the existing knowledge for improvement. Not only the technological/approach- and human/physical-centered pathways put forward benefit GREB advancement. Also, by identifying the existing research networks, GREB advocates would benefit from an awareness of the topical issues, institutions and countries involved,

and connections among all these, as well as the outlets communicating GREB research findings. Thus, researchers and practitioners can synthesize various kinds of information to capture the *status-quo* of GREB. Specifically, from the technological/approach-centred perspective, this study will give rise to:

- The development of a more efficient digital approach that integrates dynamic or factors with a high level of uncertainties (e.g., occupant behaviour and IEQ) for better GREB decision-making opportunities and cross management – especially in the post-retrofit phase.
- The development of a cross-functional digital environment (e.g., the scan-to-BIM-LCCA-GIS-IoT integration) capable of addressing the socio-economic gap in extant studies and for real-time planning, monitoring, and management of heterogeneous operations, while considering existing building stock at scale.
- A solid understanding of green technologies (i.e., supply- and demand-side management strategies) and housing conditions for establishing an effective and efficient evaluation framework for prioritizing suitable strategies in supporting the GREB practice for net-zero carbon alignment.
- The development of potential pathways, based on materials and circular thinking, to achieving circularity and net zero in GREB.
- The development of a holistic BM-for-GREB for understanding and realizing GREB investment decisions and outcomes in real projects.

From the human/physical-centred perspective, this study will give rise to:

- Establishing more appropriate and effective policy intervention strategies to promote the retrofit of existing building stock at scale to achieve the goal of carbon neutrality through harnessing multiple motivations, concerns, and perceptual factors (e.g., values that should inform energy efficiency improvements in existing buildings) toward GREB implementation.
- A comprehensive evaluation of the real challenges facing GREB implementation and how to overcome them.
- Establishing key performance targets or benchmarks for the full assessment of GREB project performance throughout the entire retrofit process.
- Conducting more research to improve the robustness and standardize methods of IEQ weighting schemes to create a benchmarking database of standard IEQ data.
- Developing more interdisciplinary approaches wherein buildings and HVAC systems, occupants, health and comfort and IEQ are investigated as interacting elements and based on an integrated approach

With the ultimate goal of promoting the conversion of the existing conventional building into nZEB, the relevance of this study's results can be summarized by all the pillars of sustainability (i.e., economic, environmental, and social). From the *economic* point of view, driving GREB implementation through technological advancement to support complex decisions (in terms of cost-effective technologies and energy efficiency measures to reduce initial investment cost) and real-time building performance management (to reduce the costs of operating the building during its service life – future cost), as a significantly improved alternative compared to the traditional ways, will bring more benefits that can be found in project flexibility, low financing cost, cost savings from reduced energy use and bills, and increased building value. From the *environmental* point of view, adopting emission-free materials and resources imbued with circular thinking will significantly help reduce GHG emissions via energy consumption reduction, reduced pollution loads, and damage to nature. Notwithstanding, through the BIM-IoT-life cycle cost assessment (LCCA) integration, for example, the environmental impacts of energy-efficient buildings can efficiently be assessed. From the *social* point of view, the interdisciplinary pathways put forward will improve occupant health and comfort due to less air pollution and a better indoor climate, both of which also lead to fewer hospitalizations and improved worker productivity. Moreover, it will inculcate the culture of energy efficiency improvement, changing attitudes and behaviour and creating job opportunities in the home improvement sector.

Some limitations are worth mentioning, despite the numerous contributions. First, only articles (i.e., peer review articles) written in English were considered in this study, indicating that relevant works published in other languages were excluded. Second, the dataset used in this study was retrieved from Scopus, and therefore, the analysis is affected by the limitations of Scopus in terms of coverage. Besides, the search string used might not be exhaustive. Therefore, the outcome of this study might not wholly reflect the available literature on GREB. Furthermore, the findings of this study were based on using social network analysis principles on citation networks. Caution should be taken when interpreting the findings in light of these limitations. Future studies could address these limitations by utilizing data from different sources (including all literature types) and based on a wider range of indicators to investigate linkages, quality, and influence in the literature.

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but with different scope, objectives and findings, may be published elsewhere. Acknowledgment is due to the editors and anonymous reviewers who provided constructive comments and suggestions that helped to improve this paper.

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