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Review

Research Progress on Carbon Emissions of Public Buildings: A Visual Analysis and Review

Zhen Gao [1], Hui Liu [1], Xiaoxiao Xu [1], Xiaer Xiahou [2], Peng Cui [1,*] and Peng Mao [1,*]

[1] Department of Engineering Management, School of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China
[2] Department of Construction and Real Estate, School of Civil Engineering, Southeast University, Nanjing 210096, China
* Correspondence: cui@njfu.edu.cn (P.C.); maopeng@njfu.edu.cn (P.M.); Tel.: +86-198-9588-0635 (P.C.); +86-138-0517-1820 (P.M.)

Abstract: As the global climate continues to change, lowering carbon emissions of public buildings (CEPB) is essential for reducing carbon emissions from the construction sector. Exploring the current status of the field is crucial to improving the effort to reduce CEPB. CiteSpace and VOSviewer are used in this research to visualize the literature on CEPB from the Web of Science Core Collection from 2002 to 2022, including an overview, collaborations, and keywords, as well as references. The paper then analyzes and reviews the research processes of CEPB in conjunction with the visualization results and the collation of information from the literature. The results show that the current research hotspots include (1) theoretical research and simulation modeling, (2) energy systems, (3) materials, (4) public building retrofitting, (5) the main factors that contribute to the reduction in CEPB. Architectural features and structures and digital technology are the frontiers of research in the field of CEPB. In general, there is still sufficient space to develop in the field. These findings intuitively encapsulate the valuable information and inherent value of a significant body of literature, which can help researchers quickly understand the field and provide some references.

Keywords: carbon emissions; public buildings; visual analysis

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1. Introduction

The environmental problems brought on by greenhouse gas emissions are becoming worse as the globe's climate continues to change, which has substantial implications for human existence and the sustainable development of nations worldwide. Reducing carbon emissions, the most abundant greenhouse gas, is an essential means to avoid a sharp increase in the effects of climate change [1]. As a result, numerous nations have gradually established pertinent regulations to measure, manage, and lower carbon emissions [2–4]. In 2015, several countries committed to taking measures to reduce building-related carbon emissions and increase energy efficiency in the Paris Climate Agreement [5]. For instance, the Chinese government has pledged to achieve carbon neutrality by 2060 and attain its carbon peak by 2030 [6].

The building sector consumes 40% of the world's energy and produces about 30% of greenhouse gas emissions [7]. A total of 346 million tons of standard coal equivalent (tce), or 33% of all building energy consumption, and 640 million tons of CO_2, or 29% of all building carbon emissions, are what public buildings in China, with an area of about 14 billion square meters, will consume in 2020, excluding heating in the north. Compared to other types of buildings, the energy consumption per unit area and carbon emission per unit area are much higher at 24.7 kgtce/m^2 and 45.7 kgCO_2/m^2, respectively [8]. The achievement of sustainable development is positively impacted by reducing carbon emissions in the building sector. Public buildings are where people perform various public activities, including office buildings, commercial buildings, educational buildings, health care buildings, and transportation buildings [9]. The many types of public buildings consume massive energy and generate extensive carbon emissions. Realizing energy saving and reduction in CEPB is of positive significance to sustainable development. Therefore, it is of great significance to provide researchers with a comprehensive review of CEPB research progress, current status, hotspots, and frontiers, to fill the knowledge gap in the area. It is of great significance to achieve sustainable development of public buildings.

Studying building carbon emissions has gained significant interest, and several researchers have reviewed various research fields for the whole building sector, including methods, technologies, materials, and laws. For instance, from the perspective of the lifecycle assessment of a building, some researchers have reviewed the "urban form on carbon emissions" and found that the urban form has a significant impact on building carbon emissions [10,11]. Some researchers have reviewed the literature on the carbon emissions of materials used in the construction phase, including steel [12] and timber [13]. Joseph et al. (2021) conducted a systematic literature review to synthesize prior findings about carbon emission management in building operations, which provides a reference to reduce or manage construction emissions [14]. Some researchers have focused on "embodied carbon emissions of buildings" [15,16]. Lu et al. (2020) conducted a holistic review of and research on carbon emissions in the green building construction industry [17]. Many reviews relating to building carbon emissions are conducted from a macro perspective, which contains all kinds of buildings. Only a few researchers have reviewed the research on the carbon emission of building types or a kind of specific building at present, especially from the public building perspective. For example, Lu et al. (2020), through a review of the literature about the carbon emissions of commercial buildings, suggest future research should focus on how to cut the carbon emissions of existing buildings [18]. However, the research excluded other types of public buildings and only reviewed the carbon emissions of the commercial building part of public buildings. Therefore, there is a shortage of comprehensive and systematic reviews of the research on CEPB. Previous research did not include comprehensive and systematic reviews of the research on CEPB. Without a comprehensive review, it is a struggle for researchers to attain a thorough understanding of the research area of CEPB, even if they have read the relevant research results and reviewed the literature. It will affect the achievement of the sustainable development of public buildings. As such, this research is needed to bridge the gaps in the field. This review uses CiteSpace and VOSviewer to analyze the literature on "carbon emissions of public buildings" from 2002 to 2022 and conducts a systematic review of the research in this field. A visualization model is established to show the research growth path, examine the current research status and hotspots, and forecast the research frontiers. This research's findings not only provide researchers with a thorough grasp of the field's research and development but also serve as a valuable resource for future theoretical research and practical development on CEPB.

The research is organized as follows: Section 2 presents research methods and processes. Section 3 presents the results of the visual analysis. The discussion of the study presents the current research status and hotspots, and forecasts the research frontiers in Section 4. Furthermore, Section 5 draws up the conclusions.

2. Research Methods

Two potent tools for visual bibliometric analysis are CiteSpace and VOSviewer. which may visually examine the scientific research's hotspots and evolution [19,20]. Additionally, they can foresee future research boundaries and trends [21–23]. Therefore, much research typically employs visual analysis software to summarize and review [24–26]. The two tools will be used in this research to visually present CEPB. This research was carried out in five steps as follows.

(1) The Web of Science Core Collection was selected as the source database for the literature. The scientific search formula is TS = ("public building*") and TS = ("carbon emission*" or "carbon dioxide emission*") and LA = ("English") and DT = ("Article" or "Review"). The period is 2000–2022, and the search time is 9 August 2022.

Public buildings include office, commercial, educational, and other types of buildings that can be used for various public activities. Each type of building also contains many types of specific buildings. For example, educational buildings include teaching buildings, libraries, and laboratories. Much literature does not mention the concept of public buildings or related building types or a kind of specific building, but the topic of study is within the scope of CEPB. Therefore, this research selected the various types of buildings and a kind of specific building included in public buildings as keywords to replace "public building*" for the second search and the third search.

Finally, a total of 690 papers were retrieved. After reading the titles, keywords, abstracts and whole papers, the invalid papers were removed based on the following standards: (1) The information in the study is lacking; (2) Public buildings are not the research object; (3) The research's primary theme has little to do with CEPB. After that, the "Remove duplicates" operation in CiteSpace was used to process and transform the data, eliminate duplicates, and finally 192 valid papers were retained. Because the papers about CEPB first appeared in 2002, the search period for those papers found to be legitimate was changed to 2002–2022. Figure 1 shows the data collection process.

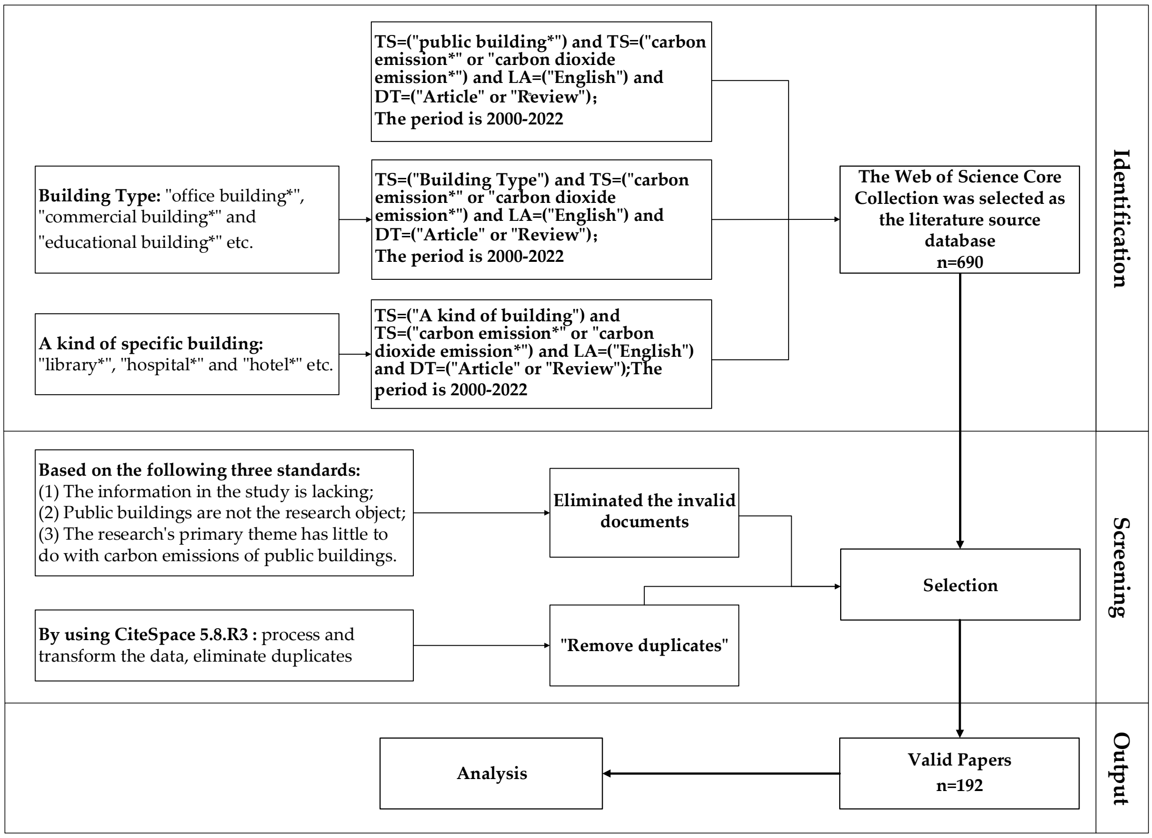

Figure 1. Data collection process.

(2) The collected literature on CEPB provided a preliminary overview analysis, which included statistics on the annual volume distribution of articles, the categories of subjects of the literature, journals, and cited frequency of papers.

(3) To uncover the relationships behind the substantial amount of literature, this study uses Citespace to visualize author collaboration, institutional collaboration, and national collaboration in its analysis of the literature on CEPB.

(4) By using Citespace to conduct keyword co-occurrence analysis and keyword clustering analysis on the collected literature, we can provide an intuitive understanding of the research processes on CEPB, and make relevant predictions for future research directions and research frontiers.

(5) Utilizing the co-citation analysis feature in VOSviewer can show the current status of the research, including references, authors, and publications, visually. It can help to find essential papers, authors, and journals in the research field of CEPB. This will provide some references for the future development of the field.

3. Results

3.1. Overview Analysis

3.1.1. Analysis of Annual Paper Volume Distribution

The annual volume of scientific research papers can, to a certain extent, reflect the trend of research comprehension and researchers' attention to research. The distribution of the annual volume of publications on CEPB from 2002 to 2022 is shown in Figure 2A. There is a general trend of a phased increase in the annual volume of CEPB papers. In particular, 62 papers were published in 2021–2022, representing 32.29% of all papers. This expanding trend in papers illustrates that academic interest in the CEPB is rising.

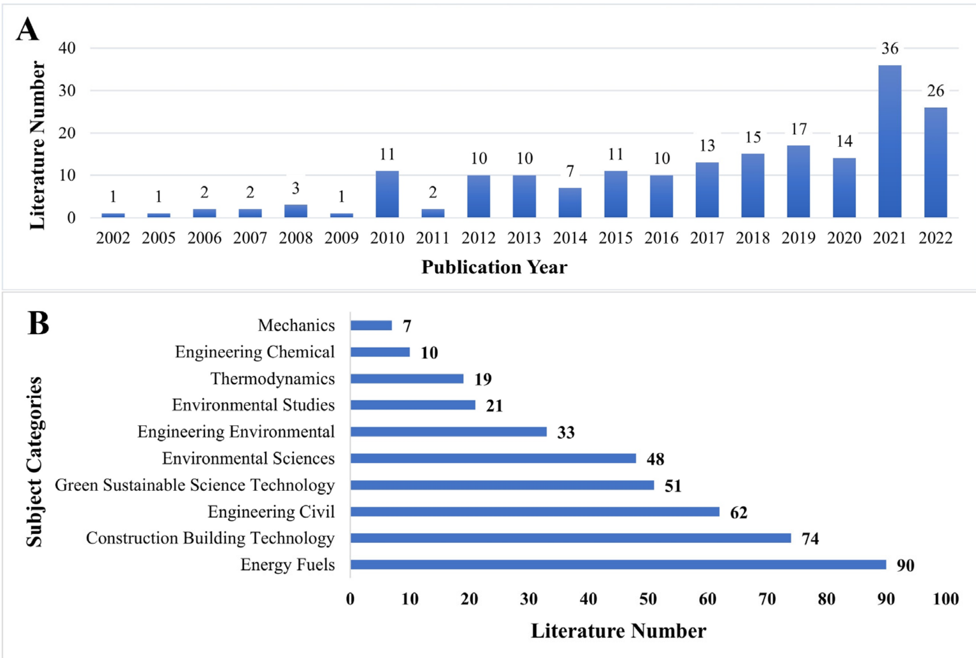

Figure 2. (**A**) The distribution of the annual volume of publications on the CEPB from 2002 to 2022, (**B**) Top ten subject categories of the Web of Science for CEPB from 2002 to 2022.

3.1.2. Analysis of the Literature Subject Categories

The top ten literature subject categories of the Web of Science for the number of publications on CEPB from 2002 to 2022 are shown in Figure 2B. Considering that there may be multiple topic categories in cross-disciplinary research in a paper, it is reasonable that the number of papers in all subject categories in Figure 2B may exceed the number of valid publications in this research. It also reflects the existence of cross-disciplinary areas involved in the research content of CEPB. In summary, this research concluded that the study on CEPB had received extensive attention from many fields and disciplines; it integrates various disciplines such as energy/fuels, construction building technology, and engineering civil. Furthermore, the research on CEPB through multidisciplinary interdisciplinary theories is gradually becoming a trend, which indirectly promotes the comprehensive development of the field.

3.1.3. Publication Analysis

The journal in which the publication is published plays a vital role in influencing the public impression. The 192 valid papers were published in 64 journals. The ten journals with the highest number of publications are shown in Table 1. In these ten journals, 116 papers were published, making up 60.42% of all papers. It shows that these periodicals have paid more attention to papers on the research of CEPB. The journal with the most papers is *Energy and Buildings*, which has 34 papers, or 17.71% of all papers. This implies that the journal is significantly higher than other journals.

Table 1. Top ten journals ranked by the number of publications on CEPB.

Rank	Journal	Quantity
1	Energy and Buildings	34
2	Sustainability	16
3	Journal of Cleaner Production	15
4	Building and Environment	13
5	Applied Energy	9
6	Energy	7
7	Sustainable Cities and Society	7
8	Buildings	5
9	Energy Conversion and Management	5
10	Journal of Building Engineering	5

3.1.4. Analysis of the Cited Frequency of Paper

Researchers can identify the influential and significant publications in the CEPB research by using the citation frequencies of the 192 papers included in this research, which can also serve as a reference point for subsequent research. Table 2 shows the information of the top ten most frequently cited papers, including the number of citations, source journal, and the specific building type of the public building researched. The data show that six of the top ten most often cited papers are related to commercial buildings. This suggests that in the current studies in this area, academics are paying more attention to commercial buildings.

Table 2. Top ten most frequently cited papers.

Rank	Citation	Journal	Building Type	References
1	320	Applied Energy	hotel building	[27]
2	261	Energy and Buildings	commercial building	[28]
3	231	IEEE Transactions on Power Systems	commercial building	[29]
4	219	Energy and Buildings	office building	[30]
5	213	Energy and Buildings	office building	[31]
6	176	Energy Conversion and Management	hospital	[32]
7	140	Energy and Buildings	commercial building	[33]
8	111	Building and Environment	commercial building	[34]
9	96	Journal of Cleaner Production	commercial building	[35]
10	90	Habitat International	commercial building	[36]

3.2. Cooperation Network Analysis

The map of visualizations of the cooperation network was generated using CiteSpace as shown in Figure 3, including countries and regions (Figure 3A), institutions (Figure 3B), and authors (Figure 3C). The nodes represent the related objects (countries, institutions, and authors), and the larger the nodes, the higher the frequency of their postings; the lines between the nodes represent a cooperation relationship between the objects, and the thicker the lines, the higher the number of their cooperations [37].

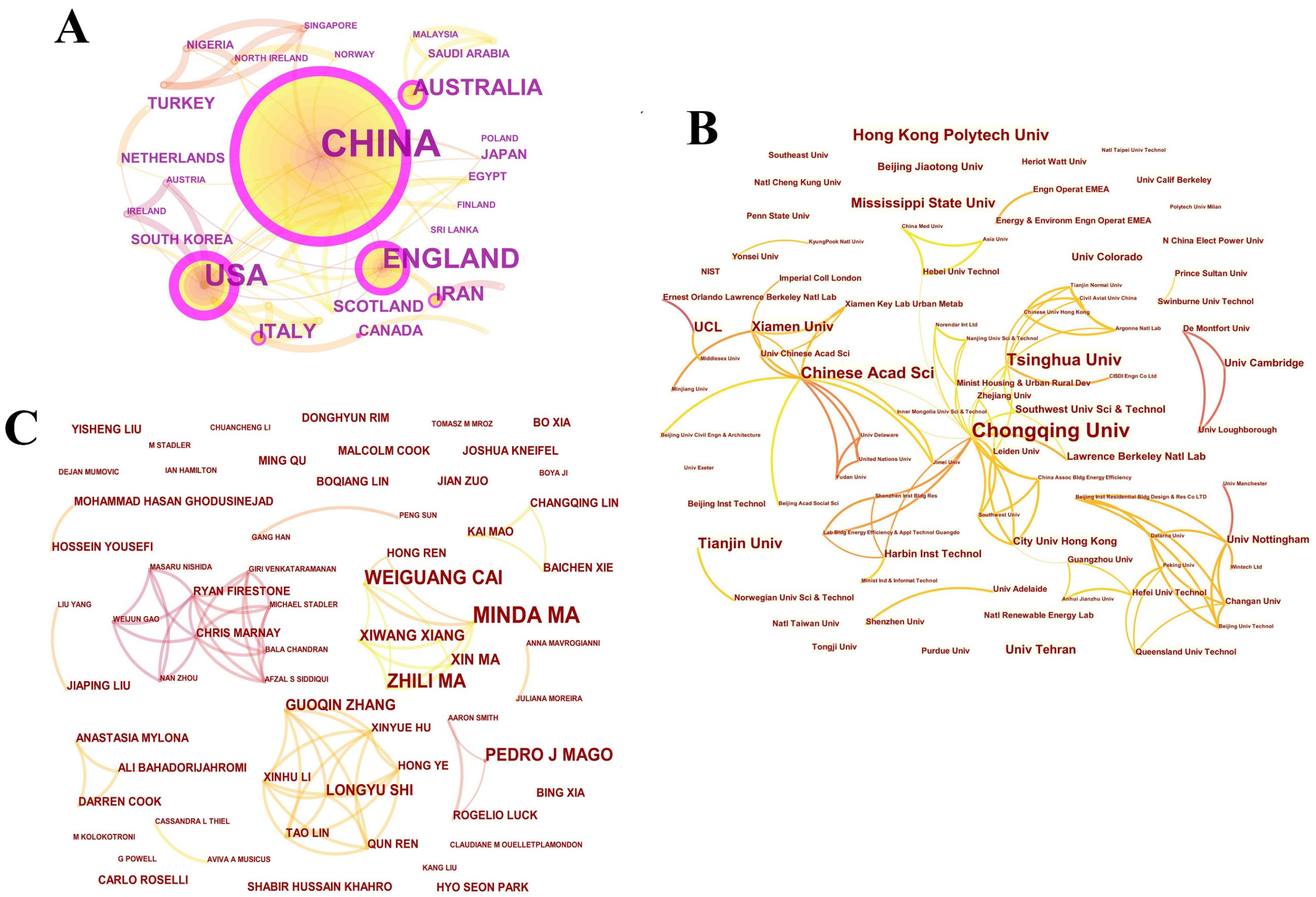

Figure 3. Visualization of the co-countryship and co-regionship (**A**), co-institution (**B**), co-authorship (**C**) network.

The research on the carbon emission of public buildings involved 56 nations/regions. The most active nations in the field of research, according to Figure 3A, are China, the United States, and England. All of this is evidenced by the relatively close national collaboration, numerous publications, and high overall frequency of citations. The USA is a pioneer in the field of study on the carbon emissions of public buildings, with publications about the topic first appearing in 2002 [38]. As a latecomer to this field, China only began to publish literature on the subject of the field in 2010 [27,30]. However, since China is the world's largest carbon emitter [39] and as a result of the Chinese government's policy to reduce carbon emissions [6], the country's research on CEPB has continued to heat up. It is now far ahead of other nations in terms of the number of publications. Nonetheless, China only averages 29.90 citations per paper, a significant decrease from the USA's 52.65. The findings suggest that China still has space to expand in the field.

According to Figure 3B, collaborative research is lacking at various institutions, including Beijing Jiaotong University, Mississippi State University, and Hong Kong Polytechnic University. It could be that little attention has been paid to the research on CEPB, which is still in the exploratory stage. Some institutions continue to work together nevertheless. There are several cooperations between institutions such as Chongqing University, Tsinghua University, and the Chinese Academy of Sciences. A total of 698 authors contributed to the 192 publications collected for this research. They are the "knowledge suppliers" in this area, particularly the outstanding authors [40]. According to Figure 3C, Ma, MD, from Chongqing University, is the author with the most publications, with eight, mainly on the carbon emissions of commercial buildings in public buildings [35,41–45] and the CEPB in China from a micro-perspective [46,47].

3.3. Keyword Analysis

Keywords aim to summarize the research content of the paper. High-frequency and high-centrality words can reflect the research hotspots and frontiers to a certain extent.

3.3.1. Keyword Co-Occurrence Analysis

This research analyzed the keywords in the literature on CEPB using CiteSpace's keyword analysis feature. Table 3 lists the top ten keywords by frequency. They indicate the study frontiers and hotspots in the field of CEPB. This research found that carbon emission (53), performance (46), building (45), system (33), energy (32), environmental impact (28), design (27), optimization (26), construction industry (25), and energy consumption (23) are the top ten keywords in the field of research on CEPB. It shows that the research using the aforementioned topics as keywords is more prevalent, and that the research on CEPB is now primarily centered in these areas. Meanwhile, the centrality reflects the pivotal role of keywords possessing the mediating property of connecting different keywords. Centrality > 0.1 is considered the critical node for the keywords. Model and efficiency are not among the top ten keywords in frequency, but they still play an important, influential role in related studies.

Table 3. Top ten keywords by frequency.

Number	Frequent	Centrality	Year	Key Word
1	53	0.03	2007	carbon emission
2	46	0.12	2007	performance
3	45	0.11	2007	building
4	33	0.07	2008	system
5	32	0.19	2010	energy
6	28	0.05	2010	environmental impact
7	27	0.35	2007	design
8	26	0.19	2010	optimization
9	25	0.11	2013	construction industry
10	23	0.17	2013	energy consumption

3.3.2. Keyword Clustering Analysis

Keyword clustering is summarizing and organizing keywords that are similar to each other in content and then dividing the research field into representative knowledge subgroups. The modularity (Q Score) and the average cluster profile value (S Score) are effective bases for evaluating the efficacy of clustering in clustering analysis [48]. Q > 0.3, the clustering structure is significant; S > 0.5, the clustering is reasonable, and S > 0.7, the clustering is convincing [49]. The keyword clustering graph for this domain research is shown in Figure 4, and it has 47 nodes and 1014 connecting lines. The clustering structure is significant and convincing, as shown by Q = 0.516 > 0.3 and S = 0.8249 > 0.7.

Table 4 provides a summary of the specific information about clustering. The clustering number ranges from 0 to 10, with smaller numbers indicating more terms in the clusters. The size value of the cluster size indicates the number of papers in each cluster; the bigger the size value, the more papers in each cluster. The silhouette is used to show how similar the papers are in the clusters that have been evaluated. The larger the silhouette value, the higher the similarity of the papers in the clusters. In this research, clusters with size values > 40 will be analyzed.

Table 4. Cluster by keywords in the study of carbon emissions of public buildings.

Cluster ID	Size	Silhouette	Year	Cluster Name	Label
0	64	0.766	2017	embodied energy	embodied energy; lifecycle assessment; carbon dioxide emissions; lifecycle analysis; Sri Lanka
1	61	0.816	2018	decoupling analysis	decoupling analysis; STIRPAT model; carbon Kuznets curve; building sector; carbon emission peak
2	59	0.737	2016	optimization	optimization; uncertainty; operation; CCHP strategy
3	34	0.88	2016	uncertainty analysis	uncertainty analysis; solar thermal system; energy analysis; hybrid cooling mode; electricity generation
4	32	0.818	2015	China	China; impact; micro-climate; behavior; embodied carbon emissions
5	30	0.939	2019	luxury hospitality	luxury hospitality; building energy efficiency; operational strategy; distributed energy system; data mining
6	27	0.905	2017	CHP system	CHP system; emission reduction; aerogel; carbon benchmarking; levelized cost of energy
7	25	0.903	2014	thermal simulation	thermal simulation; greenhouse gas (GHG); urban heat island; occupant satisfaction; electricity production
8	25	0.853	2018	energy hub	energy hub; electric vehicle; hourly efficiency power gird; photovoltaic; mixed land use
9	19	0.923	2017	thermal comfort	thermal comfort; machine learning; building energy efficiency retrofit; curtain wall; refrigeration and air-conditioning system
10	15	0.908	2019	environmental efficiency	environmental efficiency; Moran index; China's public buildings; spatial econometric model; non-radial directional distance function

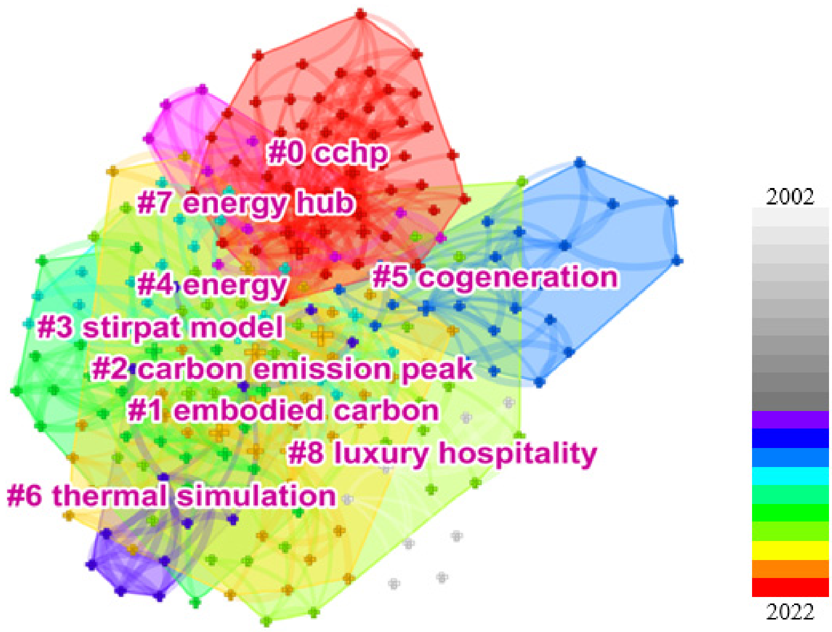

Figure 4. Keyword clustering diagram for the research of CEPB.

Clustering #0 is embodied energy, which includes 64 papers that encompass important terms such as embodied energy, lifecycle analysis, carbon dioxide emissions, and Sri Lanka. As one of the primary sources of carbon emissions at the moment, embodied energy also contributes to embodied carbon [50], which has received a lot of attention in the research on carbon emissions of buildings. According to the literature the research compiled, the focus of the majority of current research is on the following two factors:

(1) Life cycle assessment. Many researchers have examined the embodied energy of public buildings in recent years from a variety of angles, including the macro-level public

building construction industry [51], building design phase [52], building renovation [53], building energy system [54], and green building [55]. Some academics have assessed and analyzed the CEPB throughout their lifecycle assessment associated with embodied energy and provided pertinent suggestions for low-carbon development [56,57]. Others have established a carbon emission analysis framework for public buildings by combining BIM models to provide a reference for the realization of carbon emission reduction [58].

(2) Building materials. Some researchers studied the embodied energy and carbon of building materials in public buildings. Among them, some researchers examined the carbon emissions of various building materials using case studies and offered helpful recommendations for reducing carbon emissions [59,60]. Along with this, researchers examined the factors with influence on building carbon emissions from a macro level using embodied energy. He et al. (2020) have examined the impact of embodied energy and per capita building steel stock on the influence of building carbon emissions and discovered that the per capita building steel stock has a significant impact on CEPB [61].

Cluster #1 is decoupling analysis, which includes 61 papers covering keywords such as decoupling analysis; STIRPAT model; carbon Kuznets curve; building sector; carbon emission peak. Several mathematical models related to decoupling analysis that can be broadly categorized into macroscopic and microscopic views are included in the database of this research.

(1) Macroscopic perspective. In this perspective, many researchers have analyzed the CEPB mainly based on macroeconomic indicators, including the drivers of CEPB [47,62,63], the operational CEPB under the carbon neutrality target [42–44], and the spatial characteristics and regional studies of CEPB [6,35,64–66]. In addition, researchers have focused on the building sector to achieve carbon peaking as soon as feasible in consideration of the Chinese government's intention to do so [6]. For example, Huo et al. (2021) suggested that commercial buildings in public buildings will reach carbon peaking in 2038 by studying the impact of the urbanization process on carbon peaking in the construction industry [67]. These studies help governments and managers formulate and implement carbon reduction policies for public buildings from a macroscopic perspective.

(2) Microscopic perspective. The research on CEPB views it not only from a macroscopic perspective but also from a microscopic perspective, by conducting case studies on the carbon emissions of individual buildings. Building carbon emissions are significantly impacted by energy use. With the help of a variety of strategies, including building design [68–70], building materials [71,72], operations management [73,74], renewable energy [75,76], and BIM [77], many academics have focused their study on energy and carbon reduction in public buildings. This research could be beneficial to public building designers and managers, promoting the sustainable development of public buildings.

Clustering #2 is optimization, including 59 papers, covering keywords including optimization; uncertainty; operation; CCHP strategy. With the concept of low carbon emission reduction, optimizing the energy consumption and carbon emission of existing public buildings has received much attention from researchers, particularly in the operation phase. Among them, combined cooling, heating, and power (CCHP) is an energy-supply system that enables efficient use of energy through the recovery of waste heat [78]. Additionally, due to its capability to significantly reduce the CEPB, CCHP has been widely employed in the energy supply of public buildings [79]. Existing research on CCHP in CEPB mainly focuses on two aspects, as follows:

(1) Optimizing the design: to reduce carbon emissions, energy consumption, and costs, several academics have optimized the design of CCHP in existing public buildings [80–82]. For instance, some researchers have attempted to replace the conventional internal combustion engine (ICE) in CCHP with solar energy [83,84].

(2) Optimization of both management and operations: by improving the CCHP operating strategy in public buildings, several researchers hope to reduce carbon emissions, energy use, cost, etc. [85–87].

3.4. Co-Citation Analysis

Co-citation analysis is defined as two(more) papers are cited by one or more articles at the same time, then the two(more) papers have a co-citation relationship [88]. It may focus on documents, journals, and authors, frequently used to identify research hotspots in a particular academic area [89,90]. In this section, VOSviewer is used to conduct a co-citation analysis of the research on CEPB. The analysis that tries to find the key articles, authors, and core journals in the field, can provide some reference for researchers who are new to the field to grasp its intellectual background and future development.

Table 5 shows the information on the top ten cited references, journals, and authors. According to them, the research finds that there are no influential papers in the CEPB research, which may be because the fact that public buildings contain more types of buildings and the research direction is more dispersed. With the most co-citations, Energy Buildings has had the most impact on this field's research and the generally high quality of the articles published. Ma MD and Wang JJ have the most co-citations, both with 49. It also indicates that they have contributed more to the development of research on CEPB.

Table 5. Top ten most co-cited references, journals, and authors.

Rank	Reference		Journal		Author	
	Reference Name	**Count**	**Journal Name**	**Count**	**Author's Name**	**Count**
1	Ramesh et al. (2010) [91]	13	Energy and Buildings	801	Ma, MD	49
2	Mago et al. (2009) [92]	12	Applied Energy	471	Wang, JJ	49
3	Jen Chun Wang (2012) [93]	9	Energy	360	Mago, PJ	39
4	Ma et al. (2017) [94]	9	Journal of Cleaner Production	327	Ang, BW	26
5	Cabeza et al. (2014) [95]	9	Building and Environment	285	Lin, BQ	24
6	Priyadarsini et al. (2009) [96]	9	Renewable and Sustainable Energy Reviews	237	Zhang, XC	22
7	Chau et al. (2015) [97]	8	Energy Conversion and Management	206	Huo, TF	17
8	Zhang et al. (2015) [57]	8	Energy Policy	203	Lai, JHK	17
9	Wu et al. (2010) [98]	8	Applied Thermal Engineering	133	Chau, CK	16
10	Zheng et al. (2014) [99]	8	Renewable Energy	110	Jiang, P	16

4. Discussion

4.1. Research Hotspots

According to Section 3, this research again collates and analyzes the collected literature information, including the title, keywords, as well as abstract. To sum up, the article finds that the current research hotspots on CEPB are as follows.

(1) Simulator modeling and theoretical research: these are mostly used to examine CEPB, research the elements that affect carbon emissions, and either suggest matching carbon emission reduction strategies or evaluate the efficacy of those actions. From a macro perspective, theoretical research focuses primarily on: (1) Regional carbon emission reduction analysis, carbon neutralization, public building scale, carbon emissions trading, life-cycle assessment, etc.; and (2) From a micro perspective, operation strategy, carbon emission survey, building carbon footprint measurement, building upgrading, and the reconstruction of a single public building. To accomplish the sustainable development of public buildings, researchers can utilize simulations to assess, model, and anticipate the structural design of public buildings, the energy consumption of building equipment, and the carbon emissions of building materials. Commonly used simulation software includes MATLAB, SPSS, DesignBuilder, EnergyPlus, TRNSYS, TAS, GABI, and other data analysis, energy-consumption simulation, and lifecycle assessment tools. Common research methods and models mainly include regional models, genetic algorithms (GA), Malmquist Lunberger (ML), data energy analysis (DEA), logarithmic mean division index (LMDI), and stochastic impacts by regional on population, affluence, and technology (STIRPAT). In addition, it also includes highly targeted models such as building stock energy models

(BSEMs) [100], carbon Kuznets curve (CKC) model [44], orthogonal experimental design (OED) [101], and other specifically focused research models.

(2) Energy system research: this includes developing energy supply conversion systems and associated building energy-consuming equipment (such as ventilation, refrigeration, and heating). There will be a significant amount of carbon emissions produced by the energy systems of public buildings while they are in use. Therefore, reducing carbon emissions from the energy system is crucial for the sustainable growth of public buildings. Currently, the primary component of public buildings' energy supply conversion systems is Combined Head and Power (CHP). The CCHP and Integrated Energy System (IES), among other energy systems, can be designed with local climatic conditions, different types of public buildings, and load specifications of buildings to increase energy conversion efficiency, which can result in effective energy use and lower carbon emissions. With the continued advancement of renewable energy technology, public building energy systems have started to incorporate renewable energy designs, such as solar energy [84,102–104], wind energy [105,106], and tidal energy [107], to reduce the use of fossil fuels. Other considerations, including investment, operation, maintenance expenses, and environmental advantages, must be taken into account during the operation and management phases of energy equipment in public buildings, for the design and upgrading of energy systems. The multi-objective optimization model for parameters such as cost, operating energy consumption, and environmental benefits is established to achieve the sustainable development of public buildings. From this model, the equipment configuration, operation measures, and management strategies of the energy supply conversion system are developed to meet the minimum energy consumption and the maximum effect of reducing carbon emissions. With the widespread usage of electric vehicles (EVs), the energy systems of public buildings will supply benefits and satisfy the demand for charging electric vehicles. However, they also use more energy internally. According to previous research, CEPB can be decreased by developing methods to operate the carbon-emission-reduction-oriented energy system and using renewable energy [108,109].

(3) Materials: one of the sources of CEPB is the embedded carbon in the building materials. Carbon emissions from traditional building materials such as steel, wood, and concrete will be significant during the materialization phase. Due to their enormous size, public buildings need a large quantity of building materials, which has practically increased their carbon emissions. One of the crucial tasks in evaluating CEPB from the perspective of their entire lifecycle is to quantify and measure the carbon footprint and carbon emissions of the materials used in public buildings. This can be accomplished by modeling and accurate measurement, and ongoing data can be gathered using process inventories and building-based sensors. The established targeted assessment model can identify the features of CEPB materials and maximize the reduction in carbon emissions throughout the lifecycle. The reduction in CEPB is primarily broken down into the following categories from the viewpoint of building materials. Some researchers hold the view that public buildings may be developed sustainably by using new building materials in place of traditional ones, such as piezoelectric flooring [71] and the new aerogel super insulating material [110]. Through a series of coordinated changes in building design and retrofit parameters, another the part of researchers' aim is to achieve carbon emission reduction [52,77,111] and even zero-carbon design [68].

(4) Retrofitting public buildings, including the energy-saving retrofit of their equipment and parts: since public buildings often have a long lifespan, updating during that lifespan is one of the most efficient strategies to reduce carbon emissions. Retrofitting public buildings necessitates considering cost, environmental advantages, technical viability, and other factors in addition to reducing carbon emissions. It may be hard to see the reduction in carbon emissions following retrofit, which could impact public buildings' ability to develop sustainably. It could be challenging to attain the attention of public building operators if the retrofit results in a considerable decrease in carbon emissions but at a high cost. Since the complicated interplay of numerous factors makes retrofitting public

buildings difficult, there are many obstacles to overcome. It is essential to consider the current situation when reconstructing public buildings to determine whether the reduction in carbon emissions brought about by the reconstruction will be sufficient to meet the carbon neutralization and carbon peak targets, as well as whether the cost and energy usage could be kept to a minimum throughout the project's entire lifecycle. Currently, the strategies and tactics used to retrofit public buildings with energy-saving features generally focus on the following factors. (1) Building envelope: the researchers used simulation and experiment to design and optimize the parameters of the building envelope for the shape and temperature of the public building, and also assessed the effectiveness of the refit plan [112–114]. (2) Building equipment: by replacing outdated building equipment, utilizing renewable energy, and modifying operation-management strategies using multi-objective optimization techniques, such as ventilation, heating, refrigeration, lighting, and other equipment, energy consumption and carbon emissions might be lowered.

(5) The main factors that contribute to the reduction in CEPB: Table 6 shows the factors that contribute to the reduction in CEPB. "F" and "I*F" were employed to highlight the frequency of the appearance of factors and their impact "F" indicates the frequency of factors in the literature, while "I*F" indicates the total number of citations. This research grouped these characteristics into four stages in chronological sequence after gathering and summarizing the pertinent literature. In terms of the overall trend of change, the study of positive factors of carbon emission reduction shows an increasing trend over time. Only two factors—energy systems and building envelopes—appeared in stage 1 (2002–2006), indicating that less attention was paid to carbon emission reduction factors. Corresponding F and I*F scores were also underwhelming. Combined with the annual paper volume distribution, this may be because there is less research on CEPB in this period. More attention was drawn to the research on factors contributing to the decline of CEPB in stage 2 (2007–2011). During this period, operation and government factors started to receive attention in addition to energy- and building-related factors. According to the data, the sum (I*F) score is the greatest among the four stages even if the sum (F) score for this period is low. This indicates that the research on factors that contribute to the reduction in CEPB in this stage has had a great impact. Stage 3 (2012–2016) has seen a greater advancement in the investigation of carbon reduction factors in public buildings than in the preceding two stages. Not only are more factors in energy, building, and operation being explored, but other categories, including waste, material, and ecology, are also beginning to attract the interest of researchers, which indicates that researchers are beginning to consider the carbon reduction factors from a whole lifecycle perspective. In Stage 4 (2017–2022), research on factors that contribute to the reduction in CEPB has advanced significantly. More factors emerged, including the user's consciousness, which did not appear in the previous three stages. This demonstrates that the research on factors that contribute to the reduction in CEPB started to focus on users. In this stage, the sum (F) of scores reached 134 points, which is more than the total of the preceding three stages. This is probably due to the fact that governments have been paying close attention to how to reduce carbon emissions from buildings since the Paris Climate Agreement, which has helped to advance this field [5]. However, the sum (I*F) ratings are not at their highest, most likely because of the fact that related research has not yet caused a huge impact.

Table 6. The main factors that contribute to the reduction in CEPB.

Category	**Factors**	**Stage 1 (2002–2006)**		**Stage 2 (2007–2011)**		**Stage 3 (2012–2016)**		**Stage 4 (2017–2022)**		**Sum (Factors)**		**Sum (Category)**	
		F	**I*F**	**F**	**I*F**	**F**	**I*F**	**F**	**I*F**	**F**	**I*F**	**F**	**I*F**
Energy	Energy systems	2	62	8	1050	14	347	44	411	68	1870	107	2244
	Intensity of energy consumption					1	5	5	49	6	54		
	Energy structure					1	78	2	12	3	90		
	Renewable energy			1	3	3	26	22	173	26	202		
	Carbon emission coefficient					1	5	3	23	4	28		
Building	Building envelopes	1	11	5	116	4	359	15	230	25	716	43	1732
	Building structure					3	174	5	120	8	294		
	Building types			2	281			1	62	3	343		
	Building location			2	281			1	0	3	281		
	Architectural morphology							2	50	2	50		
	Floor area per capita					1	5	1	43	2	48		
Waste	Construction waste					1	89	1	1	2	90	2	90
Operation	Operation manager					1	90			1	90	14	369
	Strategy and management			2	62	1	36	10	181	13	279		
Material	Material					5	315	13	308	18	623	18	623
Ecology	Landscape					1	1	4	33	5	34	7	81
	Micro-climate							2	47	2	47		
Government	Policy and regulation			1	23	1	90	2	14	4	127	4	127
User	User's consciousness							1	10	1	10	1	10
	Sum	3	73	21	1816	38	1620	134	1767				

Among the eight categories, energy was favored by scholars, as verified by the fact that its sum (F) and sum (I*F) scores are the highest. This is partly because energy consumption is an important source of building carbon emissions, and reducing building energy consumption has a positive significance for reducing building carbon emissions. Energy systems' sum (F) and sum (I*F) scores stand out in the energy category. The importance of this factor is evident from the fact that it was studied throughout Stages 1 to 4. Considering that the energy systems undertake the process of energy delivery, conversion, and use [115], many researchers have optimized the energy systems to achieve a reduction in CEPB. These optimizations include introducing renewable energy sources [84,104,107,116,117], improving the design of energy systems [82,118–120], and optimizing the working mode of energy systems [87,117,121,122], etc. Building has the second highest sum (F) and sum (I*F) scores after energy. The sum (I*F) score for the building envelopes comes in at 716, ranking it second among the particular factors. The sum (F) score is 25, ranking it third. Similar to the energy systems, this factor also spans all stages, indicating its importance in reducing CEPB. Many researchers think that by improving the building envelopes and optimizing design, heat transmission may be decreased, resulting in a reduction in CEPB [53,112,113]. The sum (F) and sum (I*F) scores of other categories are lower than those for energy and building. In terms of the whole building lifecycle, material, waste, and operation are also components of the CEPB. Consequently, some attention has also been given to these areas. The operation has been getting notice from Stage 2 and its F and I*F ratings have been rising. The majority of the carbon emissions produced over the building's whole lifecycle are produced during the operating stage [56,57,123]. To reduce CEPB in operations, several researchers have been focusing on the optimization of the operation strategy and management from the perspective of managers [124–126]. Waste and material have also drawn some attention. In particular, the materials' sum (F) and sum (I*F) scores have reached 18 and 623, respectively, showing their significance in the effort to reduce CEPB. In this context, ecologically friendly waste recycling [55,127] and the use of low-carbon materials [59,60,128] can considerably reduce CEPB. Ecology-related factors do not start to appear until stage 3. Specifically, it has a micro-climate and green plant landscape. It is possible to significantly lower CEPB by modifying the microclimate [129] and optimizing the landscape to increase the carbon sequestration rate [130]. Although these two components have low sum (F) and sum (I*F) ratings, this category still has a large amount of space for growth in the future. Researchers have been studying the government factor since stage 2. The sum (F) and sum (I*F) scores are still not very high, however. Since public buildings contain a wide variety of building types and have significant energy consumption, numbers of laws and regulations have been implemented to support the achievement of a reduction in CEPB [131,132]. This will encourage the advancement of this field's research in the future. Not until stage 4 did researchers begin to pay attention to users. However, user consciousness and behavior also influence CEPB, because public buildings are areas where the general public congregates and engages in activity. Enhancing the consciousness of energy saving and carbon emission reduction among users of public buildings can also effectively reduce CEPB [133]. Thus, the user factors will attract more attention in the future.

4.2. Research Frontiers

This article summarizes and predicts the research frontiers for CEPB based on the prior contents and the data gathered from the literature.

(1) Architectural features and structures. Diverse climatic zones and functions for public buildings typically result in different building features and structures, which have a significant impact on carbon emissions. The energy demands of public buildings and the solar energy potential will be affected by their shape, which will change the corresponding optimal energy system [134]. Additionally, the relationship of the curtain wall to the building's geometry has a significant effect on the CEPB. The design of a curtain wall must take into account several elements, such as shading, ventilation, and natural lighting, and must satisfy user comfort requirements while minimizing energy use and carbon emissions. However, existing research on the sustainable design of curtain walls is mainly focused on office buildings [135,136], and less on other public buildings. In other building features and structures, an increase in the shear wall slenderness ratio will result in a decrease in carbon emissions as a function of building height [137]. This poses more challenges to the sustainable design of buildings. Different space types in educational buildings will use more energy than their theoretical design values, which will increase carbon emissions [73]. Therefore, the frontier of future study will be to reduce carbon emissions through the best design of building components and structures.

(2) Digital technology. Evolving digital technology is now frequently used in construction industry research. Most of the 192 documents collected for this research, including energy-consumption modeling, building lifecycle assessment, and energy-saving retrofit effect analysis, utilize digital technology to some extent. The main software tools include Revit, DesignBuilder, EnergyPlus, TRNSYS, TAS, and GABI. However, the digital interactive design of various buildings has received little consideration in the existing research. Future research could broaden the use of digital technology in public buildings and provide an interactive platform for analysis and research that takes into account the perspective of the building's lifecycle, including its area, type of building, climate, and environment. Additionally, a sizable database of public buildings should be built and linked to relevant software, taking into account the vast quantity and variety of types of public buildings, to improve the accuracy of related research.

5. Conclusions

This research reviewed and summarized articles on CEPB by using a literature review. CiteSpace and VOSviewer have acquired and aggregated 192 papers from the Web of

Science Core Collection that discuss CEPB from 2002 to 2022. We strove to obtain an overview, cooperations, keywords, research hotspots, and research frontiers for the papers on CEPB through visualizing results and collating information. The following are some of the key findings and analyses.

(1) The number of papers on the CEPB exhibited a gradual growth pattern from 2002 to 2022, indicating that the interest of researchers is growing. The three fields with the closest ties to research into CEPB are energy/fuel, construction technology, and civil engineering. Interdisciplinary theory research on the CEPB has increasingly gained popularity, which helps this field's overall growth. *Energy and Buildings* is by far the journal with the most articles on the field, compared to other journals. Commercial buildings received more attention from researchers in the current research in this field.

(2) Cooperation between nations, organizations, and researchers is dispersed in investigating CEPB. China has vast space for development in this field.

(3) Through keyword analysis, the most frequent keywords in the research on CEPB are carbon emission, performance, building, etc. Embodied energy, decoupling analysis, optimization, and other topics are part of the knowledge cluster on the CEPB. Building materials, energy consumption, carbon peak, and life cycle analysis are a few examples of the knowledge cluster associated with research areas.

(4) The lack of a significant document, journal, or author in the current research on the CEPB, as revealed by the co-citation analysis, may be attributable to the diversity of building types found in public buildings as well as the dispersed nature of the focus of the research.

(5) Theoretical research and simulation modeling, energy systems, materials, public building retrofitting, and the main factors that contribute to the reduction in CEPB are some of the research hot spots in the area. In addition, current research frontiers have focused on architectural features, architectural structures, and digital technology.

Despite its contribution to CEPB, this research has some limitations. This research restricted the search of articles to English journal articles in the Web of Science Core Collection. It might lead to the retrieval of publications that are not wholly comprehensive, since it does not completely cover all of the current literature on the topic. In this work, articles were chosen as a type of document. However, many academics have contributed to the research on CEPB through various other kinds of publications, such as books, reports, and conference papers, rather than publishing their findings as articles. The purpose of this paper is to present the previous research progress of CEPB, and to conduct quantitative analysis on measures or technologies to reduce CEPB is a future research direction.

Future researchers can gather articles on this subject from various databases and undertake more thorough research by consulting a variety of publications, which enables researchers to explore more possibilities.

Generally, this review provides researchers with a comprehensive overview of the research progress, current status, hot spots, and frontiers of CEPB. Researchers can fill in the CEPB knowledge gaps from the review, thereby expanding the research of CEPB. This not only can promote the theoretical research and practical development of CEPB but also has significance for the achievement of the sustainable development of public buildings.

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