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Review

How Can Urban Regeneration Reduce Carbon Emissions? A Bibliometric Review

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Abstract: As urbanization continues to accelerate worldwide, the consequential rise in CO_2 emissions has caused substantial environmental challenges. Urban regeneration has emerged as a promising approach to reducing carbon emissions and developing low-carbon cities. Even though both urban regeneration and carbon emissions reduction have been researched from various perspectives, a thorough review is still required to completely reveal their multifaceted relationship. Based on 231 papers published between 2001 and 2023, a bibliometric analysis was conducted to understand the overall trajectory and main focus of the existing research. Then, we qualitatively analyzed the main findings from bibliometric results in terms of key regeneration elements, specific regeneration strategies, research methodologies, as well as research trends and agendas. The results indicated that research in this field is gradually becoming more specialized and comprehensive. Buildings and energy have always been two key urban regeneration elements and research hotspots. Additionally, as a systematic project, reducing carbon emissions requires further exploration of other regeneration elements' contributions and their interactions in the urban system, which needs the corresponding support of more specific regeneration strategies and research methodologies. These findings can advance the development of innovative and impactful pathways for low-carbon oriented urban regeneration, leading ultimately to sustainable cities.

Keywords: urban regeneration; carbon emissions reduction; low carbon; bibliometric review

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1. Introduction

Climate change induced by carbon emissions leads to global environmental problems as a result of rapid urbanization, excessive fossil fuel consumption, and ecosystem damage. The reduction in carbon emissions has become a global consensus. In echoing this, the Paris Agreement calls for immediate action to "peak" greenhouse gases and to become "carbon neutral" by 2050 [1]. Rapid urbanization is considered the main factor in increasing carbon emissions in cities [2]. Urban areas cover only about 3% of the land area but produce 75% of the global CO_2 emissions [3,4]. With the intensification of urbanization in the future, this proportion is projected to rise significantly [5]. Therefore, cities are recognized as the main arenas for dealing with climate change. Developing low-carbon cities has gained a prominent place on urban agendas to achieve sustainable and high-quality development in many countries [6,7]. In this context, urban regeneration provides a critical intervention point for CO_2 reduction in urban development. As a tool to optimize the physical conditions, spatial form and functions of the entire urban system, urban regeneration will play an essential role in improving those urban elements with high energy consumption and high carbon emissions [8].

In the process of urban sprawl, the construction of new houses, infrastructures and other facilities in cities causes enormous raw material and energy consumption, resulting in considerable greenhouse gas emissions [9]. To pursue high-quality and sustainable urban development, many cities have moved their focus on urban planning from incremental expansion to stock optimization and function enhancement [10,11]. Therefore, urban regeneration has been popular worldwide during the last few decades. Urban regeneration can be seen as a "metabolic" process of reusing resources and rebuilding the urban environment [12]. It offers a comprehensive integration of regeneration vision and action geared toward addressing the myriad problems of deprived urban areas, including resource shortage, urban function decay, and environmental pollution to continuously improve economic, physical, social, and environmental conditions [13,14]. In this regeneration process, strategies for lowering carbon emissions can be coupled with other renovation initiatives to achieve synergy when they are implemented together [15]. Thus, introducing the concept of carbon emissions reduction into the process of urban regeneration can significantly promote low-carbon development and environmental sustainability in cities. Many countries have specified the goal of reducing carbon emissions in their urban regeneration blueprint to shape the sustainability and high quality of urban development [16–18].

Against this background, formulating effective strategies to reduce CO_2 emissions in the process of implementing urban regeneration practices has become a critical issue in current research. Many studies have demonstrated that suitable renovation strategies could achieve energy conservation and carbon emissions reduction [19–21]. For example, Garriga et al. [22] argued that retrofits can cost-effectively cut the energy consumption and associated carbon emissions of existing residential communities by 60%, and the best tactic is to improve the thermal performance of envelope and appliance efficiency. Raihan et al. [23] contended that climate change mitigation strategies via urban regeneration in the forestry sector like green regeneration, afforestation, reforestation and sustainable forest management could help effectively reduce emissions by boosting carbon sequestration. Fahlstedt et al. [24] performed a holistic literature review on reducing carbon emissions by refurbishing buildings, comparing the benefits and drawbacks of applied methods, the research scale used, and various carbon emission sources. Although the literature on this topic is rapidly growing, it is mostly limited to a single sector in the urban system like building and energy or the project scale. There are few systematically analyzed articles that present a cohesive body of work on different urban regeneration strategies' effects contributing to carbon emissions reduction in various research contexts. However, the overall low-carbon development of cities must rely on the performance of all components in urban regeneration, which means that a holistic review is essential [25]. Therefore, it is necessary to conduct a full review of the existing literature in different local contexts with respect to the main research areas, thematic evolution, gaps, and future research directions. Only in this way, can urban planning professionals design scientific solutions and policies in the urban regeneration process in response to climate change challenges in the future.

This study aims to offer a comprehensive scan and analysis of the literature to better understand how to reduce carbon emissions through urban regeneration. To achieve this goal, the bibliometric review is used to quantitatively examine research hotspots and the overall evolution of the existing literature. Citespace, which is a mature bibliometric software, could offer technical assistance for us to extract detailed information from the large volume of the literature as a whole. Based on the bibliometric results, we design an outline for the discussion section and read the relevant literature in detail to discuss the main findings in four aspects: key regeneration elements in CO_2 reduction, specific regeneration strategies, research methods, as well as research trends and agendas. The analysis results could contribute to the body of knowledge in both urban regeneration and carbon emissions reduction, which can inform the establishment of evidence-based policies and design the most effective patterns responding to climate change challenges in local contexts.

2. Materials and Methods

2.1. Data Collection and Search Strategy

Data were collected on 21 March 2023 from the Web of Science (Wos) Core Collection (SCI, SSCI). We used the following search rule in the "Topic" area (abstract, title, and keywords): TS = (urban OR city) AND TS = (renewal OR regeneration OR redevelopment OR rehabilitation OR renovation OR revitalization* OR heritage preservation OR heritage conservation) AND TS = ("carbon sink" OR "carbon emission" OR "carbon source" OR "carbon cycle" OR "low carbon" OR carbon). The specific data retrieval procedure involved the following steps:

- Topics were scanned using the above-mentioned search rule in the English language. In order to retrieve enough documents for a comprehensive analysis, the time span of the search was set from 1 January 1990 to 21 March 2023, resulting in 443 papers (document types including Articles, Review Articles, Proceeding Papers, Letters, and Early Access);
- Then, proceeding papers and letters were rejected, leaving 430 papers;
- To guarantee the accuracy and relevance of the literature analysis, the abstracts of each paper were examined to weed out irrelevant ones, such as literature in the categories of archaeology, microbiology, limnology, chemical engineering, etc. Finally, 231 papers (the first of which appeared in 2001) were selected for bibliometric analysis and further discussions.

2.2. Bibliometric Approach

Bibliometric analysis is a quantitative and visual method that utilizes mathematical and statistical techniques to examine the key characteristics and regular patterns of an enormous amount of literature. In this study, we employed Citespace, a mature bibliometric software tool developed by Chen [26] to conduct the quantitative review and visual presentation of the selected publications.

The specific bibliometric indicators analyzed are as follows:

- Yearly trend. The indicator reflects the number of articles published each year which shows the trend of research interest in the field;
- Output by countries. The indicator shows the distribution of publications contributed by each country in this research field;
- Co-occurrence analysis of keywords. A co-occurrence analysis of keywords is used to visualize the relationship network among topics of the existing research. The analysis was performed by calculating the frequency in which two keywords co-occur in the same paper, indicating the association structure of keywords in the current research [27];
- Keywords clustering and timeline analysis. Keywords clustering analysis refers to creating a clustering map to show categories of research topics. Each cluster in the map represents a significant branch or direction of current academia. The more often keywords appear together, the stronger the association and similarity between them, so they are more likely to belong to the same cluster. The names of clusters are determined by the software utilizing the log-likelihood ratio (LLR) [28] of the software. The modularity value is used to assess the clustering quality with a higher value indicating a more well-defined cluster. To depict the progression of research topics, keywords after the clustering are placed on a horizontal timeline, sorted by the year in which the keyword first appeared;
- Keywords burst citation. This indicator aims to calculate the burst strength of keywords as those with a sudden increase in the usage frequency signify a research hotspot in the field of study.

3. Bibliometric Results

3.1. Yearly Trend and Output by Countries

Figure 1 depicts the number of annually published papers between 2001 and 2022. The number of publications on this topic rose from 1 in 2001 to 40 in 2022, which shows an overall continuous upward trend. In particular, 62.61% of the papers were published in the last five years of the period under consideration, indicating a significantly increased interest in the current research on urban regeneration and carbon emissions.

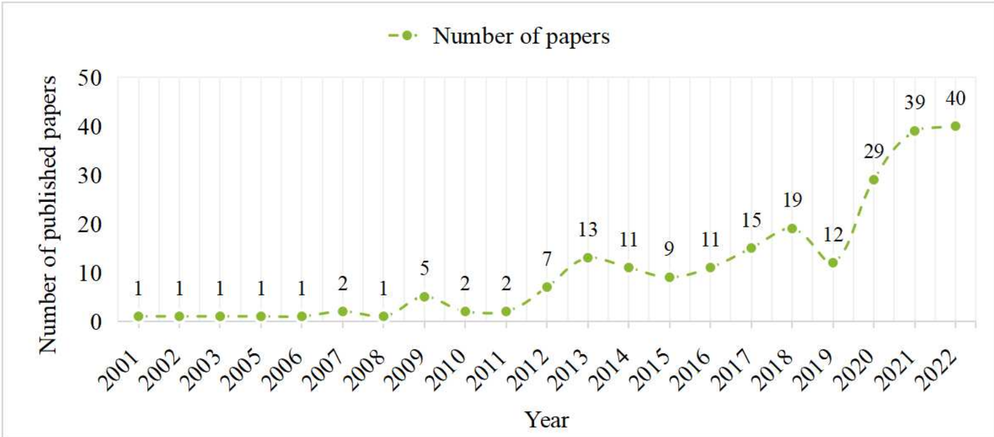

Figure 1. The annual number of published papers from 2001 to 2022.

Regarding the geographical distribution, the selected papers were published by authors from 49 nations. Figure 2 presents the geographical distribution of publications from different nations. According to the statistics, China is ranked first with 46 papers, contributing 14.42% of the total research output, followed by the USA (37 papers, 11.60%), and the United Kingdom (36 papers, 11.29%). When considering regional distribution, the most publications are performed in Europe (170 papers), which has the largest number of countries contributing more than five papers. Next is Asia (70 papers), North America (42 papers), and Oceania (25 papers). Finally, a few studies take place in South America (nine papers), and Africa is the continent with the lowest number of papers (only one). Overall, developed countries have a larger production in this field, which states that research on low carbon-oriented urban regeneration is mostly promoted by authors from these countries.

3.2. Co-Occurrence Analysis of Keywords

Figure 3 shows the co-occurrence analysis of keywords derived from 231 publications analyzed by the Citespace tool. By applying the criteria of g-index (k = 25) and Top N (N = 50) set in the software, a co-occurrence network map with 350 nodes and 909 edges was presented. Then, the threshold of keywords was set as four which defines the minimum frequency for labels of keywords to be displayed on the map, and 49 keywords that met the criterion were finally filtered out as shown in Figure 3. In the co-occurrence network map, each node represents a keyword, and its size reflects how frequently it appears in the selected papers, while edges shown as lines between nodes indicate the co-occurrence between two keywords. Purple circles in the map indicate keywords with high centrality calculated by the software's built-in algorithm. Centrality (Betweenness Centrality) is a measure of the importance of a node in a network, indicating the extent to which a node is a 'mediator' for other nodes. Therefore, such keywords in Figure 3 act as "communication bridges" in the network graph.

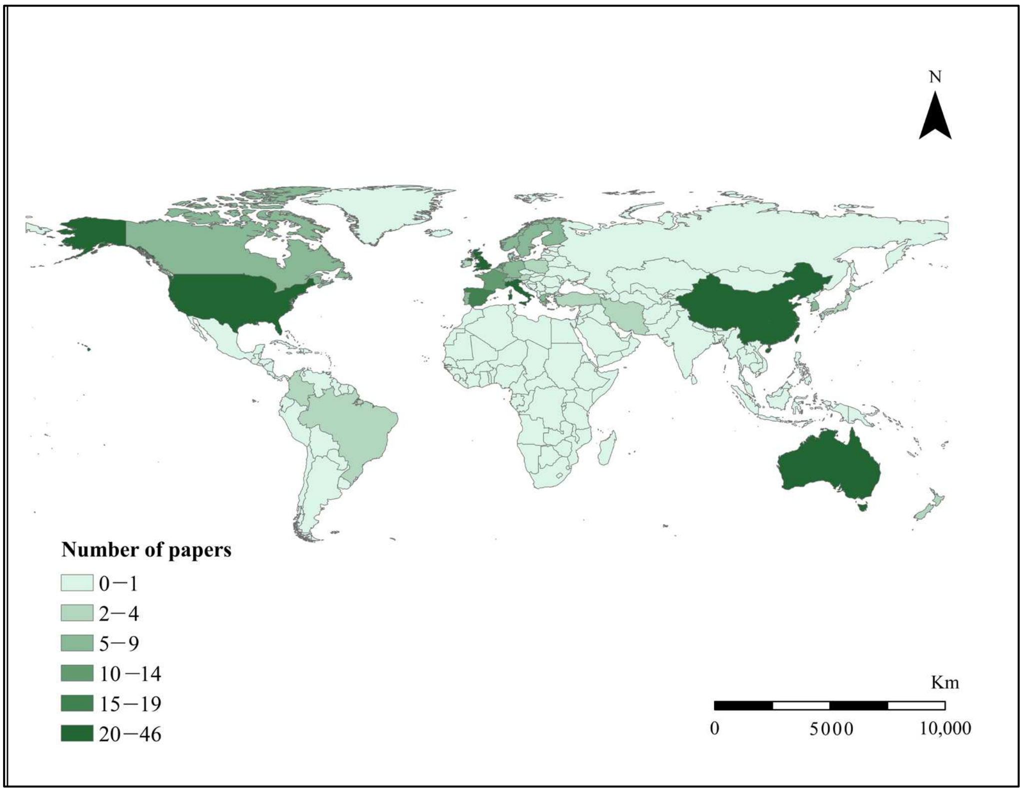

Figure 2. Geographical distribution of publications.

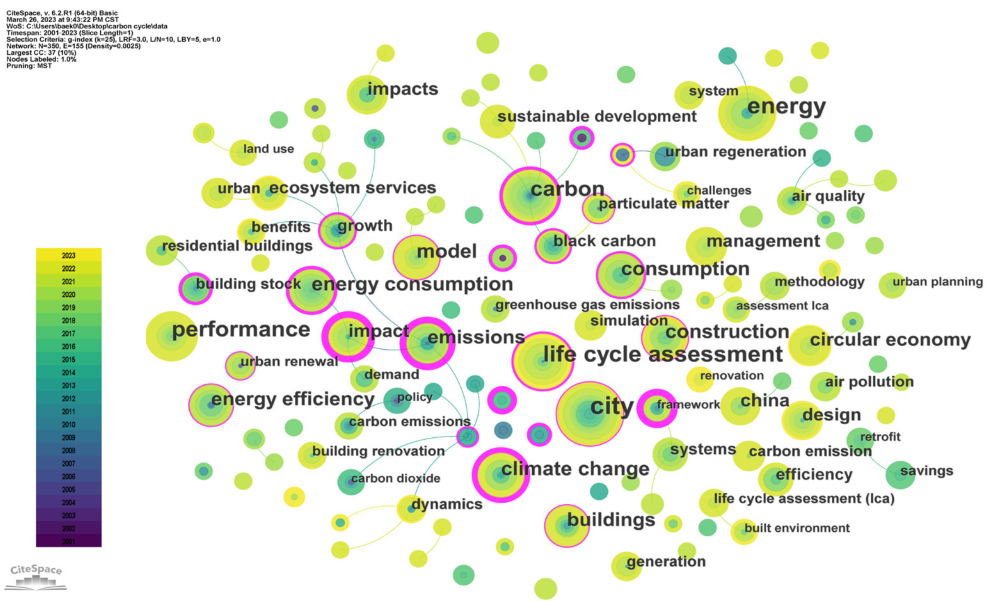

Figure 3. Network visualization for the co-occurrence of keywords.

The wide range of keywords presented in the network map highlights the multi-dimensional and multi-subjective nature of the research on urban regeneration and carbon emissions. Keywords such as "city" (Freq = 27, centrality = 0.24), "carbon" (Freq = 16, centrality = 0.24), "climate change" (Freq = 13, centrality = 0.19), "emissions" (Freq = 12, centrality = 0.45), and "urban regeneration (renewal)" (Freq = 11) show that many researchers have focused directly on the relationship between urban regeneration and carbon emissions. And this focus can also be seen from the high centrality of these keywords. Furthermore, it is worth noting that the keyword "China" has emerged as one of the most recurrent keywords in recent years, reflecting the country's great role in this research field and its efforts to address climate change challenges in the context of rapid urbanization.

Energy-related issues, represented by keywords like "energy" (Freq = 21), "energy consumption" (Freq = 13), and "energy efficiency" (Freq = 12) are a hot research branch in urban regeneration strategies with a relatively high frequency of keywords. In addition, "buildings" with the Top 5 frequency could also be seen as the main object to regenerate to reduce carbon emissions in the urban system. Meanwhile, various research methods have been widely applied by scholars to analyze the relationship between urban regeneration and carbon emissions. Among these keywords, "life cycle assessment", "model", and "simulation" have gained significant popularity.

3.3. Keywords Clustering and Timeline Analysis

Based on the co-occurrence network map in Section 3.2, the relevance of keywords was identified by calculating the frequency of their co-occurrence in the same document. Then, a clustering map was graphed by placing keywords with high relevance into the same cluster using Citespace's built-in algorithm. In Figure 4, eight clusters represented by convex hulls were identified and each contained at least 20 keywords to ensure the meaningful classification of research topics and directions. Cluster's name labels were extracted from noun phrases in the keywords of each cluster utilizing the log-likelihood ratio (LLR). The network has high modularity (0.7888), indicating that different clusters are well-defined.

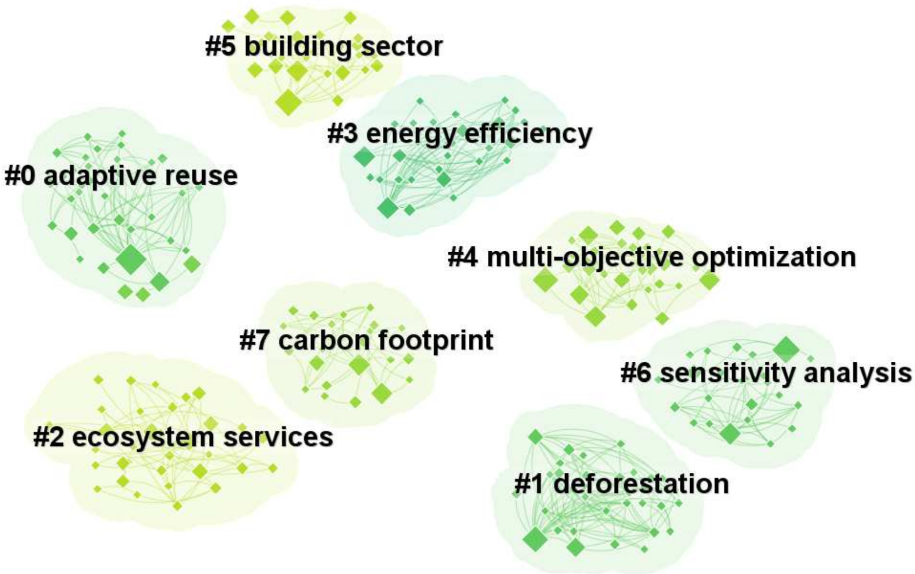

Figure 4. Network visualization for keywords clustering map.

According to the number of keywords in each cluster, the largest cluster is #0 "adaptive use" with 35 keywords associated with "brownfield regeneration", "built heritage", "circular economy", etc. Adaptive reuse (also called building reuse) refers to the repurposing of underutilized or abandoned buildings for new uses. It is regarded as a good strategy to redefine the relationship between buildings and carbon emissions by extending the building's lifespan, minimizing demolition waste, encouraging materials and energy reuse as well as providing significant social and economic benefits [29]. Scholars in this cluster have carried out research on low-carbon oriented adaptive reuse strategies of buildings, mainly including studying their practical challenges, implementation techniques, environmental impacts, as well as indicators or assessment models for reuse potential. Similarly, articles in the #5 cluster also concentrate on how the "building sector" impacts carbon emissions, especially its contribution to energy saving in different urban regeneration strategies.

Cluster #1 "deforestation" and #2 "ecosystem services" encompass studies on carbon sinks in the ecological dimension of urban regeneration, particularly in terms of forestry and green spaces. Green regeneration and ecosystem optimization to increase carbon storage are considered crucial strategies for mitigating carbon emissions in this research category.

Cluster #3, labelled "energy efficiency", contains keywords related to "model", "savings", "policy", "building stock", "Netherlands", etc. Scholars from all over the world in this cluster have made great efforts to find technologies, policies, and solutions for energy retrofitting in urban regeneration to save energy at various scales—from individual buildings to neighborhoods, regions, and cities.

Clusters #4 and #6, labelled "multi-objective optimization" and "sensitivity analysis", respectively, imply a specialization in methodologies and analysis tools for versatile research to provide scientific regeneration recommendations for reducing carbon emissions. The final cluster is #7 "carbon footprint", which means the greenhouse gas emissions released directly or indirectly by the study subject throughout its entire life cycle. The introduction of this concept has promoted a more comprehensive and scientific accounting of the emission reduction effects of different renewal strategies.

To reflect an evolution of research topics in this field, Figure 5 represents the timeline of keywords clustering. And the curves in the timeline chart are co-occurrence links. It can be observed that #6 "sensitivity analysis", #1 "deforestation", and #3 "energy efficiency" cluster are pioneering topics and last longer in this field, whereas the rest of the clusters occur at later stages. The most recently evolving topics within urban regeneration and carbon emissions are "ecosystem services" and "carbon footprint". This signifies a shift towards comprehensive and specialized investigations in this field from the single building or energy sector to diverse sectors, as well as more advanced concepts. Moreover, some of the large nodes with high frequency like "city" and "circular economy" also have citation bursts incorporating the following burst citation detection in Section 3.4, which demonstrates the influence of these topics on this research field.

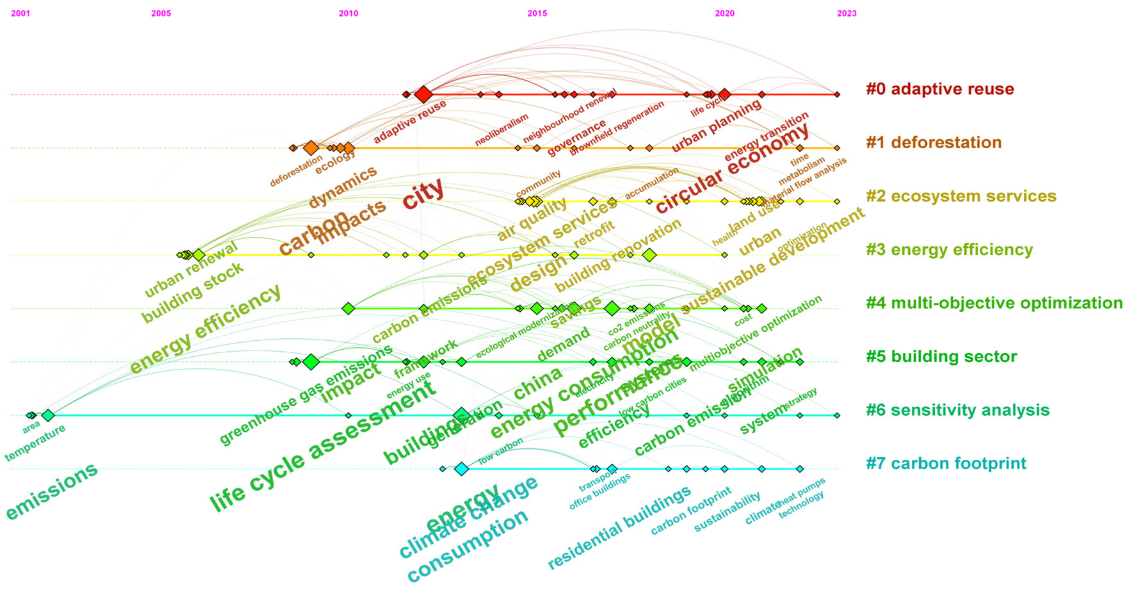

Figure 5. Timeline of keywords in clusters.

3.4. Keywords Burst Citation

Figure 6 illustrates the results of burst citation detection and fourteen bursting keywords are identified by the software using the algorithm proposed by Kleinberg [30]. The strength value indicates the extent to which the usage frequency of a keyword suddenly increases or explodes in a short period of time. The higher the intensity value and the longer the time duration of the outburst (represented by red lines in Figure 6), the more active and hotter the topic is in the research field [31]. The keywords "city" (Strength = 3.2), "savings" (Strength = 2.92), "energy consumption" (Strength = 2.54), and "urban regeneration" (Strength = 2.21) have the highest citation burst values. Among them, keywords like "city", "circular economy", and "energy consumption" are also the most recurrent keywords as observed in Figure 3, which suggests a significant interest in these topics.

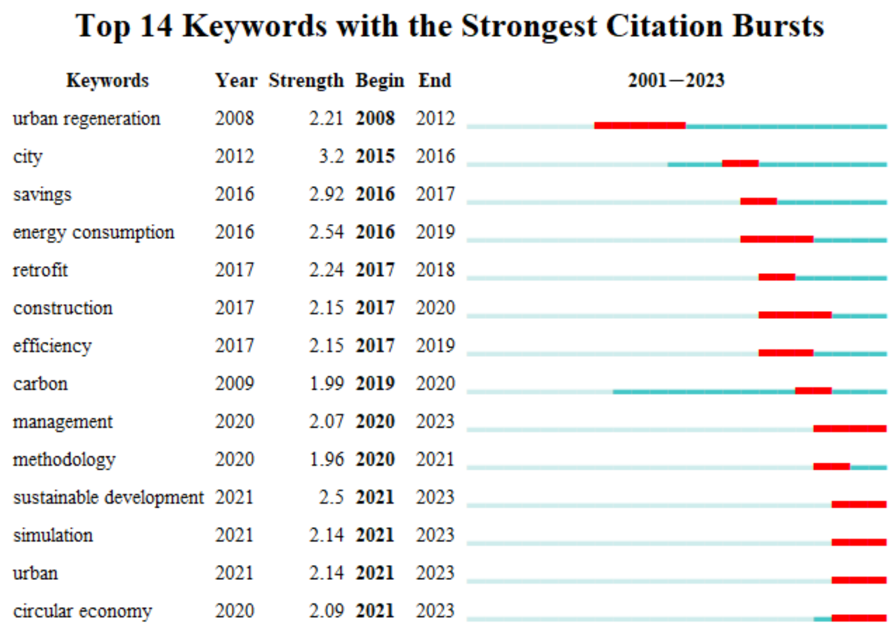

Figure 6. Top 14 keywords with the most powerful citation bursts.

Analyzing the temporal information, we find that the earliest keywords with the longest time span are "urban regeneration", "energy consumption", and "construction". Then, these are subsequently replaced by others such as "management", "sustainable development", "circular economy", and "simulation". These evolving characteristics of hot research topics are congruent with the analysis of the timeline of keywords clustering, highlighting the systematization and specialization to cope with the greenhouse gas threats in academia.

4. Discussion

The above bibliometric analysis in Section 3 has provided valuable insights into the overall research landscape of carbon emissions reduction and urban regeneration, which can be summarized as various regeneration elements (e.g., buildings, energy and forestry), relevant regeneration strategies (e.g., adaptive use and energy retrofit), and methodologies (e.g., simulation, life cycle). Building upon the classification of these results, we now discuss the main findings by qualitatively reviewing the literature, respectively. Firstly, the key elements in the urban system contributing to carbon emissions reduction in urban regeneration are identified. Accordingly, from the perspective of the carbon cycle, specific urban regeneration strategies of each element for reducing carbon emissions can be systematically designed to help develop low-carbon cities. Then, we summarize diverse research methodologies utilized in the selected articles to compare their characteristics and functions in different contexts. Finally, the research trend, gaps, and potential future research areas are presented.

4.1. Key Regeneration Elements in CO_2 Reduction

According to Figures 3 and 4, the building sector and energy sector are two main material elements for mitigating global warming in the urban system due to their significant influence in cutting carbon emissions. This can be further supported by the summary of the top-cited papers related to carbon urban regeneration and carbon emissions (see Table 1).

Table 1. Highly cited papers in this field.

Paper Title	Authors	Citations
Need for an embodied energy measurement protocol for buildings: A review paper	Dixit et al. [32]	537
Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability?	Power [33]	483
A hybrid decision support system for sustainable office building renovation and energy performance improvement	Juan et al. [34]	418
Implementation challenges to the adaptive reuse of heritage buildings: Towards the goals of sustainable, low carbon cities	Yung and Chan [9]	398
Thermal upgrades of existing homes in Germany: The building code, subsidies, and economic efficiency	Galvin [35]	170
Towards nearly zero energy buildings in Europe: A focus on retrofit in non-residential buildings	D'Agostino et al. [36]	153
Energy performance optimization of existing buildings: A literature review	Hashempour et al. [37]	100

It is well known that the building sector in the metropolitan system is recognized as a highly energy-intensive and carbon-emitting sector, responsible for 40% of all greenhouse gases, showing great potential for regeneration [38]. In China, the total carbon emissions from the whole process of the building industry in 2019 were 4.997 billion t CO_2, which accounts for 50.6% of the national carbon emissions [39]. As a result, lowering carbon emissions from the building sector has been appreciated as a critical pathway to addressing climate change through urban regeneration. Many scholars argued that refurbishment and renovation of buildings are effective strategies for optimizing the building structure, functions, and energy performance [40,41]. For instance, Gillott et al. [42] investigated the drivers, obstacles, and enablers affecting the implementation of the vertical extension to promote low-carbon-oriented adaptive reuse of stock buildings. To achieve the maximum potential for carbon emissions reduction in the building sector, the perspective of the life cycle has been widely used by scholars [43]. Luo et al. [1] conducted a life cycle assessment to compare the carbon emissions reduction effects of various technical approaches of renovating old residential areas. Foster and Kreinin [44] reviewed the environmental benefits of repurposing cultural heritage buildings, and integrated strategies that aim to reduce life cycle carbon emissions through a circular product supply chain perspective.

The energy sector is another key element contributing to carbon emissions reduction within urban regeneration. Energy use in urban areas has been found to be the largest source of CO_2 emissions, making it a leading factor in climate change [45]. In Europe, cities presently account for around 70% of the overall primary energy consumption, and this figure is projected to rise to 75% by 2030 [46]. Consequently, many studies tend to develop energy retrofit technologies and analyze their effects across various aspects of urban regeneration projects. Typical energy-saving technologies have been integrated into urban regeneration practices with other urban elements, including retrofitting solar energy and water storage, adding insulation to building envelopes, fitting energy-efficient electric appliances, recycling waste and using eco-friendly materials, etc. [47,48]. For instance, Hashempour et al. [37] identified obstacles to promoting the replacement of low-carbon technologies in space heating based on regeneration cases in the Netherlands. Amoruso and Schuetze [49] developed three renovation solutions of common building types for energy conservation using hybrid timber technologies in the Republic of Korea, which offers a low-carbon alternative to redevelopment. At the macro urban planning scale, Deakin et al. [50] established the baseline for integrating the energy retrofit proposal into an urban regeneration masterplan that is committed to converting towards an energy-efficient and low-carbon zone.

Furthermore, other elements within the urban system such as transportation and urban green space, as shown in the #1 Cluster, #2 Cluster and #7 Cluster in Figure 5, also play significant roles in the overall efforts to mitigate carbon emissions through urban regeneration practices. For example, Sobrino and Monzon [51] investigated how to enhance the traffic management of urban mobility to prevent climate change in the context of urban regeneration in Spain. Lehmann [52] proposed the comprehensive idea of green urbanism and analyzed one of the largest urban regeneration projects in Australia, highlighting the need for new forms of green spaces in urban precincts to combat the city's warming environment. In addition, there is a relatively small amount of literature focusing on optimizing the urban layout, upgrading industries, improving waste management and restoring the water body and soil through urban regeneration to maximize carbon reduction benefits [53–55].

To sum up, nine key elements in the urban system, namely, building, energy, transportation, urban layout, industry, waste, green space, water, and soil should be incorporated into urban regeneration practices to achieve the aim of lowering carbon emissions [56]. By considering joint efforts of these elements, cities can efficiently address the challenge of climate change by creating a more friendly and sustainable urban environment.

4.2. Urban Regeneration Strategies to Reduce Carbon Emissions

Based on the above-identified urban regeneration elements for CO_2 reduction, we further systematically summarize specific strategies which can be applied to the regeneration practices in referrence to the nine elements based on the carbon cycle theory.

The carbon cycle theory describes the movement of carbon through the Earth's various systems, comprising two primary processes: carbon sources and carbon sinks. A carbon source is any process or system that emits carbon into the atmosphere, while a carbon sink is any system or process that removes carbon from the atmosphere [57]. If carbon sinks become overwhelmed or carbon sources increase, the concentration of CO_2 in the atmosphere would increase, leading to global climate change [58]. As noted by Wigley and Schimel [59], this theory offers a scientific way to manage the global carbon cycle to design effective measures to control greenhouse gas emissions from carbon sources and enhance the capacity of carbon sinks to absorb and store carbon from the atmosphere. According to this theoretical cornerstone, Figure 7 illustrates the movement of CO_2 in the form of carbon sources and carbon sinks within a carbon cycle system between the atmospheric pool and the nine urban elements.

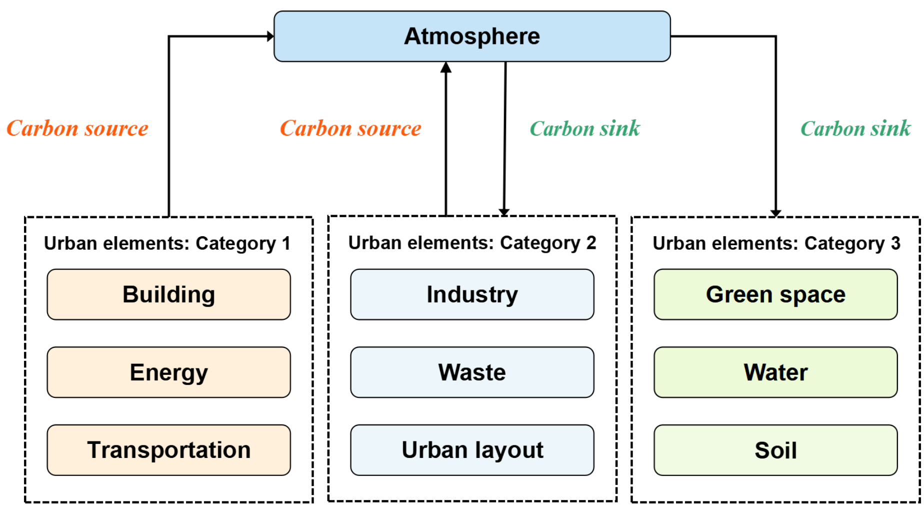

Figure 7. Nine urban elements within a carbon cycle system.

In Figure 7, urban regeneration elements can be classified into three catalogues by authors in line with their impacts on the two processes (carbon sources and carbon sinks). Based on this, we have browsed through the content of all the selected literature and identified carbon reduction strategies that have proven to be effective in the literature for the implementation of urban regeneration practices. In order to ensure the feasibility and scientific validity of these listed strategies, the literature containing case studies, empirical data, calculation models, and practical policies was prioritized and referenced to demonstrate the positive benefits of CO_2 reduction. Then, relevant regeneration strategies focused on reducing carbon emissions and their supporting references can be placed into these three catalogues as shown in Table 2.

Table 2. Regeneration strategies to reduce carbon emissions within the urban system from the carbon cycle perspective.

Category	Elements in the Urban System	Carbon Reduction Strategies in Urban Regeneration	References
1: reducing carbon sources	Building	✓ Adaptive reuse to extend building lifespan ✓ Install a solar panel photovoltaic system ✓ Install rainwater storage and water recovery system ✓ Renovate building maintenance structures using nested envelopes or adding insulation to walls, floors, and roofs ✓ Replace building furnaces with solar boilers or heat pumps (ground source and air source) ✓ Fit energy-efficient electric appliances (e.g., intelligent control technologies in lighting systems) ✓ Use recycling and eco-friendly materials	[60–63]
	Energy	✓ Switch from fossil fuels to renewable and clean energy (e.g., wind, solar, hydro, biomass, and geothermal energy) ✓ Use energy storage technologies (e.g., waste heat recovery technologies), carbon capture and storage technologies	[64–66]
	Transportation	✓ Optimize the layout of the public transport network and increase the proportion of nonmotorized modes (walking and biking) ✓ Promote fleet renovation and the application of new energy vehicles, hybrid vehicles and relevant supporting facilities	[67–70]
2: reducing carbon sources and increasing carbon sinks	Industry	✓ Retrofit high-energy consumption industries ✓ Transform industries towards high efficiency in product manufacturing and produce more multi-functional products ✓ Develop the sharing industry and sharing economy, (e.g., Bicycle-sharing and Charger-sharing) ✓ Develop urban agriculture to reduce food transportation ✓ Develop green and innovative industries ✓ Expand the scale of high-end industrial agglomeration	[71–73]
	Waste	✓ Recycle and reuse construction materials and infrastructure components ✓ Enhance waste separation and collection systems to encourage recycling and composting ✓ Retrofit landfills for gas capture and biodegradation	[42,74–76]
	Urban layout	✓ Curb urban sprawl and prioritize urban regeneration ✓ Shift to compact and mixed-use urban form, like renovating communities into a mix of residential, commercial, and retail uses ✓ Change land use types to restore ecological land	[64,77,78]
3: increasing carbon sinks	Green space	✓ Increase urban green areas (e.g., afforestation, urban forestry, green parks, green roofs, and green walls) ✓ Optimize the species and densities of greenery ✓ Change land use (e.g., turning unused public areas into ecological land) ✓ Minimize the frequency of renewal and manual involvement in maintenance (e.g., using organic fertilizers and natural irrigating ways like rain gardens and permeable paving)	[79–81]
	Water	✓ Restore water bodies ✓ Expand water areas and improve their connectivity	[82,83]
	Soil	✓ Restore degraded or contaminated soil by adding organic matter, planting vegetation, and using biochar	[84,85]

The first catalogue concludes regeneration strategies reducing carbon sources in terms of three main elements in the urban system: building, energy, and transportation. The second catalogue comprises regeneration strategies that address another three elements, including urban layout and waste management, with the aim of both lowering carbon sources and boosting carbon sinks. The third collection of measures focuses on green space, water, and soil concentrating to increase the capacity of carbon sinks to absorb and store carbon from the atmosphere.

However, the implementation of the above urban regeneration strategies entails a series of human activities like producing and transporting materials, using machinery and disposing of demolition waste, which would also generate greenhouse gas during the materialization, operation, and demolition stages of regeneration projects. These emissions by carbon-inducing activities may offset the benefits of carbon reduction achieved through regeneration strategies. Therefore, it is crucial to select proper urban regeneration implementation modes to maximize the carbon reduction potential while applying specific regeneration strategies in Table 2.

Based on bibliometric results and reading the selected articles, there are several urban regeneration modes, typically including demolition and redevelopment, renovation, adaptive use, retrofit, etc. In general, wider arguments and research evidence support the viewpoint that renovation and adaptive reuse are preferable to large-scale demolition. Numerous studies contend that in contrast to negative consequences caused by demolition and reconstruction, the modes of renovation, adaptive use or retrofit in all except very few extreme cases are more beneficial to CO_2 reduction and less detrimental to the built environment and local society [86]. For example, after analyzing three regeneration studies of existing housing, Power [33] countered the notion that large-scale and expedited demolition would be helpful in achieving our climate change mitigation and sustainable development goals. The reason is that demolition and reconstruction typically involve higher capital costs, increased material wastage, more embodied carbon inputs, associated pollution impacts as well as complicated social conflicts. In contrast, renovating and repurposing the existing stock provide cost-effective, easy, and sustainable implementation modes to shape future low-carbon cities [87].

4.3. Methodologies Utilized in the Reviewed Articles

Due to the lack of information and the complexity of implementation, regeneration initiatives with the goal of reducing carbon emissions are typically characterized by high degrees of uncertainty, risk, and huge investments [88]. Therefore, scientific research methodologies are needed to avoid mistakes and help promote more effective solutions. Figures 3 and 5 in the bibliometric analysis have shown some main research methods of the existing research landscape. Together with the extensive reading of the literature content, eight main methodologies used in these reviewed articles were divided into two categories, namely qualitative and quantitative (see Table 3).

Table 3. Main methodologies applied in the selected studies in this field.

Category	Methodology	References
Category 1: qualitative	Literature review	[44,74]
	Case study	[29,89,90]
	Semi-structured interview	[69,91]
Category 2: quantitative	Carbon monitoring and accounting	[82,92]
	Life cycle method	[93–95]
	Multi-objective optimization	[48,65,96]
	Simulation	[87,97,98]
	Sensitivity analysis	[99–101]

Qualitative methodologies in Category 1 such as literature reviews, case studies, and semi-structured interviews are the most commonly used in exploring carbon emissions reduction in urban regeneration. Studies employing these methods generally focus on analyzing current strategies, practical cases and challenges faced in low carbon oriented urban regeneration practices in order to provide effective promotional solutions for policymakers.

Quantitative methods in Category 2 include carbon monitoring and accounting, life cycle (LC) method, multi-objective optimization, simulation and sensitivity analysis (summarized mainly based on Figure 5). The first quantitative method is carbon monitoring and accounting. Accurate measurement and prediction of carbon emissions or carbon sequestration are the prerequisites for evaluating the potential emission reduction and effectiveness of different regeneration strategies. Accounting methods, typically emission factors and software tools, have been widely used by authors to calculate carbon emissions or sequestration in different phases of urban elements such as buildings, parks, and infrastructures. Furthermore, various concepts in this field, such as embodied carbon, carbon footprint, and life cycle are introduced into accounting to enhance a more comprehensive analysis.

The second quantitative approach, the life cycle (LC) method, is a broad term with the distinct attribute of focusing on the entire life cycle of products which avoids problem shifting [102]. LC method mainly refers to two specific methods, namely life cycle assessment (LCA) and life cycle cost (LCC). LCA is a common and mature tool for estimating the total carbon emissions or other environmental impacts generated by different elements in the urban system throughout their life cycle before and after regeneration practices [103]. On the other hand, the feasibility of regeneration strategies to reduce carbon emissions often requires considering economic factors, so LCC, is used to calculate the life cycle costs associated with regeneration practices according to research needs and specific circumstances.

The third methodology applied, denoted as multi-objective optimization, requires integrating several tactics to identify optimized regeneration solutions considering two or more parameters (e.g., cost, energy, carbon emissions, thermal comfort, etc.) [24]. To circumvent the extensive time required to simulate numerous outcomes from tons of solutions, some studies apply mathematical optimization techniques, such as artificial neural networks (ANN), genetic algorithm (GA), multi-objective mixed integer nonlinear programming model (MINLP), etc.

Some other articles not using the aforementioned quantitative methods tend to employ simulation software or models (e.g., BIM, Pleiades LCA software, IDA-ICE model, EnergyPRO software) to develop scenarios to detect strategies with the greatest carbon reduction benefits. Finally, sensitivity analysis is a common validation method, which is used to ensure the accuracy of analysis results and identify sensitive factors in regeneration programs that have a significant impact on carbon reduction benefits owing to changes in uncertain data [104].

To sum up, these above-mentioned methods possess different advantages and characteristics. Thus, these methods are sometimes combined to perform different functions for achieving optimal solutions in one study. The choice of methodologies employed in articles may differ based on the objectives and needs of the specific research context.

4.4. Research Trend and Agenda

The analysis of bibliometric results and the preceding discussions reveal a widening research scope and specialization of existing studies on low-carbon-oriented urban regeneration practices. Initially centered on the building and energy sectors, the research focus has now expanded to encompass various elements within the urban system, including transportation, industry, green spaces, etc. In line with this, regeneration strategies for carbon emissions reduction are increasingly incorporating a combination of carbon source reduction and carbon sink enhancement. This trend is also accompanied by the emergence of advanced concepts, tools, and methodologies aimed at better addressing the threats of greenhouse gas emissions through urban regeneration, thereby indicating the reliability and accuracy of current research. Another interesting aspect is that the research focus in this field varies among different countries which is closely related to the local context including economic performance, urban development, climate, and geography. In terms of the geographical distribution of article output, bigger countries and large groups of regions like China, the USA, and Europe with advanced economies produce more publications. This is not surprising, given that these countries or regions continue to be leaders in the global economy and urbanization with richer resources to support the vision of green cities. Furthermore, urban regeneration strategies to mitigate climate change in different countries show significant geographical features. It is typical that in countries at high latitudes, such as Finland, there is a greater research interest in heating retrofits in urban regeneration projects to reduce energy consumption and associated carbon emissions [48].

As for Malaysia, a tropical country rich in forest resources, many studies emphasize the preservation of the carbon storage capacity of forests, reduction in carbon-intensive manual maintenance, and expansion of urban forests as critical means to mitigate carbon emissions [92].

However, the existing literature also perceives some shortcomings that could serve as future research agendas:

Firstly, although scholars have begun to focus on multiple elements' potential in the urban system to develop low-carbon cities, research on urban layout, waste, soils, and water is still insufficient. It would be difficult to achieve overarching low-carbon development by tackling certain elements in the urban system. [105,106]. Because of this, further investigation is needed to explore each regeneration element's CO_2 reduction potential, as well as their effective regeneration strategies and associated challenges.

Secondly, it is essential to adopt a holistic perspective that considers urban regeneration from a regional or city-level standpoint to achieve carbon reduction goals. Existing studies are overwhelmingly based on individual projects or the neighborhood scale to investigate carbon reduction approaches in urban regeneration projects. However, the micro-perspective and tailored analysis may not be adaptive to different scenarios and unsuitable for broad-scale implementation at the city level. Therefore, future research should strive to develop adaptive frameworks that formulate effective urban regeneration strategies from a systematic perspective to provide general references. On the other hand, carbon emission problems are complicated and interconnected between multi-elements in the urban system, which requires joint efforts from all aspects of cities. The contribution of every element and how they interact with each other in carbon emissions reduction strategies must be investigated deeply to find the synergistic mechanism in shaping low carbon development in the urban regeneration process. For example, the interaction between buildings and the built environment around them, such as building location, may jointly influence carbon emissions through people's transportation activities (known as induced-mobility emissions). The interrelationships in carbon emissions reduction could help urban regeneration practices to achieve a "1 + 1 > 2" effect.

Thirdly, in terms of supporting methodologies and tools in this field, science-based management methods have yet to be completely utilized in the exploration of reducing carbon emissions through urban regeneration. For example, theories and methods from operations research, management process theory, system dynamics theory, game theory, and complex network theory could be incorporated to enhance scientific decision-making, explore interactions of urban elements, and amplify synergistic benefits in carbon emissions reduction through urban regeneration practices. Also, big data-based analysis approaches like machine learning and cloud technology may be integrated in the future to precisely identify the local status and design optimal strategies to ensure the urban regeneration strategies cope with local genuine realities and needs.

Finally, it appears that there is a lack of in-depth comprehension and new concerns about the social phenomenon during low-carbon-oriented urban regeneration process. Although many scholars have studied various social problems associated with urban regeneration or climate change respectively, typically such as segregation, displacement, environmental justice and gentrification, new political formations, social impacts, and public behavior that accompany urban regeneration initiatives embedded with CO_2 reduction features are not completely explored. In fact, urban regeneration and the development of low-carbon cities will both significantly change the living environment and lifestyles of residents, which requires a people-centered principle. The urgency for consensus on carbon emissions reduction plans necessitates removing as many obstacles as possible in the wheel of the low-carbon oriented urban regeneration process. If our focus is only on physical measures and technology development, the potential social barriers will be detrimental to the widespread promotion of low-carbon urban regeneration practices. Only when understanding the positions of different social subjects and gaining support from the whole society can the best regeneration solutions be developed and implemented.

5. Conclusions

The dramatic CO_2 emissions from cities due to rapid urbanization poses significant environmental challenges, hindering the attainment of sustainable development in cities. In light of these challenges in lowering carbon emissions experienced by international cities, urban regeneration has been regarded as an effective strategy for creating low-carbon cities.

This study conducted a bibliometric review combining a quantitative and qualitative analysis to examine 231 selected articles between 2001 to 2023 from the Web of Science Core Collection Database about carbon emissions reduction in urban regeneration. These bibliometric results summarized the most active research topics and the overall evolution of current research in the academic field. Based on these results, we qualitatively discuss the main findings in terms of four aspects: key regeneration elements in the urban system, specific regeneration strategies, research methodologies, and research trends. The findings of this study show that there is a significant increase in research interest in this field. China, the USA, and the United Kingdom are the main contributors to the research area, which can provide valuable references and practice experience for other countries. In addition, there is a significant evolution towards increasing comprehensiveness and specialization in terms of concerning topics, research methodologies, and specific strategies in low-carbon-oriented urban regeneration practices. And buildings and energy have always been two key urban regeneration elements and research hotspots. Finally, the following aspects could be highlighted as future study directions: (1) clarification of each regeneration element's CO_2 reduction function and potential; (2) holistic perspectives and synergy mechanisms upon carbon reduction strategies into the urban regeneration vision, scheme and practices at different scales; (3) application of advanced big-data based technologies and methods in management science; (4) wide concern for social impacts under urban regeneration with goals of CO_2 reduction.

How to reduce carbon emissions through urban regeneration is a complicated issue which needs multidisciplinary convergence and scientific understanding of existing research in this field. This article's contribution and scientific significance lie in the systematic review for both the research and professional communities, including academic researchers, urban planners, the government, and relevant practitioners. The recommendations of future works provide a reference for conducting more in-depth investigations of effective urban regeneration practices for CO_2 reduction, ultimately fostering the creation of green, low-carbon, and sustainable cities.

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