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Systematic Review

Urban Building Carbon Sinks Under the Carbon Neutrality Goal: Research Hotspots, Measurement Frameworks, and Optimization Strategies

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Abstract

In the context of urban carbon neutrality, buildings are shifting from carbon emission sources to potential urban carbon-sink units. Yet existing studies mostly examine single materials or isolated technologies, and a systematic integration of building carbon sinks is still missing. To address this gap, this study reviews literature from 2007–2025 using statistical analysis, bibliometrics, and network analysis to identify research priorities, technological pathways, and development trends. The results show that: (1) Publications have grown steadily, surging after 2020; research has evolved from material carbonation mechanisms to building-system carbon sinks and then to active carbon-capture technologies, indicating strong multidisciplinary integration. (2) A three-stage framework for quantifying and monitoring building carbon sinks has been formed, but current methods differ by scale and no unified standard exists for urban building carbon-sink assessment. (3) A life-cycle enhancement strategy is summarized, including improving carbonation performance with solid-waste utilization, increasing building exposure area, integrating ecological attached sinks with active capture technologies, and reusing crushed construction waste. This review integrates fragmented findings on the carbon-sequestration efficiency of urban buildings and provides references for future urban emission reduction and climate-neutrality goals.

Keywords: carbon neutrality; building carbon sinks; concrete carbonation; direct air capture (DAC); carbon sequestration measurement; life-cycle assessment (LCA); design strategy

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1. Introduction

Global climate change is one of the most severe challenges to sustainable development faced by human society, with its root cause being the excessive emissions of greenhouse gases, particularly carbon dioxide (CO_2) [1]. In response to this crisis, achieving carbon neutrality has become a shared global goal, forming a broad consensus under frameworks such as the Paris Agreement [2]. As the center of global population and economic activities, cities are the primary sources of energy consumption and carbon emissions, contributing to approximately 75% of global CO_2 emissions [3]. In this context, the building sector has garnered significant attention due to its substantial carbon footprint throughout its entire lifecycle (from material production, construction, operation, to demolition) [4]. Traditional decarbonization pathways for buildings mainly focus on improving energy efficiency and utilizing renewable energy to reduce emissions from buildings as "carbon sources".

Building carbon sinks represent one of the key methods for long-term carbon storage, achieved by absorbing and fixing CO_2 in the atmosphere throughout the entire lifecycle of buildings. Buildings, with their unique material structures and energy metabolism characteristics in urban ecosystems, play a pivotal role in the carbon cycle, influenced by the materials used, spatial forms, and functional systems [5]. Through carbonation reactions at the material level, ecological integration in building design, and emerging active carbon capture technologies, buildings can participate in carbon absorption and sequestration processes at different scales [6]. The concept of viewing buildings as "carbon sink units" expands the traditional definition of buildings solely as energy consumers and carbon emitters, transforming them into potential "artificial carbon sink systems" that play an important role in achieving carbon neutrality [7]. Building carbon sinks not only help mitigate the rise of CO_2 concentrations in urban environments but also offer additional benefits, such as extending material lifespan, improving microclimates, and enhancing ecological service value [8]. With the rapid development of low-carbon and negative-carbon building concepts, research on building carbon sinks is increasingly becoming an important topic at the intersection of architecture, materials science, and environmental engineering, with theoretical refinement and technological innovation holding profound significance for achieving sustainable urban transformation.

Although the concept of building carbon sinks holds great potential, current research is still in an exploratory stage and the knowledge system remains fragmented across scales and disciplines. At the material scale, cement and concrete studies have demonstrated that carbonation can provide a non-negligible global carbon sink and that engineered mineral carbonation can intentionally enhance CO_2 uptake in cement-based materials [9,10]. At the same time, research on recycled concrete aggregates and accelerated carbonation has shown that demolition waste can both be upgraded and used as a medium for additional CO_2 sequestration [11,12]. At the building and urban scales, studies on green roofs, green façades, and broader urban green infrastructure have quantified carbon sequestration, microclimate regulation, and co-benefits of nature-based solutions [13–15]. Meanwhile, life-cycle and embodied-carbon studies have provided systematic approaches for evaluating building-related emissions, but they primarily treat buildings as carbon sources rather than potential carbon sinks [16,17]. As a result, despite progress at each scale, there is limited integration among material-level carbonation, nature-based solutions, and building-system technologies, leaving a fragmented understanding of how these components can work together within real building or urban systems.

This fragmentation leads to several methodological bottlenecks. First, there is still no unified standard or systematic framework for measuring and assessing building carbon sinks. Laboratory-scale methods that quantify CO_2 uptake in cementitious materials—such as controlled accelerated carbonation testing—are not directly compatible with field-scale monitoring of building or district carbon fluxes, making cross-scale coupling difficult [11,17]. Second, many studies focus on a single stage of the building life cycle, resulting in incomplete "cradle-to-grave" or "cradle-to-cradle" carbon-sink accounting. Reviews of embodied carbon in buildings have similarly highlighted inconsistencies in system boundaries, data sources, and methodological choices, which hinder comparability and the establishment of benchmarks [16,17]. Third, passive carbonation strategies (e.g., natural or accelerated carbonation of concrete and recycled aggregates) and active or semi-active carbon-capture approaches (e.g., building-integrated capture systems, carbon-storing binders, biotic building envelopes) are often studied in isolation, and their synergies within building systems remain poorly examined [12,18]. These issues make it difficult to objectively compare technological pathways, evaluate life-cycle carbon-sink performance, and translate research outcomes into design guidelines and policies.

Against this background, there is a pressing need for a systematic and comparative review that integrates these fragmented research efforts under a unified urban building carbon-sink framework. Based on literature from 2007 to 2025 in the Web of Science Core Collection, this paper applies statistical analysis, bibliometric and network analysis, and qualitative synthesis to: (1) quantify development trends in the field, including annual publication patterns, collaborative networks, and the evolution of research hotspots; (2) construct a multi-scale technical framework that integrates material-level carbon sinks, spatial-design carbon sinks, and active carbon-capture technologies, clarifying their mechanisms and interactions; (3) systematically compare measurement and monitoring methods from material scale, building-system scale, to active-technology scale; and (4) summarize life-cycle optimization strategies while identifying key bottlenecks and future development directions. By doing so, this study aims to help transform the field from isolated case studies into a coherent knowledge system for urban building carbon sinks, providing theoretical support and practical references for architects, engineers, and policymakers working toward negative-carbon buildings.

2. Materials and Methods

2.1. Search Methodology

A topic search was conducted using the Web of Science (WOS) and Scopus core collection databases. To identify literature related to building carbon sinks, we selected terminology describing near-natural environmental processes—such as carbon sink, carbon storage, and active capture—and referenced keyword systems proposed in recent comprehensive reviews on carbon sequestration in the built environment [19]. These studies provide a broader and more systematic foundation for defining search terms related to carbon storage mechanisms, bio-based materials, mineral carbonation, and building-scale sequestration pathways.

Furthermore, the search-term development and the database selection followed widely adopted methodological guidelines for systematic literature reviews. Recommendations by Arksey & O'Malley [20] for scoping systematic searches, Xiao & Watson [21] for structured multi-step search strategy development, and Cooper [22] for research synthesis were used as methodological references to improve transparency and reproducibility of the search protocol.

The restricted search string was defined as follows:

TS = ((“building” OR “architecture” OR “construction”) AND (“carbon sink” OR “carbon sequestration” OR “CO_2 uptake” OR “carbon storage”) AND (“measurement” OR “model” OR “quantification” OR “life cycle assessment” OR “LCA” OR “simulation”)).

The final data collection was completed on 18 September 2025.

2.2. Inclusion Criteria

For quality assessment of retrieved literature, the titles and abstracts of all identified publications were independently screened by the first two authors. Full texts were downloaded for studies meeting the following inclusion criteria:

1. The research focuses on carbon sink technologies or materials related to buildings.
2. The study involves measurement or evaluation methods for building carbon sinks.
3. The article is a peer-reviewed academic publication.

Studies that did not meet these criteria were excluded. In particular, papers that broadly mentioned the effectiveness of carbon sinks in urban buildings without in-depth analysis were removed. The overall screening and eligibility assessment followed the PRISMA 2020 guidelines for systematic reviews [23], and reviewer agreement procedures referenced in the Cochrane Handbook [24] as well as methods proposed by Booth et al. [25]. The PRISMA Checklist is provided in the Supplementary Materials.

These methodological sources ensured transparent inclusion/exclusion decisions, minimized selection bias, and improved reliability of screening outcomes.

Any disagreements or ambiguities among co-authors were discussed thoroughly until consensus was reached.

2.3. Literature Statistical Analysis Combined with Qualitative Analysis

First, Section 3 reports two statistical analyses: (1) A descriptive analysis—conducted via statistical methods—covering annual publication trends, geographical and national distributions, source journals, research institutions, and authorship patterns; (2) Early research focused primarily on the materials scale, aiming to optimize the carbon sequestration efficiency of cement-based materials through "accelerated carbonization" technology. Subsequently, the research expanded to the building system scale, combining building envelopes such as green roofs with the concept of "biocarbon" to assess their comprehensive carbon sequestration capacity. Ultimately, the research has moved towards a new paradigm of proactive carbon sequestration, which aims to transform buildings from single carbon emission sources into living systems capable of actively capturing and storing carbon dioxide through the deep integration of ecology and architecture, thus achieving a complete strategic upgrade from materials science to systems engineering.

To further elucidate the relationship between buildings and carbon sinks, this study investigated multiple aspects of the built environment. Section 4 summarizes the three major dimensions of building carbon sinks. Section 5 systematically classifies and reviews existing measurement and monitoring methods, based on statistical categorization of the methodologies reported in each paper's Methods section. Section 6 synthesizes research on integrated design strategies linking building systems and urban carbon sinks.

Finally, Sections 7 and 8 discuss potential future research directions and existing challenges. To promote public participation in the design and implementation of building carbon sinks, a theoretical framework was proposed, accompanied by critical reflections on current limitations.

2.4. Summary of the Methodological Workflow

To improve transparency, the research procedure in this review followed the following sequential steps: (1) Database selection and search-term construction based on prior carbon sequestration reviews and systematic search guidelines [19–22]. (2) Execution of the database search using the predefined Boolean string. (3) Deduplication of all retrieved records. (4) Title and abstract screening according to predefined criteria. (5) Full-text evaluation following PRISMA 2020 procedures [23]. (6) Data extraction and coding of carbon sink mechanisms, research scale, and measurement methods. (7) Descriptive statistics and qualitative synthesis based on established mixed-method review techniques [25].

3. A Literature Review on Urban Building Carbon Sequestration Research

3.1. Literature Statistical Analysis

3.1.1. Reference Resource

To conduct this study, we retrieved 3783 publications from the WOS and Scopus Core Collection databases covering the period from 2007 to 2025. Each article's title and abstract were carefully reviewed, and irrelevant studies were removed. After de-duplication, 3714 unique documents remained. Following keyword screening for building carbon sink and building construction, 2021 studies met the inclusion criteria for detailed review. After full-text screening, 135 papers were ultimately included in the final systematic mapping process (Figure 1).

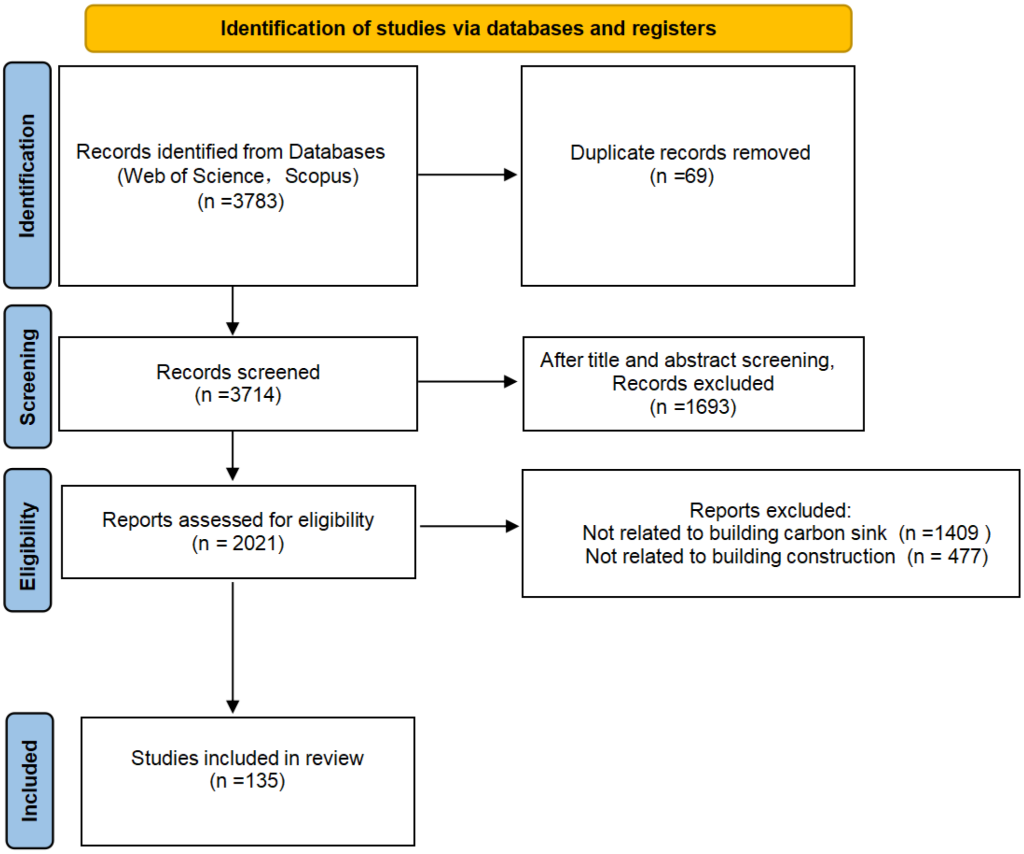

Figure 1. Illustrates the document screening workflow in accordance with the PRISMA Statement.

3.1.2. Annual Publication Trends

Publications on urban building carbon sink capacity have increased steadily year by year, with particularly rapid growth after 2020. Between 2020 and 18 September 2025, 166 papers were published—almost six times the total from 2007–2020 (29 papers) (Figure 2). This rapid surge reflects the growing recognition of urban building carbon sinks not only as an intrinsic performance of the built environment but also as an essential strategy for environmental protection and carbon neutrality.

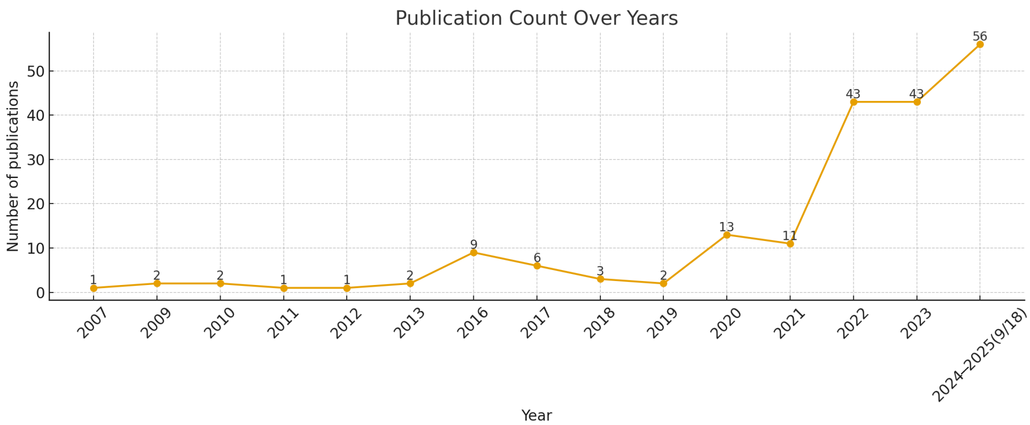

Figure 2. Annual publications from 2007 to 18 September 2025.

3.1.3. Geographical Distribution of Studies

Publications originated from 40 countries and regions worldwide (Figure 3). The most active research regions were Asia (35%), Europe (28%), and North America (23%), while Africa (6%), Oceania (5%), and South America (3%) contributed smaller shares—indicating global but regionally uneven engagement in this research area.

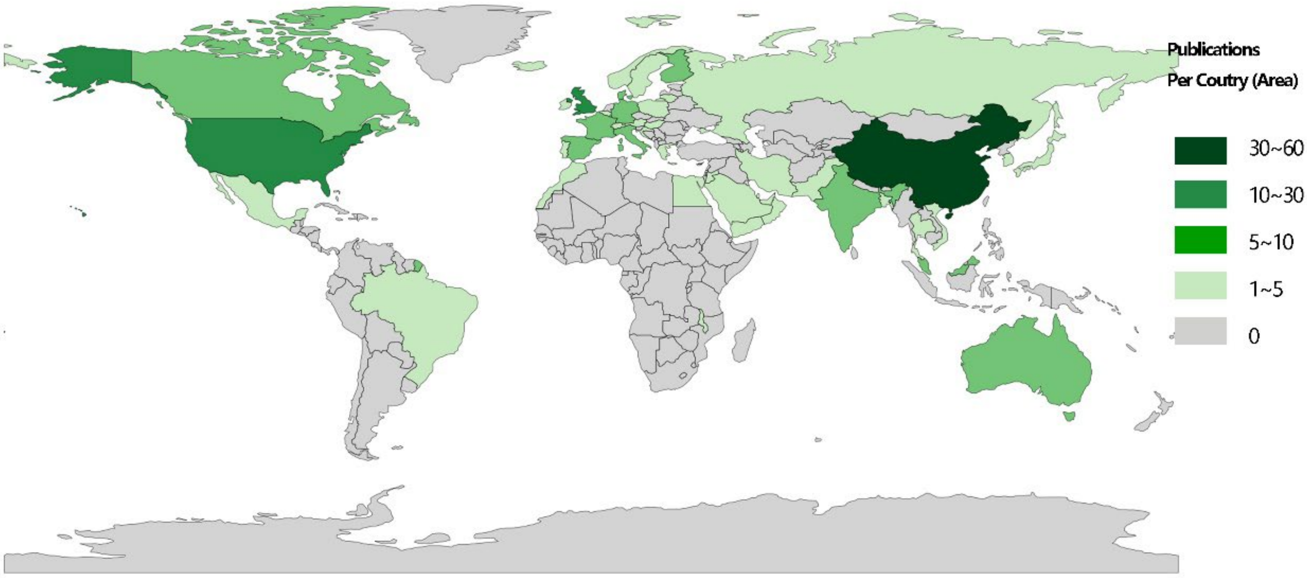

Figure 3. Global distribution of retrieved studies.

China, Nordic countries, and the United States emerged as major contributors, with China accounting for 30% of all publications—making it the leading country in the field. Two factors may explain the observed geographic concentration: (1) The search was restricted to English-language journals, potentially underrepresenting non-English research. (2) There is a relatively larger research community in China focused on building carbon sink technologies.

3.1.4. Institutional Contributions

The 12 most productive institutions in building carbon sink research from 2007 to 2025. Chinese research institutions clearly dominate this domain (Figure 4). The Hong Kong Polytechnic University leads with six publications. Tongji University, the Chinese Academy of Sciences, Hunan University, and Tsinghua University each published five papers, underscoring the strong research capacity of Chinese universities and national institutes. Outside China, Aalto University (Helsinki, Finland), the University of Cambridge (Cambridge, UK), and the University of California system (Oakland, CA, USA) each contributed four papers, highlighting Europe's and North America's sustained engagement. CNRS (Paris, France), University of Colorado Boulder (Boulder, CO, USA), and CSIC (Madrid, Spain) each published three papers, while Aarhus University (Aarhus, Denmark) contributed two. Overall, these results demonstrate broad international collaboration and the remarkable prominence of Chinese institutions in advancing this field.

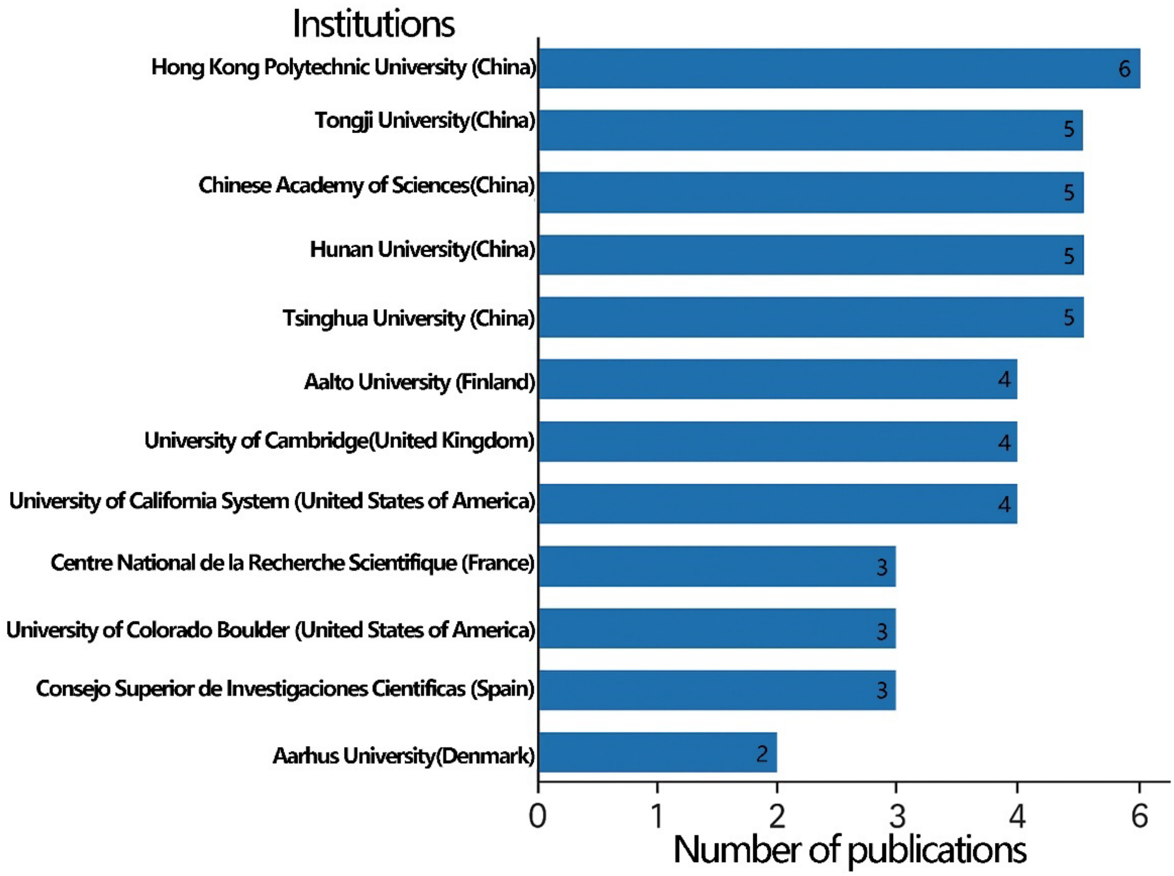

Figure 4. Top 12 most productive institutions on carbon sinks in urban buildings during the period of 2007–2025.

3.2. Literature Analysis: Analysis of Carbon Sequestration Processes

Based on the aforementioned systematic review of literature statistics and content analysis, this study identifies three distinct evolutionary stages in the field of urban building carbon sequestration. This finding not only reveals the historical trajectory of research hotspots in this field but, more importantly, highlights its overall trend of deepening development from the micro-level of technology to the macro-level of systems. By deeply analyzing the core issues, technological paths, and research paradigms of each stage, we can clearly observe how this field has evolved from initial basic research in materials science to integrated applications in building systems, ultimately moving towards a complete evolutionary process of proactive building carbon sequestration.

Specifically, these three stages exhibit clear logical progression (Figure 5). The first stage, centered on materials science, focused on the carbonization mechanism and performance optimization of cement-based materials, establishing a solid theoretical foundation. The second stage broke through the limitations of the materials scale, expanding the research perspective to the building system level, exploring the organic integration of green infrastructure and the building itself. The third stage further leaps to proactive building carbon sequestration, emphasizing the development of ventilation systems and various facilities within buildings in conjunction with the building structure to achieve proactive carbon sequestration. Each evolutionary stage achieves breakthroughs in research paradigm and methodological innovation based on the previous stage, reflecting the continuous improvement and deepening of the knowledge system in this field.

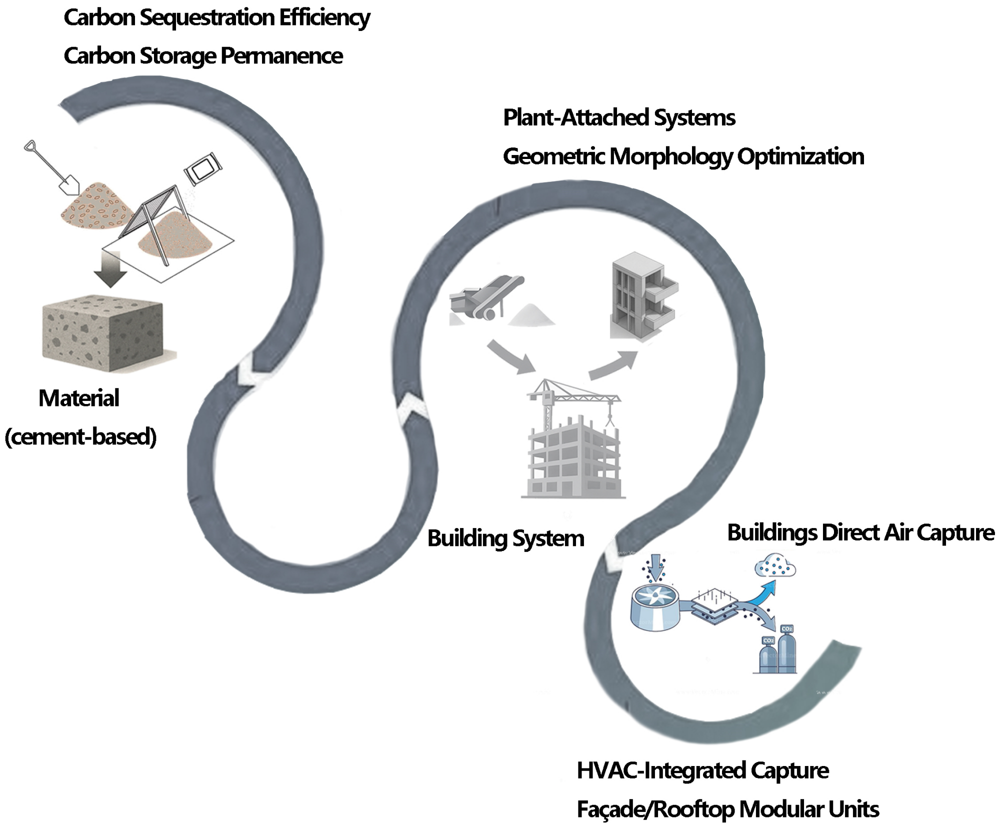

Figure 5. The Progression of Carbon Sink in Architecture.

4. Evolution of Research Hotspots in Urban Building Carbon Sinks

4.1. Carbon Sinks in Building Materials

4.1.1. Carbon Sink Mechanisms of Different Materials

Research on building-related carbon sinks indicates that the physicochemical properties of materials fundamentally determine their carbon fixation potential and mechanisms. Existing studies generally classify carbon sink materials into three categories: bio-based materials, natural mineral materials, and artificial mineral-based composite materials. Among them, concrete—the representative of the third category—has increasingly become the focus of recent research (Table 1), owing to the significant differences among materials in carbon sequestration efficiency, applicability, and sustainability.

Bio-based materials (e.g., wood, bamboo, and agricultural by-products) store carbon through photosynthetic CO_2 uptake during plant growth and thus exhibit high carbon storage density [26]. However, their long-term carbon retention is limited; biodegradation and reduced durability over extended service periods can diminish their storage stability [27]. Moreover, their sequestration potential is constrained by land availability and forestry resources, making them insufficient for large-scale urban construction needs [28].

Natural mineral materials—such as magnesium-based minerals and carbonate rocks—achieve long-term geological carbonation through mineral carbonation [29]. Despite excellent storage stability, their carbonation reactions proceed slowly under natural conditions and require thermal, mechanical, or chemical activation to improve kinetics. Limited resource availability and energy-intensive processing and transportation may offset their life-cycle carbon benefits, restricting large-scale practical application.

Although concrete production—particularly cement calcination—is a major CO_2 emission source [30], concrete can reabsorb CO_2 through natural carbonation during hardening and service life, functioning simultaneously as an emitter and a latent carbon sink. Its advantages as a carbon-sink material are threefold. First, as the most widely used construction material globally, accounting for over 70% of total building material mass [31], even its relatively low unit uptake yields substantial carbon sequestration at the urban scale [9]. Second, carbonation reactions continually convert atmospheric CO_2 into stable calcium carbonate throughout hardening and service stages, enabling in-service carbon fixation [32]. Third, its carbon sink performance can be enhanced through mineral admixtures, alkaline industrial by-products, and nano-additives, which optimize pore structure and reaction kinetics [33]. Additionally, concrete production aligns well with existing urban construction systems, unlike bio-based materials—requiring entirely new supply chains—or natural minerals, which demand new extraction and processing infrastructures.

Considering carbon storage stability, reaction controllability, scalability to urban applications, and industrial compatibility, concrete is positioned as the core material within building-sector carbon sink systems. This centrality not only explains its prominence in current research but also establishes a basis for future integration with building systems and active carbon capture strategies.

Table 1. Comparison of carbon sequestration from different building materials.

Material Type	Carbon Sink Mechanism	Advantages	Limitations	Applicability at Urban Scale
Bio-based materials (e.g., wood, bamboo, agricultural by-products)	Absorb atmospheric CO_2 through photosynthesis during plant growth and store it as biogenic carbon	High carbon storage density; renewable; strong ecological benefits	Prone to degradation; limited durability; high fire risk; constrained by land and forestry resources, making large-scale use difficult	Moderate to low
Natural mineral materials (e.g., magnesite, carbonate rocks)	Combine with CO_2 through mineral carbonation to form stable carbonate minerals	High carbon storage stability; capable of long-term sequestration	Slow natural carbonation rate; limited availability; high energy consumption in processing and transportation	Moderate
Concrete	Reacts with atmospheric CO_2 during hardening and service life, forming calcium carbonate minerals	Largest global usage; significant scale effect; stable carbon storage; carbonation rate and capacity can be enhanced through material design	Low unit carbon uptake; high emissions during production	High

4.1.2. Carbon Sink Mechanism of Concrete

As shown in Equation (1), calcium hydroxide reacts with CO_2 to form $CaCO_3$. And Equation (2) demonstrates the decalcification of C–S–H during carbonation.

Following hydration, concrete generates abundant alkaline products—primarily calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (C–S–H)—which provide the essential reactants for subsequent carbonation processes. When atmospheric CO_2 diffuses into concrete through its pore network, it reacts with these phases to form stable calcium carbonate ($CaCO_3$). The reactions are expressed as:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O, \quad (1)$$

$$C–S–H + CO_2 \rightarrow CaCO_3 + SiO_2 \cdot H_2O, \quad (2)$$

These reactions not only achieve CO_2 fixation but also generate silica gel, which fills internal pores and improves the microstructure and durability of concrete.

4.2. Building-Scale Carbon Sinks: Intrinsic and Attached Design Strategies

At the spatial and system scales, carbon sink mechanisms extend the inherent CO_2 absorption capacity of materials to architectural and environmental contexts. In contrast to single-material sinks, system-level carbon sinks emphasize how geometric configuration, surface interfaces, exposure conditions, and ecological attachments amplify carbon capture performance [5]. Through integrated architectural design and optimization of building envelopes, buildings can passively strengthen carbon uptake, facilitating a cross-scale transition from material-level to system-level sinks.

4.2.1. Carbon Sink Processes in Building Structures: Design Optimization for the Building Itself

Carbon sink processes within building structures primarily arise from the carbonation of concrete components, which exhibit distinct geometric and volumetric effects at the architectural scale. The spatial configuration and form of structural elements directly influence CO_2 exposure and, consequently, overall sequestration efficiency.

CO_2 diffuses through exposed surfaces of the building envelope and reacts with alkaline phases in concrete, forming stable $CaCO_3$ deposits (Figure 6a). Studies demonstrate that increasing exposed surface area by 20–30% can enhance carbonation rates by approximately 15–25%, substantially improving life-cycle carbon storage [34].

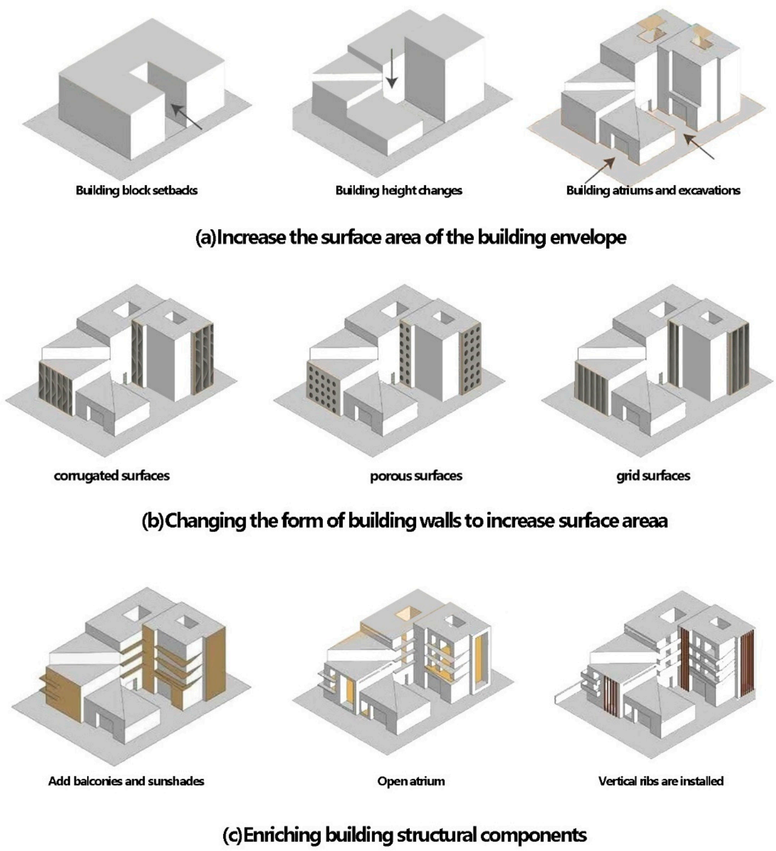

Figure 6. Common strategies to optimize the carbon sink performance of building structures: (**a**) Increasing building envelope surface area; (**b**) Modifying wall geometry to enhance carbonation efficiency; (**c**) Incorporating diverse structural elements to promote CO_2 diffusion.

Design strategies such as porous walls, gridded façades, and corrugated surfaces (Figure 6b) effectively enlarge CO_2 contact interfaces. Porous concrete walls, for example, expand reaction surfaces and introduce a three-dimensional diffusion network, enabling carbonation to penetrate deeper into structural components [35].

Exposed vertical and horizontal elements—such as columns, shading panels, and fins—also contribute significantly to surface carbonation (Figure 6c). Features like protruding ribs or fins enhance local air turbulence, accelerate CO_2 transport, and reduce moisture retention on surfaces, thereby improving carbonation conditions [36].

Carbonation exhibits pronounced spatiotemporal dynamics over a building's life cycle. In early stages, carbonation is concentrated on exposed surfaces; over time, the reaction front progresses inward. Exterior walls, balconies, and shading devices carbonize more rapidly due to elevated CO_2 exposure, whereas interior and core structural elements exhibit slower carbonation rates [37].

4.2.2. Carbon Sinks via Building Attachments: Vegetation, Moist Substrates, and Photocatalytic Interfaces

Beyond the structural body, the external surfaces and attached systems of buildings also offer considerable carbon sink potential. As the main interface between buildings and the atmosphere, the building envelope can be transformed from an inert shell into an active carbon-absorbing surface through plant-based symbiotic systems, moist porous substrate adsorption layers, and photocatalytic materials [8].

1. Vegetation-Based Attachment Systems: Leaf-Surface Carbon Uptake and the "Biological Pump" Effect

Plants are one of the most efficient natural carbon fixation mechanisms, converting atmospheric CO_2 into organic carbon via photosynthesis. "Building–plant coupled systems", such as vertical greenery, green façades, and rooftop ecosystems (Figure 7a), significantly increase carbon absorption per unit building surface area while enabling additional sequestration through rhizospheric microbial mineralization [38]. Empirical studies show that vertical greening systems can achieve 0.44–3.18 kg CO_2-eq/m^2·year of carbon uptake through biomass accumulation [39]. These systems also improve microclimate regulation, thermal comfort, and air quality, providing ecological and architectural co-benefits.

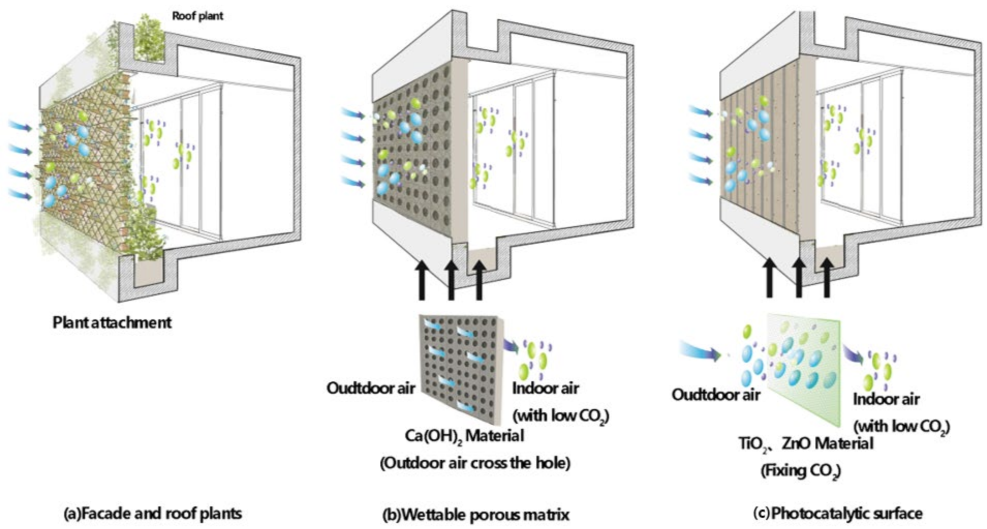

Figure 7. Three main carbon sink strategies for building attachments: (**a**) Plant-based attachment systems via photosynthetic carbon fixation; (**b**) Moist porous substrate systems for passive adsorption and mineralization; (**c**) Photocatalytic surfaces for CO_2 conversion and carbonate formation.

2. Moist Porous Substrate Systems: Passive Adsorption and Mineralization Interfaces

Moist porous substrate systems enhance the carbon sink capacity of building envelopes through combined physical adsorption and chemical mineralization (Figure 7b). Substrates containing $Ca(OH)_2$ undergo in situ carbonation, converting CO_2 into solid $CaCO_3$ for long-term storage [40]. Recent studies show that alkaline or hydroxide-loaded sponge-like materials selectively adsorb CO_2 while allowing gases such as N_2 to pass through, converting the captured CO_2 into mineral carbonates during regeneration cycles [41]. These systems are suitable for high-rise façades or non-vegetated zones, functioning as cladding layers that integrate thermal and acoustic insulation with passive carbon sequestration.

3. Photocatalytic Surfaces: Artificial "Leaf" Systems for CO_2 Conversion

Photocatalytic surfaces imitate natural photosynthesis, converting the building exterior into an artificial carbon-fixing interface (Figure 7c). Photocatalysts such as TiO_2 and ZnO use solar radiation to catalyze reactions between CO_2 and water vapor, generating carbonate deposits and other stable products. Practical applications demonstrate that TiO_2-coated façades not only fix carbon but also remove air pollutants, acting as dual-function purification surfaces [42]. These functional envelopes thus shift buildings from passive sinks to active atmospheric remediation systems, offering a promising pathway for urban carbon cycle management and net-zero architecture.

4.3. Active Carbon Capture in Buildings: From Spatial Devices to Urban Carbon-Cycle Nodes

While passive carbon-sink strategies—such as accelerated carbonation and biogenic sequestration—offer noteworthy potential, their fixation capacity and reaction rate are fundamentally limited by material chemistry, the exposed surface area of structural components, and environmental conditions such as temperature and humidity. These intrinsic constraints create a performance ceiling that prevents passive methods from achieving full life-cycle carbon neutrality or net-negative emissions. When the sequestration potential of materials alone becomes insufficient, a more proactive and controllable approach—Active Carbon Capture in Buildings—becomes necessary.

In contrast to natural carbonation, which depends on spontaneous contact between CO_2 and material surfaces, active carbon-capture systems use mechanical components to drive airflow, selectively capture CO_2, and enable controlled release or utilization. This shift transforms buildings from passive absorbers into operational carbon-management infrastructures [43,44]. Its importance lies in extending carbon management beyond embodied carbon to encompass operational emissions and avoided emissions at the urban-metabolic scale, thereby broadening the role of architecture in achieving full life-cycle carbon neutrality.

Active Carbon Capture: Principles and Building Integration

Direct Air Capture (DAC) technologies actively remove low-concentration atmospheric CO_2 ($\approx$0.04%) by drawing ambient air through systems equipped with high-selectivity sorbent or absorbent materials. Air is delivered into the capture unit via fans, ventilation shafts, or pressure differentials, where CO_2 molecules are bound while other gases pass through. The captured CO_2 is subsequently released through heating, pressure reduction, or electrochemical regeneration for reuse or storage [45]. DAC mechanisms fall into two broad categories. As shown in Equation (3), Liquid absorption commonly uses strong alkaline solutions (e.g., NaOH, KOH) to react with CO_2, forming carbonates or bicarbonates:

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O \quad (3)$$

This method offers fast kinetics and high absorption capacity, suitable for centralized DAC facilities. Equations (4) and (5) demonstrate that solid adsorption employs amine-functionalized porous materials, metal–organic frameworks (MOFs), or alkaline oxides to reversibly bind CO_2:

$$R\text{–}NH_2 + CO_2 \rightarrow R\text{–}NH\text{–}COOH \quad (4)$$

$$MgO + CO_2 \rightarrow MgCO_3 \quad (5)$$

Unlike passive carbonation, these sorbents can be regenerated via thermal or pressure-swing processes and reused for hundreds of cycles, improving efficiency and reducing costs [46]. Integrating DAC systems into buildings extends architectural functionality, transforming structures into active nodes of the urban carbon cycle. Several design pathways enable this integration. One approach embeds DAC modules into natural or mechanical ventilation systems so that incoming air passes through capture units before entering indoor spaces (Figure 8). This method achieves CO_2 removal while maintaining the building's external appearance and is especially suitable for large public and commercial buildings with continuous air flows [46].

Another strategy installs modular DAC units on façades, rooftops, or curtain walls, enabling buildings to operate as "carbon-capture towers" that continuously extract CO_2 from surrounding air (Figure 9). This "skin-based" approach views the building envelope as an active air-management interface rather than relying solely on material porosity or reactivity [47]. A representative real-world example is the Climeworks facility in Iceland, where modular collectors capture CO_2 directly from air and store it underground through mineralization, illustrating the feasibility of decentralized building-integrated capture systems.

Despite their promise, building-integrated DAC systems face several challenges (Table 2). First, DAC remains energy-intensive and costly, with current capture costs reaching several hundred U.S. dollars per ton of CO_2 [48]. The process requires continuous high-temperature heat and electricity, placing significant burdens on building energy systems. Moreover, these energy needs are highly dependent on the carbon intensity of the energy supply, with systems powered by fossil fuels failing to deliver net-negative emissions. Only DAC systems using renewable or low-carbon energy sources can truly achieve net-negative emissions, while fossil-based energy inputs may diminish or even reverse the CO_2 capture benefits [49].

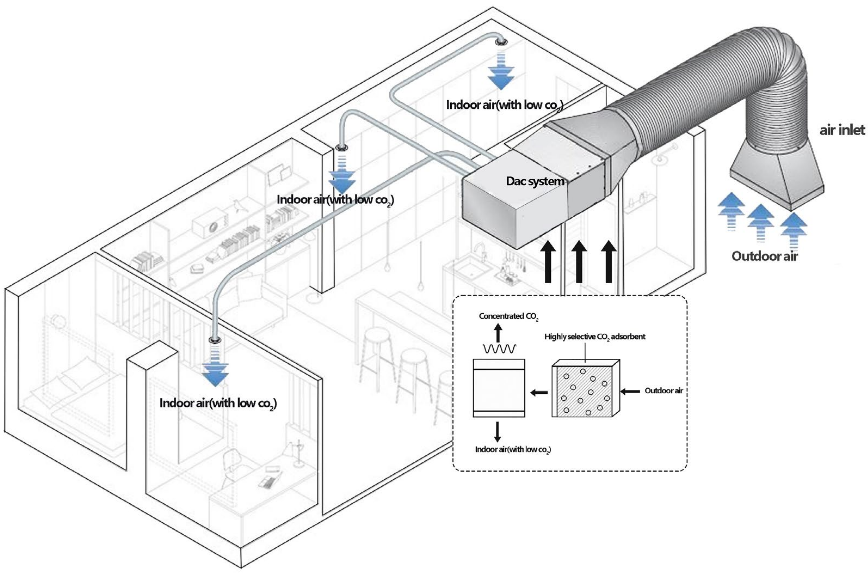

Figure 8. HVAC-integrated carbon-capture system within building ventilation networks.

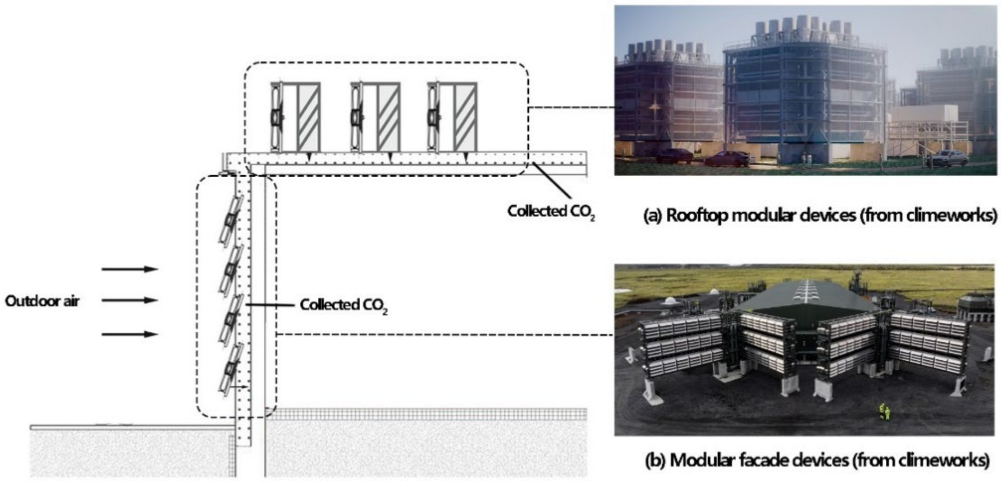

Figure 9. Façade and Rooftop Modular Systems.

Second, the integration of DAC modules into HVAC systems requires considerable spatial allocation and increases building energy consumption by 10–15%, alongside higher maintenance demands [50]. This highlights the feasibility concerns, as widespread adoption may not be viable without substantial infrastructural adjustments and energy efficiency improvements. Additionally, long-term operational costs remain uncertain, with capital investment still high for the initial installation, though advances in system optimization and the integration of renewable energy sources could help bring costs down to USD 200–400 per ton of CO_2 by 2030 [43].

Third, effective carbon removal requires secure transport, storage, or utilization pathways—capacities that most buildings currently lack [51]. The infrastructure for safely and reliably transporting and storing the captured CO_2 is often unavailable, making the integration of DAC systems into urban environments more complex and less feasible in some cases. Furthermore, MRV (Measurement, Reporting, and Verification) methodologies for DAC remain subject to significant uncertainties. Accurately measuring CO_2 removal, accounting for potential leakage, and validating the carbon captured under varying environmental conditions remain challenges. Robust and standardized MRV protocols are critical for ensuring that DAC systems deliver their claimed carbon sequestration potential.

Table 2. Comparison of Passive and Active Carbon Capture Strategies.

Comparison Metric	Passive Carbon Sink Strategies	Active Carbon Capture (DAC) Strategies
Cost	Low cost, primarily driven by materials (e.g., concrete, vegetation) and maintenance over the life cycle	High initial investment (USD 600–900/t CO_2/yr), but higher capture efficiency
Capture Rate	Low capture rate, typically 5–15 kg $CO_2/m^3 \cdot yr$ (e.g., concrete)	High capture rate, typically 50–80 kg $CO_2/m^2 \cdot yr$ (e.g., amine-based DAC systems)
Life-cycle Storage	Long-term storage (decades to centuries), but influenced by environmental changes	High short-term capture efficiency, but requires efficient storage, transport, and utilization systems
Practical Constraints	Limited by building design, material availability, climate impacts, and construction complexity	High energy consumption and operational costs, reliance on stable low-carbon energy, MRV uncertainties
Applicability	Widely applicable to large-scale infrastructure (e.g., urban buildings, green infrastructure)	Suitable for specific high-efficiency areas, such as building facades and industrial zones

Table 2. *Cont.*

Comparison Metric	Passive Carbon Sink Strategies	Active Carbon Capture (DAC) Strategies
Energy Demand	No additional energy requirements, mainly influenced by natural environment and building design	High energy demand, reliant on renewable energy to ensure net-negative emissions
Technology Maturity	Mature technology, widely applied in architectural design and urban greening	Still under development and demonstration, facing challenges with integration and scalability
Long-term Feasibility	Strong sustainability, relying on natural processes (e.g., plant photosynthesis, carbonation)	Requires optimization of energy consumption, cost reduction, and MRV system improvement for widespread deployment

Despite these challenges, DAC integration expands architectural carbon-sink strategies beyond material optimization or vegetative absorption. It redefines buildings as environmentally responsive infrastructures that interact dynamically with energy systems, urban carbon networks, and industrial carbon cycles. However, its success hinges on overcoming these technical and economic hurdles, along with improving the transparency and reliability of MRV systems. Ultimately, while active carbon capture represents a technological breakthrough, it also necessitates a paradigm shift in architecture and urban planning, positioning buildings not just as passive consumers of energy but as active participants in climate governance and carbon-neutral urban development [52].

5. Measurement Framework of Urban Building Carbon Sinks

Research on building carbon sinks depends not only on advances in materials, systems, and technologies, but also on rigorous, systematic, and comparable measurement methods that form the basis for scientific evaluation and design optimization. From microscopic material reactions to macroscopic building systems and active carbon-capture devices, carbon fixation, adsorption, and transformation involve multi-level and multi-scale processes [7]. This chapter reviews existing measurement approaches across three levels—materials, architectural systems, and active capture devices—to clarify their applicability, strengths, and limitations (Table 3).

Table 3. Summary and Comparison of Carbon Capture Methods.

Method Type	Key Methods	Advantages	Challenges
Material-level	TGA, XRD, FTIR, Chemical Titration	High precision, suitable for lab-scale studies	Does not capture environmental effects
System-level	Phenolphthalein, Gas Exchange, Sensors	Real-world performance, applicable at building scale	Environmental interference, high cost
Active Carbon Capture (DAC)	Mass Balance, Breakthrough Curve, NDIR Gas	High efficiency, direct CO_2 removal	High energy demand, complex integration

5.1. Carbon Measurement Methods at the Material Level

At the material scale, the primary goal is to characterize the microscopic mechanisms, reaction kinetics, and storage potential of carbon fixation [9] (Table 4). Methods derived from materials science and physical chemistry are used to evaluate how composition, porosity, alkalinity, and additives influence carbonation performance [30].

Table 4. Principal Methods for Material-Level Carbon Measurement.

Method	Technical Principle	Applicable Object	Advantages	Limitations
Thermogravimetric Analysis (TGA)	Measures sample mass change with temperature/time; calculates CO_2 fixation from carbonate decomposition loss	Concrete powder, mineral admixtures	High precision; quantitative; allows kinetic analysis	Destructive; requires sample grinding
X-ray Diffraction (XRD)	Identifies crystalline phases (e.g., $CaCO_3$, $MgCO_3$) via diffraction patterns	Carbonated concrete, mineral-sequestration materials	Strong phase identification; semi-quantitative	Insensitive to amorphous phases; costly instrumentation
Fourier Transform Infrared Spectroscopy (FTIR)	Detects characteristic C=O vibration bands in $CO_3{}^{2-}$ groups to determine bonding states	Cement hydrates, alkali-activated materials	High sensitivity; simple preparation	Low quantitative precision; requires calibration curves
Chemical Titration	Quantifies carbonate via acid-base neutralization or precipitation	Cement paste, industrial residues	Low-cost, simple, fast screening	Interference from impurities; subjective endpoint

As shown in Equation (6), TGA is a benchmark technique for quantifying carbonate content. Under controlled heating, the decomposition of $CaCO_3$,

$$CaCO_3 \rightarrow CaO + CO_2\uparrow \tag{6}$$

produces a characteristic mass loss corresponding to fixed CO_2. Zhan et al. measured CO_2-cured recycled aggregates using TGA and reported a fixation rate of up to 4.5 wt%, equivalent to ~45 kg CO_2 per ton of aggregate [53]. Although highly accurate and reproducible, TGA is destructive and cannot capture macrostructural effects.

XRD identifies crystalline phases through diffraction patterns, with each $CaCO_3$ polymorph exhibiting distinct peaks. Rostami et al. [52] found substantially increased calcite peaks in CO_2-cured concrete compared with steam-cured samples. Quantitative refinement indicated 12.8 wt% calcite in CO_2-cured concrete versus 3.6 wt% in steam-cured specimens, equivalent to ~90 kg CO_2/m^3 additionally sequestered. XRD is authoritative for crystalline phase identification but limited for amorphous carbonation products.

FTIR characterizes chemical bonds through infrared absorption. Carbonate ions show characteristic peaks at 710 cm^{-1}, 875 cm^{-1}, and 1420–1480 cm^{-1}. Ashraf and Olek observed that peaks at 875 and 1450 cm^{-1} increased with carbonation duration, with normalized areas rising from 0.05 to 0.35, corresponding to 0.12 g CO_2 per g $Ca(OH)_2$ fixed [54]. FTIR is rapid and effective for qualitative analysis and process monitoring but less precise quantitatively.

Chemical titration quantifies carbonate content through acid–base neutralization. Steinour established the theoretical basis linking titration results to the stoichiometry of calcium phases and CO_2 reactions [55]. Although inexpensive and suitable for bulk screening, titration offers lower accuracy compared with instrumental methods.

In material-level carbon assessments, multiple techniques are often combined to obtain robust results. Global studies show that while cement production emitted ~381 Gt CO_2 from 1930 to 2013, cement carbonation reabsorbed ~165 Gt CO_2, demonstrating concrete's substantial yet underrecognized role as a global carbon sink [52].

5.2. Carbon Measurement at the Building-System Level

At the system scale, carbon measurement focuses on macro-level carbon balance, accounting for carbonation depth, vegetation uptake, and surface adsorption within architectural environments [5] (Table 5). These methods rely heavily on in situ monitoring, sensor networks, and field observations to reveal how geometry, exposure conditions, and climate influence overall sequestration potential [56].

Table 5. Principal Methods for Building-System -Level Carbon Measurement.

Method	Technical Principle	Applicable Object	Advantages	Limitations
Phenolphthalein Indicator	Detects carbonation depth via color change (pink → colorless below pH 10.2)	Concrete walls, beams, columns	Fast, low-cost, intuitive	Semi-quantitative; destructive; humidity-sensitive
Gas Exchange Chamber	Monitors CO_2 concentration change inside a sealed chamber over time	Green façades, carbonated surfaces	Direct CO_2 flux; real-environment data	Microenvironment disturbance; small sampling area
Embedded Sensors	Measures pH/CO_2 inside concrete over time via micro-sensors	Infrastructure, long-term monitoring	In situ, continuous, non-destructive	High cost; limited sensor lifespan
Model Estimation	Uses building or urban-scale models to estimate total sequestration	Single buildings or cities	Integrates multiple factors; macro insights	Dependent on assumptions; uncertainty high
Remote Sensing	Uses LiDAR or hyperspectral imaging to infer biomass/carbon stock	Green roofs, urban forests	Wide coverage, repeatable, scalable	Indirect; requires ground validation

The phenolphthalein indicator remains widely used on construction sites to visualize carbonation depth via pH-induced color change. Villain et al. demonstrated strong agreement between phenolphthalein and TGA results, though humidity variations may cause deviations of up to 20% [57].

Gas exchange chambers provide direct measurement of CO_2 flux across building surfaces. Teemusk and Mander (2019) applied this method to green roofs in Estonia, observing consistent daytime CO_2 uptake and slight emissions during drought or nighttime periods [58]. The technique offers realistic environmental data and bridges laboratory and field evaluations.

Embedded sensors enable long-term monitoring by measuring pH or CO_2 within concrete. Figueira's fiber-optic pH system captured carbonation-front movement in real time and revealed the influence of environmental fluctuations on carbonation rates [59], providing valuable input for digital carbon management and service-life prediction.

Model-based estimation integrates material carbonation, vegetation absorption, and building parameters into life-cycle assessments. Fick's second-law-based models have shown high predictive accuracy; for example, an analysis of 72,860 buildings in Zhengzhou (203 km^2) estimated total sequestration at 1.65 Mt CO_2 [60].

Remote sensing methods estimate biomass and carbon stocks using LiDAR or multispectral imagery. Nowak et al. achieved >85% accuracy in urban vegetation assessments [61], and in Shenyang (45,500 ha), remote sensing indicated 1.70 Mt CO_2 sequestered—equivalent to 4.39% of annual fossil-fuel emissions [62].

At the system level, carbon measurement expands from material-scale testing to whole-building analysis, requiring integration of geometry, environmental exposure, and ecological elements [57–59]. Nevertheless, many current evaluations remain model-dependent and thus retain considerable uncertainty.

5.3. Measurement Methods for Building-Integrated Active Carbon Capture

Unlike passive mechanisms, active carbon capture (DAC) uses mechanically driven physical or chemical processes to extract CO_2 directly from ambient air [7,45] (Table 6). Accordingly, performance evaluation focuses on capture efficiency, energy consumption, adsorption capacity, operational stability, and system-level carbon balance [9].

Table 6. Principal Methods for Evaluating Active Carbon-Capture Performance.

Method	Technical Principle	Applicable Object	Advantages	Limitations
Mass Balance	Calculates total captured CO_2 via inlet–outlet concentration difference and airflow rate	Building-integrated DAC units	Simple, real-time, system-level assessment	Requires airtight operation
Breakthrough Curve	Tracks outlet CO_2 concentration vs. time in adsorption beds (S-shaped curve)	Sorbent testing, adsorption modules	High precision; kinetic parameters	Lab-scale; not for large systems
NDIR Gas Analysis	Measures CO_2 via IR absorption at 4.26 μm	All CO_2-monitoring processes	High accuracy; fast response; compact	High cost; periodic calibration

Mass balance calculations, grounded in mass conservation, quantify captured CO_2 using differences between inlet and outlet concentrations. Wurzbacher et al. applied this method to a temperature–vacuum swing DAC system and recorded ~1 mmol CO_2 per g sorbent per cycle under ambient conditions [63], enabling real-time operational assessment.

The breakthrough curve method, a fundamental sorbent-evaluation technique, plots outlet concentration against time as CO_2 flows through a fixed-bed reactor. Sinha et al. reported that mmen–Mg_2(dobpdc) achieved more than double the dynamic adsorption capacity of MIL-101(Cr)-PEI-800 at 400 ppm CO_2, demonstrating superior sorbent performance [64]. This approach is essential for sorbent screening and kinetic modeling.

Non-dispersive infrared (NDIR) gas analysis detects CO_2 via its characteristic absorption at 4.26 μm. Chen et al. evaluated commercial NDIR devices and found accuracy within ±1.5% FS and response times below 30 s, meeting the monitoring requirements of building-integrated DAC systems [65]. Owing to their precision and stability, NDIR sensors are indispensable for performance evaluation and process control.

Building-integrated DAC systems exhibit exceptionally high carbon-removal efficiency. Studies indicate that amine-based systems can capture 50–80 kg CO_2 $m^{-2}\cdot yr^{-1}$, validated through multiple demonstration projects [66], whereas conventional concrete carbonation captures only 5–15 kg CO_2 m^{-3} yr^{-1} under standard conditions [9]. Economically, current capital costs for building-integrated DAC range from USD 600–900 per t CO_2 per yr capacity, with operating costs of USD 150–300 per t CO_2 [4]. Although initial investment remains high, DAC efficiency—30–50 times greater than passive pathways—provides significant long-term environmental benefits. With continued optimization and greater use of renewable energy, total costs are projected to decline to USD 200–400 per t CO_2 by 2030 [44].

6. Life-Cycle Optimization Design of Urban Building Carbon Sinks

6.1. Material Production Phase: Feedstock Selection and Mix Design

The starting point of a building's carbon-sink capacity lies in material production. At this stage, feedstock choices, microstructural tuning, and additives jointly optimize the system—controlling initial emissions while laying the groundwork for subsequent carbon fixation.

Partial clinker substitution with industrial by-products (e.g., steel slag, fly ash, ground granulated blast-furnace slag) can markedly reduce calcination emissions and strengthen later-age carbonation via latent hydraulic/pozzolanic activity. Under accelerated carbonation, replacing 35% cement with steel slag has been shown to absorb up to 15 wt% CO_2 (equivalent to 15 g CO_2 per 100 g of material) while improving later strength [67].

Moderate porosity promotes CO_2 ingress and carbonation depth, excessive porosity, however, compromises mechanics. A hybrid pore system—coordinating micro- (μm) and meso-/nano-pores—balances uptake and strength. mesopores of 5–50 nm as dominant CO_2 transport channels, with mesopore volume fraction directly linked to carbonation rate [68]. For reference, 5–50 nm is the size range of many viruses or fine smoke particles—small enough for CO_2 molecules to move easily through these pores.

Incorporating reactive MgO or Ca–Mg oxides boost carbonation kinetics and storage via mineral carbonation, forming stable carbonates and prolonging sequestration lifetimes. Reviews report that mixing 10–50% reactive MgO (RMC) can increase CO_2 uptake by 20–35% within 7–56 days, with 28-day carbonation degrees ranging from ~4% to 46% depending on mixture and curing conditions [69]. This means the material can absorb CO_2 equal to about one-fifth to one-third of its own weight in just a few weeks.

6.2. Design and Construction Phase: Spatial Geometry and Structural Strategies

Whether material-level potential scales up to spatial-level performance depends on form, structural system, massing, and construction methods, which together govern contact area, diffusion pathways, and reaction efficiency.

Carbonation is an interface-controlled process; larger surface-to-volume (S/V) ratios accelerate uptake. Industry practice indicates that doubling S/V can raise unit-volume CO_2 uptake rate by ~60–120%, especially in thin plates, grids, and perforated morphologies with high exposure [70].

Long-span grids, double shells, and porous partitions both reduce concrete volume and lengthen airflow paths, thereby expanding exposed area and promoting diffusion/mineralization. Quantitatively, prefabricated elements can reach unit-area uptake of ~20 $g \cdot m^{-2} \cdot y^{-½}$; Twenty grams is roughly the weight of a small spoonful of sugar. with geometric optimization, unit-volume uptake increases by ~30–50% over conventional members [71].

Factory prefabrication plus controlled carbonation converts high-S/V designs into measurable sink capacity. Reports indicate ~35% CO_2 fixation in precast production with simultaneous early-strength gains [72]. This means each 1 kg element can bind about 0.35 kg of CO_2, roughly the weight of a typical 500-mL water bottle. Further, ~20% pre-drying (moisture loss) followed by ~16 h accelerated carbonation markedly elevates uptake and strength development [73]. 16 h is about half a day, showing that substantial CO_2 storage can occur in a very short period.

Bottom line: design–construction optimization is a systems-level spatial engineering task that amplifies material-scale sinks into durable building-scale performance.

6.3. Operations Phase: Dynamic Cycling and Replaceability

The operations and maintenance phase is the longest and central to the dynamic evolution of sink performance. Unlike earlier static fixation, O&M strategies emphasize continuous uptake, replaceable components, and iterative upgrades.

Circular-economy frameworks enable reversible envelopes (e.g., façade panels removable after ~20 years) for factory re-carbonation, extending sink functionality via repeated cycles [74]. A 20-year cycle aligns with common façade renovation intervals, meaning re-carbonation can occur without additional maintenance burden.

Prefabricated add-on layers (vegetation, photocatalytic coatings, CO_2-sorptive membranes) can be seasonally or climatically tuned. TiO_2-coated façades have been reported to reduce ambient CO_2 by ~5–10% over one year while delivering co-benefits in air quality [75]. This is equivalent to lowering the CO_2 concentration of a typical room by about one-twentieth to one-tenth, which is significant at an urban scale.

Integrating DAC modules with HVAC allows indoor CO_2 capture and transfer to exterior adsorption/mineralization units. Energy–carbon analysis suggests that, despite ~10–15% additional energy use, a single office building can achieve net-negative annual emissions under appropriate operating regimes and clean power supply [76]. This is roughly comparable to the additional energy used during a peak summer month of air-conditioning.

6.4. End-of-Life: Demolition and Regeneration to Extend the Carbon Cycle

The end of service does not end sequestration. Appropriate deconstruction and valorization strategies prolong storage and supply feedstock for the next material cycle.

Crushed debris exhibits vastly increased specific surface area, yielding faster, deeper carbonation than intact members. Under flue-gas–like conditions, recycled aggregates carbonate ~5–8× faster than natural aggregates [77].

Re-introducing crushed carbonated concrete or carbonate fines into new mixes—e.g., using carbonated recycled powder as hydrate nucleants—accelerates hydration and raises early-age carbonation uptake by ~12% [78]. This means that for every 100 g of CO_2 fixed, an extra 12 g is stored, about the weight of a small coin (≈8–10 g).

LCA-guided pathways. Life-cycle assessment differentiates end-of-life options; compared with landfilling, carbonation treatment of recycled aggregates can deliver >50% emission reductions [79]—a decision-grade basis for demolition planning. equivalent to avoiding the CO_2 emissions generated by driving a gasoline car for roughly 4000–5000 km.

7. Outlook and Challenges

7.1. Public Awareness and Societal Alignment

Scaling architectural carbon sinks are as much a societal shift as a technological one. The "active carbon uptake" role of buildings remains poorly recognized by users, developers, and policymakers, limiting value capture [8]. Educational programs, policy incentives, and market mechanisms are needed to forge consensus and accelerate deployment.

7.2. Toward Multi-Pathway Synergy and Integration

Future progress requires integrated, multi-pathway systems beyond single-technology optimization [80]. Coupling passive carbonation with active capture can close the loop across materials–structures–devices. For example, DAC-captured CO_2 can feed accelerated carbonation of precast elements, achieving capture–utilization–re-sequestration cycles [81]. Combining PV, photocatalysis, and vegetative systems enables multifunctional skins delivering power generation, carbon uptake, and shading [81]—an energy–carbon–form co-design paradigm.

7.3. Robust Measurement and Standardized MRV

A lack of standardized measurement, reporting, and verification (MRV) is a key bottleneck. Lab rates rarely map directly to component/building scales, and urban models often lack ground-truthing, yielding divergent results [82].

Future work should establish digital-twin platforms with IoT sensing for real-time sequestration monitoring and multi-source data fusion to calibrate models across scales [83]. Joint standards from academia, industry, and government are essential to give architectural carbon sinks policy recognition and market tradability.

7.4. Study Limitations and Future Directions

This study primarily centers on the building body, with limited scope on cross-domain couplings (energy, waste, climate systems). Future research should strengthen links with urban energy networks, waste-heat recovery, and solid-waste circularity [84]. As sources are predominantly English-language, regional/non-English work may be underrepresented; expanding coverage and integrating empirical datasets will enrich the knowledge graph. Finally, deeper integration of LCA with energy–carbon coupled models is needed to support the transition from low-carbon to net-negative buildings and to maximize life-cycle sequestration.

8. Conclusions

Drawing on a statistical analysis and systematic review of the 2007–2025 literature, this paper elucidates research characteristics and trends in building carbon sinks, summarizing global hotspots, methodologies, and challenges. The main conclusions are:

1. Rapid growth with cross-disciplinary convergence. The field has accelerated since 2020, with leading contributions from China, the United States, and Nordic countries. Building carbon sink research now spans materials science, environmental engineering, building technology, and ecology, forming a robust interdisciplinary landscape.
2. Thematic evolution mirrors rising technical maturity. Research has progressed from material-level carbonation mechanisms to building-system passive sinks, and now to active capture integration—broadening from single-material performance to spatial design and system optimization driven by carbon-neutrality goals.
3. Multi-scale measurement remains challenging. Material-level methods (e.g., TGA, XRD) and system-level field techniques (e.g., phenolphthalein, static chambers) coexist with mass-balance approaches for active capture. Yet a cross-scale standardized MRV framework is still lacking, limiting comparability and synthesis.
4. Life-cycle optimization is the key lever. Enhancing sink capacity requires systemic strategies spanning material production (optimized mixes, industrial by-products), design & construction (geometry to increase exposure), operations (ecological attachments and DAC coupling), and end-of-life (reuse and re-carbonation of wastes);
5. Future direction: active integration and urban-scale benefits. With maturing DAC and related technologies, buildings can become active infrastructures for urban carbon regulation. Improved LCA practice will underpin optimized design toward net-zero/negative outcomes.

Building carbon sinks are evolving toward more systemic and integrated paradigms that are central to climate action and sustainable urbanism. As attention shifts from mere emission reduction to enhanced carbon uptake, the technologies and applications discussed here are poised for broader impact and deployment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15244445/s1, The PRISMA Checklist for this systematic review is provided as Supplementary Material.

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