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Distributed carbon capture in urban environments: Emerging architectures for building-integrated CO_2 Removal

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Abstract

Urban environments, responsible for ~40% of global CO_2 emissions, demand innovative carbon capture, utilization, and storage (CCUS) solutions to achieve net-zero targets. Distributed carbon capture, integrating CO_2 removal into urban infrastructure, offers a scalable alternative to centralized systems, leveraging buildings as capture hubs. This review explores emerging architectures for building-integrated CO_2 removal in urban settings, focusing on modular direct air capture (DAC) units, CO_2-absorbing materials, HVAC-integrated systems, and hybrid urban-green infrastructures. Modular DAC units enable retrofitting, capturing CO_2 via sorbents like metal-organic frameworks, while carbon-absorbing concrete and algae-based facades provide passive sequestration. HVAC systems utilize existing airflow for efficient capture, and hybrid systems combine with urban forests for synergistic benefits. The paper synthesizes recent advancements, evaluating technical feasibility, energy demands, and economic viability. Case studies, including Climeworks' Zurich DAC (900 tons CO_2/year) and Hamburg's BIQ House algae facades, illustrate practical applications but highlight scalability limits. Environmental co-benefits, such as improved air quality, and social impacts, including public perception, are assessed. Challenges, ranging from high energy costs, urban policy gaps, to CO2 storage constraints persist, necessitating material innovations and regulatory incentives. This review underscores distributed CCUS's potential to decarbonize cities, proposing a roadmap for scaling through interdisciplinary collaboration. By addressing technical and societal barriers, building-integrated CO_2 removal can redefine urban climate strategies, aligning with global sustainability goals.

Keywords: Integrated Carbon Capture; Distributed Carbon Capture; Direct Air Capture (DAC); Urban Decarbonization; CO_2-Absorbing Materials; HVAC-Integrated CO_2 Removal; Algae-Based Facades; Net-Zero Cities

1. Introduction

The escalating concentration of atmospheric carbon dioxide (CO_2), driven by anthropogenic activities, poses a critical threat to global climate stability, necessitating urgent mitigation strategies. As of 2023, global CO_2 emissions reached approximately 37.4 billion tons annually, with projections indicating further increases without aggressive intervention [1]. Carbon capture, utilization, and storage (CCUS) has emerged as a pivotal technology to curb emissions, complementing renewable energy and efficiency measures. Traditional CCUS systems, primarily deployed in industrial

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settings like power plants, capture CO_2 at point sources for storage or utilization. However, these centralized approaches often require extensive infrastructure and are less adaptable to diverse emission sources, limiting their applicability in densely populated areas where innovative solutions are most needed [1-3].

Urban environments, accounting for nearly 70% of global CO_2 emissions, present unique challenges and opportunities for climate mitigation. Cities, characterized by high emission densities from transportation, buildings, and industrial activities, face spatial constraints that hinder the deployment of large-scale CCUS facilities [4]. Moreover, urban energy demands and infrastructure complexity exacerbate the difficulty of integrating conventional capture technologies. For instance, buildings alone contribute approximately 40% of urban emissions, underscoring the need for solutions tailored to urban landscapes [5]. The concentration of emissions in cities, coupled with limited land availability, demands decentralized approaches that can seamlessly integrate with existing infrastructure to achieve meaningful CO_2 reductions [4-6].

Distributed carbon capture offers a promising alternative to centralized CCUS by deploying smaller-scale, localized systems across urban areas [2]. Unlike industrial-scale capture, which targets high-concentration CO_2 streams, distributed systems focus on diffuse sources, including ambient air and building emissions. This approach enhances flexibility, reduces the need for extensive CO_2 transport networks, and aligns with urban spatial constraints [7]. Recent advancements in direct air capture (DAC) and adsorption-based technologies have enabled the development of compact capture units suitable for urban deployment. By dispersing capture systems across multiple sites, distributed CCUS can address emissions at their source, potentially transforming cities into active participants in global decarbonization efforts [6,8].

A particularly innovative subset of distributed CCUS involves building-integrated CO_2 removal, where capture technologies are embedded within urban infrastructure, such as building facades, HVAC systems, or construction materials [9]. This approach leverages buildings as platforms for CO_2 capture, utilizing their surfaces, airflow, or structural components to sequester carbon. For example, CO_2-absorbing concrete incorporates carbonation processes to store CO_2 permanently, while algae-based facades use photosynthesis to capture emissions. HVAC-integrated systems exploit existing ventilation networks to capture CO_2 from indoor or outdoor air, offering retrofitting potential. Building-integrated systems not only address emissions but also enhance urban aesthetics and functionality, aligning with sustainable city planning [10].

The novelty of building-integrated CO_2 removal lies in its ability to reframe urban infrastructure as a climate solution, shifting CCUS from industrial to societal applications. While industrial CCUS targets large emitters, urban systems address diffuse sources, offering scalability through widespread adoption [11]. However, challenges such as energy efficiency, cost, and integration with urban planning remain underexplored, necessitating a comprehensive review of emerging technologies and their feasibility [11]. This paper fills this gap by synthesizing recent advancements in distributed CCUS, with a focus on building-integrated architectures, and evaluating their potential to decarbonize urban environments.

The objective of this review is to critically assess emerging architectures for building-integrated CO_2 removal in urban settings, including modular DAC units, CO_2-absorbing materials, HVAC-integrated systems, and hybrid urban-green infrastructures. By analyzing technical feasibility, economic viability, and case studies, the paper aims to elucidate the role of distributed CCUS in urban climate strategies. It also explores environmental and social impacts, identifying co-benefits like improved air quality and challenges such as public acceptance. The review is structured as follows: Section 2 provides a literature review of CCUS and urban challenges; Section 3 details emerging architectures; Section 4 presents case studies; Section 5 evaluates feasibility; Section 6 discusses impacts; Section 7 outlines challenges and future directions; and Section 8 concludes with recommendations for scaling urban CCUS.

2. Background and Literature Review

2.1. CCUS Overview

Carbon capture, utilization, and storage (CCUS) is a suite of technologies aimed at mitigating climate change by capturing carbon dioxide (CO_2) from industrial processes or the atmosphere, either storing it underground or repurposing it into valuable products. According to Greig et al. [12], CCUS is indispensable for achieving net-zero emissions, particularly in sectors like cement, steel, and power generation, where decarbonization is challenging. Post-combustion capture, which employs chemical solvents like amines to extract CO_2 from flue gases, dominates industrial applications due to its compatibility with existing infrastructure. Findings from Raganati & Ammendola [13] indicate that post-combustion systems achieve capture efficiencies of 85–90%, but their energy penalty, often 20–30% of plant output, limits cost-effectiveness. Pre-combustion capture, involving fuel gasification to isolate CO_2, and oxy-fuel combustion, which produces a CO_2-rich exhaust, offer alternatives but require significant capital investment [14]. Direct air capture (DAC), an emerging technology, removes CO_2 from ambient air using solid sorbents or liquid absorbents. According to McQueen et al. [15], DAC systems, while versatile, face high costs and energy demands, hindering large-scale deployment. Centralized CCUS systems, designed for point sources, rely on extensive infrastructure, making them less adaptable to urban environments where spatial constraints and diffuse emissions predominate. Recent advancements in material science and energy efficiency are shifting focus toward decentralized solutions, setting the stage for urban applications.

2.2. Urban Emission Challenges

Urban areas are critical battlegrounds for climate mitigation, contributing approximately 70% of global CO_2 emissions due to concentrated activities in transportation, industry, and buildings. According to Ürge-Vorsatz et al. [16], buildings account for nearly 40% of urban emissions, driven by heating, cooling, and electricity use. Cities face unique barriers to CCUS adoption, including limited land for large capture facilities and high energy demands that complicate integration. Findings from Iwuanyanwu et al. [17] highlight that urban sprawl, aging infrastructure, and dense populations exacerbate these challenges, as retrofitting conventional capture systems is often impractical. Moreover, urban air quality issues, exacerbated by co-pollutants like particulate matter, necessitate technologies that address multiple environmental concerns. According to Chen et al. [18], urban emission inventories reveal significant variability, with some cities emitting up to 100 tons of CO_2 per capita annually, underscoring the need for localized solutions. The compact nature of urban landscapes demands innovative, space-efficient CCUS approaches that can integrate with existing infrastructure, such as buildings and public spaces, to achieve meaningful reductions without disrupting city functions.

2.3. Distributed CCUS

Distributed CCUS involves deploying small-scale, localized capture systems across urban areas, contrasting with centralized facilities that target large point sources. According to Lackner and Guelpa [19], distributed systems are ideal for cities, as they can capture CO_2 from diffuse sources, including ambient air and building emissions, without requiring extensive pipeline networks. Direct air capture technologies, using amine-based sorbents or metal-organic frameworks (MOFs), are central to this approach, offering modularity and adaptability. Findings from Chowdhury et al. [7] suggest that DAC costs could decline to below \$200 per ton of CO_2 by 2030 with advancements in sorbent efficiency and renewable energy integration. Adsorption-based systems, which cycle between CO_2 capture and release using temperature or pressure swings, show promise for urban deployment. According to Li and Yao [20], temperature-vacuum swing adsorption in DAC units achieves capture efficiencies of 80–90%, but energy demands remain a hurdle. Challenges include limited urban-scale pilots and high operational costs, particularly in energy-constrained cities. Research by McQueen et al. [15] emphasizes that distributed CCUS could reduce urban emissions by 5–10% if integrated with renewable energy and urban planning, highlighting its transformative potential. The flexibility of distributed systems positions them as a cornerstone for urban decarbonization strategies.

2.4. Building-Integrated Systems

Building-integrated CO_2 removal embeds capture technologies within urban infrastructure, such as building facades, HVAC systems, or construction materials, to address emissions at their source [21,22]. This technology, tested in pilot projects, offers permanent sequestration but faces scalability challenges due to production costs [22]. Algae-based facades, which capture CO_2 via photosynthesis, have been implemented in structures like Hamburg's BIQ House [23]. Findings from Mahmood et al. [24] indicate that algae systems not only reduce CO_2 but also produce biomass for biofuels, though maintenance and energy inputs limit adoption. HVAC-integrated systems, using sorbents or membranes, leverage buildings' airflow to capture CO_2 efficiently. According to Rossi et al. [25], membrane-based HVAC systems achieve capture rates of 0.5–1 kg CO_2 per hour in high-traffic buildings, but retrofitting costs and energy penalties remain barriers. Research by Cao et al. [26] highlights that life-cycle assessments of building-integrated systems reveal trade-offs between capture capacity and material durability, necessitating material innovations. Gaps persist in scaling these technologies, optimizing energy use, and integrating them with urban policy frameworks, underscoring the need for interdisciplinary research to advance urban CCUS.

3. Emerging Architectures for Building-Integrated CO_2 Removal

This section explores the innovative architectures driving building-integrated CO_2 removal, a cornerstone of distributed carbon capture in urban environments. By embedding capture technologies within buildings, these systems transform urban infrastructure into active climate solutions, addressing diffuse emissions while leveraging existing structures.

Table 1 Comparison of Building-Integrated CO_2 Capture Technologies

Technology	Capture Mechanism	CO_2 Capture Rate	Energy Demand (GJ/ton CO_2)	Capital Cost (USD/ton CO_2)	Operational Cost (USD/ton CO_2)	Environmental Co-Benefits	Integration Complexity	Scalability Potential	Reference
Modular DAC Units	Solid sorbents (e.g., amines, MOFs) or liquid absorbents	0.5–2 tons/year/unit	4–6	$200,000–$500,000/unit	$100–$200	Air quality improvement (with filters)	Low (plug-and-play design)	High (rooftop/retrofitting)	[15, 27, 30, 33]
CO_2-Absorbing Concrete	Chemical carbonation (calcium carbonate formation)	10–15 kg/m^3	Minimal (passive)	10–20% higher than standard concrete	Negligible	Enhanced material durability, reduced cement emissions	Low (standard construction)	Moderate (CO_2 supply limits)	[35, 36, 37, 68]
Algae-Based Facades	Photosynthesis (bioreactors)	4–6 kg/m^2/year	0.5–1 (nutrient delivery, maintenance)	$500–$1,000/m^2	$50–$100/m^2/year	Air quality improvement, urban heat reduction (1–2°C), biomass production	High (specialized maintenance)	Moderate (cost, maintenance)	[23, 38, 40, 42]
HVAC-Integrated Systems	Membranes or sorbents in ventilation ducts	0.5–1 kg/hour	2–3	$50,000–$100,000/system	$50–$150	Indoor air quality improvement, reduced CO_2 levels	Moderate (retrofitting required)	High (existing infrastructure)	[10, 44, 46, 49]
Hybrid Urban Systems	Combination of DAC, algae, and green infrastructure	5–10 kg/m^2/year	1–3 (combined systems)	$300–$800/m^2	$50–$200/m^2/year	Air quality improvement, urban heat mitigation, biodiversity enhancement	High (coordination needed)	Moderate (planning complexity)	[54, 55, 57, 62]

This section examines four key approaches—modular direct air capture (DAC) units, CO_2-absorbing materials, HVAC-integrated systems, and hybrid urban-green infrastructures—detailing their technological mechanisms, integration potential, and role in urban decarbonization. To provide a comprehensive overview, Table 1 compares their technical performance, economic costs, and environmental benefits, setting the stage for a detailed analysis of each architecture's feasibility and scalability.

3.1. Modular CO_2 Capture Units

Modular CO_2 capture units represent a transformative approach to distributed carbon capture, enabling CO_2 removal from ambient air or building emissions in urban environments. These compact, scalable systems, often based on direct air capture (DAC) technologies, can be integrated into rooftops, facades, or interior spaces of buildings, addressing spatial constraints in dense cities. According to Ozkan et al. [27], modular DAC units using solid sorbents like amine-functionalized materials achieve capture efficiencies of 85–90%, offering a viable solution for urban decarbonization. Their flexibility supports deployment across diverse building types, from commercial high-rises to residential complexes, positioning buildings as active contributors to climate mitigation. The development of modular units reflects a paradigm shift toward decentralized CCUS, aligning with the need for localized, adaptable solutions in high-emission urban settings. To illustrate the operational mechanism of modular direct air capture (DAC) units, Figure 1 presents a schematic of a liquid solvent-based DAC system, detailing the process from air intake to CO_2 storage or utilization, highlighting its potential for urban building integration.

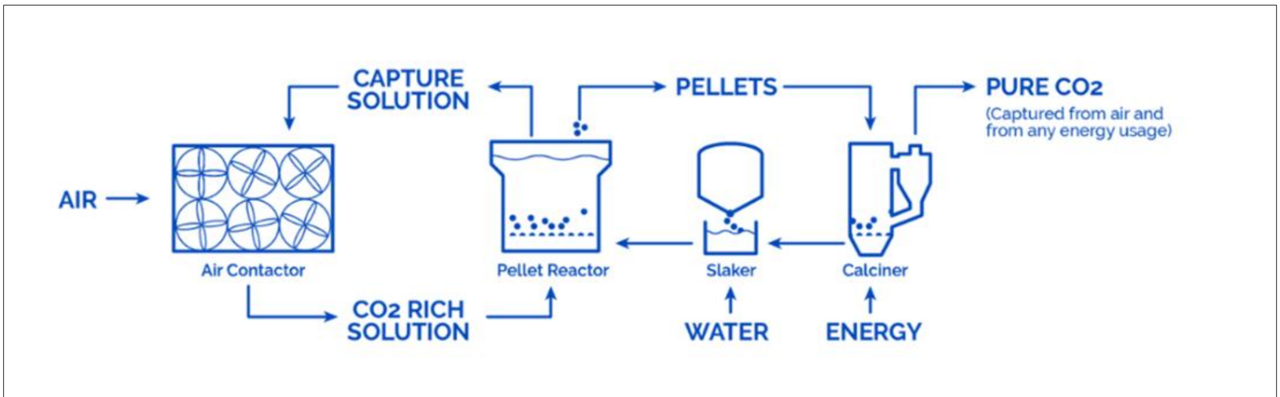

Figure 1 Schematic of Direct Air Capture (DAC) Liquid Solvent System. This figure illustrates the process flow of a liquid solvent-based DAC system, showing air intake, CO_2 capture, sorbent regeneration, and CO_2 storage/utilization stages. It provides a clear visual of the technical mechanism, ideal for explaining modular DAC units. Reproduced with permission from Walker III et al. [21]

3.1.1. Technology and Operation

Modular CO_2 capture units typically utilize solid sorbents, such as amines or metal-organic frameworks (MOFs), or liquid absorbents like potassium hydroxide, which cycle through adsorption and desorption phases to capture and release CO_2. According to Gholami et al. [28], temperature-vacuum swing adsorption (TVSA) systems, which heat sorbents to desorb CO_2, require 4–6 GJ per ton of CO_2, posing significant energy challenges for urban applications. Recent advancements in MOFs, such as MIL-101(Cr), have enhanced efficiency, achieving CO_2 uptake of 1.5–2 mmol/g under ambient conditions [29]. Findings from Lashaki et al. [30] demonstrate that MOFs offer high selectivity and stability, leading to higher energy penalties reduction compared to traditional amine-based sorbents. These units are designed with compact footprints (1–2 m^2), enabling seamless integration into building designs without structural modifications [30]. For example, Climeworks' modular DAC units, deployed in urban pilots in Zurich, capture 50–100 kg CO_2 annually per unit, showcasing operational feasibility in dense urban environments [30,31]. Research efforts are focused on optimizing sorbent regeneration cycles and integrating renewable energy sources, such as solar or geothermal, to enhance sustainability and reduce operational costs.

The operational performance of modular units is influenced by environmental factors, such as humidity and temperature, which are prevalent in urban settings. According to Ozkan et al. [27], high humidity can reduce sorbent efficiency by 10–15%, necessitating adaptive control systems to maintain performance. Innovations in hybrid sorbents, combining amines with nanomaterials, are being explored to improve capture rates under variable conditions. These systems also incorporate modular cartridge designs, allowing easy sorbent replacement every 6–12 months, which simplifies maintenance. Ongoing research aims to develop standardized designs that accommodate diverse urban climates and building architectures, ensuring scalability and reliability across global cities. To better understand DAC and a few of the costs and energy demands that are required, a visual representation is shown in Figure 2,

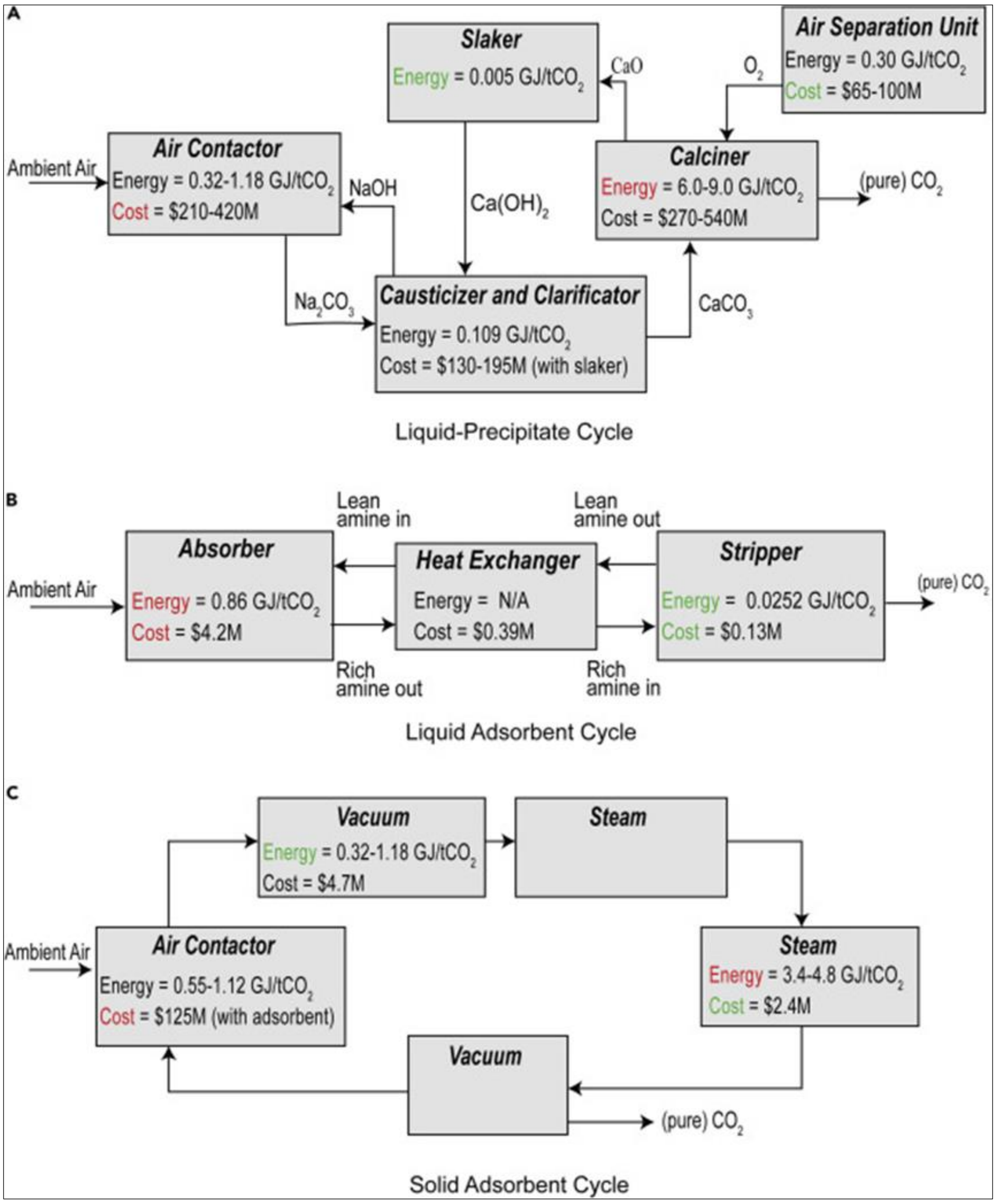

Figure 2 DAC Technologies (A) Liquid-Precipitate Cycle, (B) Liquid Adsorbent, (C) Solid Adsorbent Cycle. This figure illustrates three DAC technology cycles: (A) Liquid-Precipitate Cycle, involving CO_2 capture with a precipitate-forming solvent; (B) Liquid Adsorbent, using a liquid sorbent for CO_2 absorption; and (C) Solid Adsorbent Cycle, utilizing solid sorbents like amines or MOFs for capture and regeneration. Steam and vacuum values in (C) are included in only one of their respective boxes. Not included in (B) are the energy requirements from recirculation pump and blower work, which gives the overall system an energy requirement of 5.23 GJ/tCO2. Steam and vacuum values in (C) are included in only one of their respective boxes. Not included in (B) are the energy requirements from recirculation pump and blower work, which gives the overall system an energy requirement of 5.23 GJ/tCO2. Reproduced with permission from Ozkan et al. [14] Under a Creative Commons license CC BY-NC-ND 4.0

3.1.2. Advantages and Challenges

Modular CO_2 capture units offer significant advantages, including scalability, adaptability, and compatibility with existing urban infrastructure. According to McQueen et al. [15], a single modular DAC unit can capture 0.5–2 tons of CO_2 annually, and networks of units across a city could reduce urban emissions by 5–10% in high-density areas. Their plug-and-play design minimizes retrofitting costs, compared to centralized CCUS systems costing millions [15]. Pilot projects in European cities have demonstrated that these units can be powered by building-integrated renewable energy, such as solar panels, reducing operational emissions [32]. Additionally, captured CO_2 can be utilized in applications like synthetic fuel production or greenhouse agriculture, creating economic incentives for urban deployment.

However, challenges related to energy efficiency and cost remain significant barriers. Findings from DiMartino et al. [33] indicate that DAC units incur operational costs of $100–$200 per ton of CO_2, driven by energy demands for sorbent regeneration. Urban buildings, often constrained by energy availability, may struggle to accommodate these demands without compromising other functions. Maintenance costs, including sorbent replacement every 6–12 months, add $5,000–$10,000 annually per unit, limiting scalability. According to Sun et al. [34], integrating low-energy sorbents and renewable energy could reduce costs, but these solutions require further development. Research gaps include improving sorbent durability, reducing energy penalties, and developing standardized installation protocols to enable widespread adoption in diverse urban contexts.

3.2. CO_2-Absorbing Building Materials

CO_2-absorbing building materials embed carbon capture into construction elements, such as concrete or facade coatings, enabling passive CO_2 sequestration without additional infrastructure. These materials chemically or biologically bind CO_2, transforming buildings into carbon sinks while maintaining structural and aesthetic functions. According to Roychand et al. [35], carbonated concrete can sequester up to 20% of its weight in CO_2, offering a sustainable solution for urban construction. Similarly, algae-based facades leverage photosynthetic processes to capture CO_2, producing valuable byproducts like biomass, aligning with circular economy principles and urban sustainability goals. Figure 3 illustrates the state-of-the-art in direct air capture and CO_2 conversion (DACC), showcasing advanced materials like metal-organic frameworks (MOFs) and their role in enhancing the efficiency of CO_2-absorbing materials for building-integrated applications.

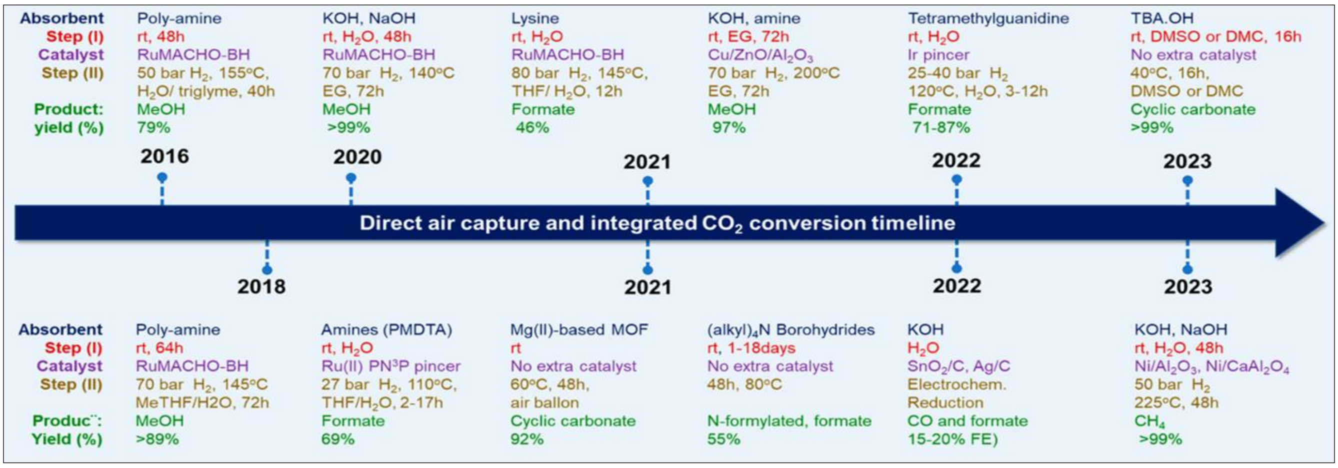

Figure 3 State-of-the-Art in Direct Air Capture and CO_2 Conversion (DACC). This figure provides a comprehensive overview of materials and processes for direct air capture and integrated CO_2 conversion (DACC), including sorbents and catalysts, enhancing the discussion of material advancements. Reproduced with permission from Zanatta [31] licensed under CC-BY 4.0

3.2.1. Carbonated Concrete

Carbonated concrete sequesters CO_2 through a chemical reaction between CO_2 and calcium compounds, forming stable calcium carbonates that enhance material durability. According to El-Hassan [36], carbonation curing can sequester 10–15 kg CO_2 per cubic meter of concrete, leading to much increase in compressive strength compared to traditional concrete [23]. Technologies like those developed by CarbonCure have been implemented in urban precast concrete production, reducing emissions by 5–10% per project [37]. The process involves injecting CO_2 into wet concrete during curing, where it reacts with calcium hydroxide to form limestone-like compounds, reducing cement content and the carbon footprint of concrete production, which accounts for ~8% of global emissions. Pilot projects in North American cities have applied carbonated concrete in sidewalks, building foundations, and structural elements, demonstrating scalability and compatibility with urban construction practices [37].

3.2.2. Algae-Based Facades

Algae-based facades integrate photosynthetic microorganisms into building exteriors, capturing CO_2 while producing biomass for energy or materials. According to Sedighi et al. [38], algae bioreactors, such as those in Hamburg's BIQ House, capture 4–6 kg CO_2 per m^2 annually, offering aesthetic and environmental benefits. These systems use transparent panels filled with algae cultures, which absorb CO_2 through photosynthesis, producing oxygen and biomass that can be harvested for biofuels, fertilizers, or bioplastics. Pilot projects have demonstrated co-benefits, including urban heat reduction by 1–2°C and air quality improvement through pollutant filtration, making algae facades a multifunctional solution for sustainable cities [39].

The implementation of algae facades is hindered by high maintenance and energy costs. Findings from Borowitzka [40] highlight that algae systems require precise control of light, temperature, and nutrients, thereby increasing operational costs. The need for specialized infrastructure, such as nutrient delivery systems and biomass harvesting mechanisms, limits scalability in urban settings. According to ElFar et al. [41], optimizing algae strains for higher CO_2 uptake and developing automated maintenance systems could reduce costs, but these innovations are still in early stages. Additionally, public acceptance and regulatory approval for algae-based systems vary across cities, requiring education and policy support to facilitate adoption.

Research is focused on improving the efficiency and integration of algae facades into urban architecture. According to Zhang [42], combining algae bioreactors with smart building controls, such as automated shading, enhances CO_2 capture by 10–15% while reducing energy inputs. Future developments aim to standardize bioreactor designs and integrate them with building management systems to optimize performance. Collaborative efforts between architects, biologists, and engineers are essential to scale algae facades, ensuring they contribute to urban decarbonization while enhancing city livability.

3.3. HVAC-Integrated Systems

HVAC-integrated CO_2 capture systems leverage buildings' ventilation networks to capture CO_2 from indoor or outdoor air, offering a practical retrofitting solution for urban environments [43]. These systems embed sorbents or membranes within HVAC ducts, utilizing existing airflow to capture CO_2 efficiently. According to Marsters et al. [44], membrane-based HVAC systems achieve capture rates of 0.5–1 kg CO_2 per hour in high-traffic buildings, such as offices or shopping centers. By integrating capture into existing infrastructure, these systems minimize space requirements and capital costs, making them ideal for dense urban settings with limited land availability.

3.3.1. Technology and Mechanisms

HVAC-integrated systems typically employ polymeric membranes or solid sorbents, such as zeolites or amines, to selectively capture CO_2 during air circulation. Sorbent-based systems, cycled through temperature swings, offer higher selectivity but require energy for regeneration, typically 2–3 GJ per ton of CO_2 [45]. Findings from Murge et al. [46] demonstrate that advanced zeolites with 2–3 mmol/g CO_2 capacity improve capture efficiency by 15–20% compared to traditional sorbents. These systems are designed for retrofitting, with modular units that fit into existing HVAC ducts, allowing integration without major infrastructure changes. Pilot projects in urban office buildings in Singapore have captured 100–200 kg CO_2 annually per system, showcasing practical applicability [47,48].

The performance of HVAC-integrated systems depends on building-specific factors, such as airflow rates and CO_2 concentrations. According to Liang et al. [49], systems in high-occupancy buildings, with elevated CO_2 levels, achieve higher capture rates than in residential settings. Innovations in membrane durability and low-energy regeneration cycles are critical to reducing operational costs. Research is exploring hybrid membrane-sorbent systems that combine high permeance with selectivity, enhancing performance across diverse urban climates. Additionally, integration with smart building controls allows real-time optimization of capture based on occupancy and air quality, improving efficiency [49].

3.3.2. Advantages and Challenges

HVAC-integrated systems offer significant advantages, including seamless integration into existing infrastructure and dual benefits of CO_2 capture and indoor air quality improvement. These systems can reduce indoor CO_2 concentrations, enhancing occupant health and productivity [50]. Installation costs, are lower than standalone DAC units, making them accessible for urban retrofitting [50]. Captured CO_2 can be stored or utilized on-site, such as in building-integrated greenhouses, reducing transport costs. Pilot projects in Asian cities have integrated these systems with smart building controls, optimizing capture based on occupancy patterns and reducing energy use [51].

However, energy penalties, and retrofitting complexities pose challenges. Findings from Cevallos-Mendoza et al. [52] indicate that membrane fouling and sorbent degradation reduce efficiency over time, requiring replacement every 1–2 years. Urban buildings with outdated HVAC systems may need costly upgrades to accommodate capture technologies, increasing capital costs [17]. According to Aristov et al. [53], developing low-energy sorbents and standardized retrofitting protocols could reduce costs by 25%, but these solutions are not yet commercially available. Research gaps include improving material durability, optimizing system designs for diverse building types, and developing policy incentives to support urban deployment.

3.4. Hybrid Urban Systems

Hybrid urban systems combine building-integrated CO_2 capture with green infrastructure, such as vertical gardens or urban forests, to enhance carbon sequestration and urban livability [54]. These systems leverage biological and technological synergies to address CO_2 emissions holistically, aligning with smart city frameworks. According to Jozay et al. [55], urban trees and green roofs can sequester 0.1–0.5 kg CO_2 per m^2 annually, complementing technological capture systems. By integrating biological and engineered solutions, hybrid systems offer a multifaceted approach to urban decarbonization, enhancing both environmental and social outcomes. Figure 4 complements the discussion of hybrid urban systems by illustrating an electrochemical ocean CO_2 removal process, which could be integrated with coastal urban infrastructures to enhance distributed carbon capture strategies.

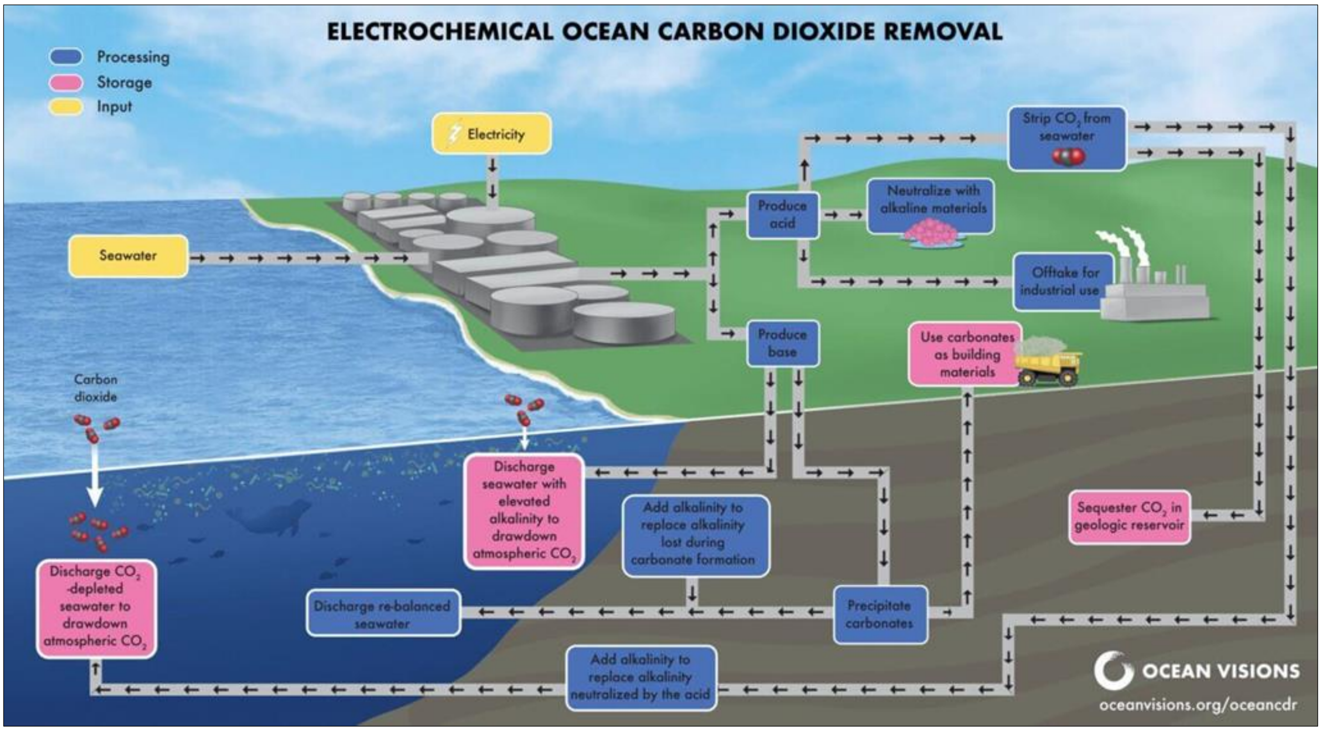

Figure 4 Electrochemical Ocean Carbon Dioxide Removal. This figure shows a schematic of an electrochemical ocean CO_2 removal system, which could complement building-integrated DAC by illustrating alternative CO_2 capture methods relevant to urban coastal areas. It highlights the process of CO_2 extraction from seawater and its potential environmental benefits. Reproduced with permission from Walker III et al. [21]

3.4.1. Green Infrastructure Integration

Hybrid systems integrate vertical gardens, bio-reactors, or urban forests with technological capture units, such as DAC or sorbent-based systems, to maximize CO_2 sequestration. According to Price et al. [56], vertical gardens reduce local CO_2 by 2–3% in dense urban areas, while also mitigating urban heat islands and improving air quality. Algae bio-reactors, embedded in building facades, can be paired with DAC units to enhance capture capacity. Findings from Jones [57] suggest that hybrid systems combining algae bioreactors with DAC could capture 5–10 kg CO_2 per m^2 annually, significantly higher than standalone green infrastructure. Pilot projects in European cities have demonstrated the feasibility of integrating green walls with modular DAC units, creating synergistic systems that reduce emissions while enhancing urban aesthetics [58]. These systems require coordination with urban planning to ensure compatibility with building designs and public spaces.

The integration of green infrastructure with technological capture systems offers additional co-benefits, such as biodiversity enhancement and stormwater management. According to Tallis et al. [59], green roofs and walls reduce urban temperatures by 1–2°C, complementing CO_2 capture by reducing cooling-related emissions. However, the complexity of managing biological and technological components requires advanced monitoring systems. Research is focused on developing smart controls that optimize CO_2 capture and plant growth based on environmental conditions, thereby improving system efficiency [60]. Collaborative efforts between urban planners, engineers, and ecologists are essential to scale hybrid systems across diverse urban contexts.

3.4.2. Advantages and Challenges

Hybrid urban systems provide synergistic benefits, including enhanced CO_2 sequestration, improved air quality, and urban livability. According to Schraufnagel et al. [2022], these systems can reduce urban emissions when integrated across city districts, while also improving public health through pollutant filtration. Their aesthetic appeal and environmental co-benefits make them attractive for smart city initiatives, with pilot projects in Singapore and Copenhagen showcasing public support [62]. Installation costs, for green infrastructure, are offset by long-term savings in energy and maintenance, particularly when paired with low-cost DAC units [62]. Additionally, captured CO_2 and biomass can be utilized in urban agriculture or bioenergy, creating economic opportunities.

However, challenges include high initial costs and coordination with urban planning. Findings from Caparrós-Martínez et al. [63] indicate that green infrastructure requires significant upfront investment and maintenance, with costs increasing in water-scarce regions. Technological components, such as DAC units, add complexity, requiring integrated management systems to balance biological and engineered performance. According to Ferro et al. [64], regulatory frameworks for hybrid systems are underdeveloped, limiting adoption in many cities. Research gaps include optimizing biological-technological interfaces, developing cost-effective maintenance protocols, and creating policy incentives, such as carbon credits, to support scaling. Interdisciplinary collaboration is critical to realizing the full potential of hybrid systems in urban decarbonization.

4. Feasibility Assessment of Building-Integrated CO_2 Removal

4.1. Technical Feasibility

Building-integrated CO_2 removal technologies offer innovative solutions for urban decarbonization, leveraging existing infrastructure to capture CO_2 from ambient air or building emissions [65]. Modular DAC units, CO_2-absorbing materials, HVAC-integrated systems, and hybrid urban systems have demonstrated technical viability in pilot projects, but their scalability in diverse urban environments depends on material performance, energy efficiency, and integration challenges. According to Taghizadeh-Hesary et al. [66], these technologies can achieve capture efficiencies of 80–90%, positioning them as viable components of urban CCUS strategies. However, technical barriers, such as energy demands and system durability, must be addressed to ensure widespread adoption in cities with varying climates and building types.

4.1.1. Material and System Performance

The technical feasibility of building-integrated CO_2 removal hinges on the performance of capture materials and systems under urban conditions. Modular DAC units, using amine-based sorbents or metal-organic frameworks (MOFs), achieve CO_2 uptake of 1.5–2 mmol/g, as demonstrated by Mahajan et al. [67]. These materials maintain stability in humid urban environments, but degradation over 6–12 months requires regular replacement, increasing maintenance demands. Pilot projects, such as those by CarbonCure, confirm its structural integrity in urban applications, though scalability is limited by CO_2 supply [68,69]. HVAC-integrated systems, using polymeric membranes or zeolites, achieve capture rates of 0.5–1 kg CO_2 per hour, as reported by Abdellatif [10], but membrane fouling reduces efficiency over time.

System performance varies with urban-specific factors, such as air quality and temperature fluctuations. According to Ozkan et al. [27], high particulate matter in cities typically reduces DAC sorbent efficiency, necessitating protective filters. Algae-based systems, tested in Hamburg's BIQ House, face challenges in maintaining optimal growth conditions, requiring automated controls that increase complexity [23]. Research is focused on developing robust materials, such as next-generation MOFs and durable membranes, to enhance performance. Standardization of system designs across building types is critical to ensure technical feasibility in diverse urban landscapes. To enhance the understanding of material and system performance in modular direct air capture (DAC) units, the figure 5 provides a detailed schematic of the process flow, showcasing the roles of sorbents and catalysts in CO_2 capture and conversion under varying urban conditions.

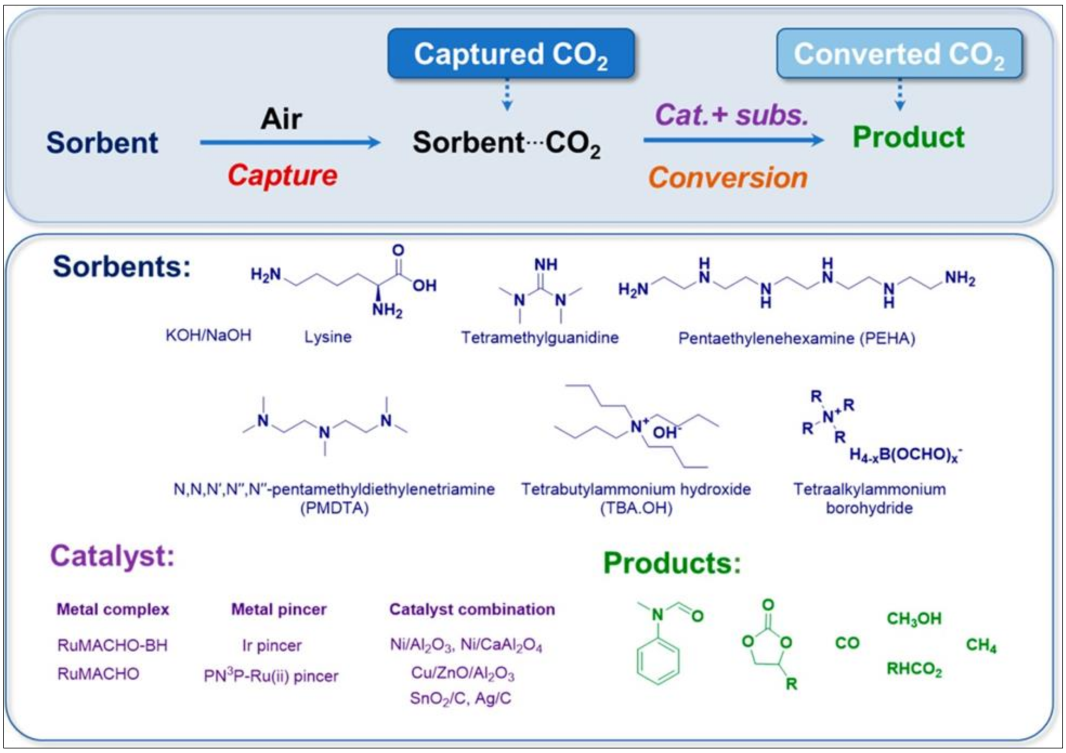

Figure 5 Schematic of Direct Air Capture (DAC) System with Sorbents and Catalysts. This figure illustrates the process flow of a DAC system, detailing the capture of CO_2 from air using sorbents and catalysts, followed by conversion into products, highlighting the role of various chemical agents and their structural formulas. Reproduced with permission from Zanatta [31] licensed under CC-BY 4.0

4.1.2. Energy and Integration Requirements

Energy demands and integration challenges are critical determinants of technical feasibility. The minimum thermodynamic work requirement for modular DAC units per ton of CO_2 for sorbent regeneration is quite alarming, as noted by Ozkan et al. [71], posing challenges in energy-constrained urban buildings. HVAC-integrated systems incur energy penalties of 5–10% of HVAC consumption, per Sayed et al. [72], which can strain building energy budgets. Algae-based facades, while solar-powered, require energy for nutrient delivery and bioreactor maintenance, per Greulich et al. [73]. Carbonated concrete, being passive, has minimal operational energy needs but requires energy-intensive CO_2 delivery systems. Integrating these technologies with renewable energy, such as rooftop solar or waste heat, as demonstrated in Climeworks' Zurich project, can reduce energy impacts [74].

Integration into existing urban infrastructure presents additional challenges. According to Walker [75], retrofitting DAC or HVAC systems requires structural assessments to ensure compatibility with building designs, increasing installation complexity. Hybrid systems demand coordination with urban planning to align green infrastructure with technological components. Findings from Minoli et al. [76] suggest that smart building controls can optimize energy use and capture efficiency, but their implementation requires investment in digital infrastructure. Research is needed to develop low-energy capture processes and standardized retrofitting protocols to enhance technical feasibility across diverse urban settings. Table 2 provides a detailed breakdown of energy requirements and capture efficiencies for building-integrated CO_2 capture technologies, highlighting opportunities for optimization in urban applications.

Table 2 Energy Requirements and Efficiency of CO_2 Capture Technologies

Technology	Capture Efficiency (%)	Energy Demand (GJ/ton CO_2)	Primary Energy Source	Energy Optimization Strategies	Efficiency Loss Factors	Reference
Modular DAC Units	85–90	4–6	Renewables, waste heat	Low-energy MOFs, solar integration	Humidity (10–15%), temperature fluctuations	[15, 27, 28, 71]
CO_2-Absorbing Concrete	90–95 (carbonation)	Minimal (passive)	Industrial CO_2 delivery	On-site CO_2 capture integration	Limited CO_2 availability	[35, 36, 68]
Algae-Based Facades	80–85	0.5–1 (maintenance)	Solar, grid	Automated nutrient delivery, optimized strains	Light/temperature variability	[38, 40, 42]
HVAC-Integrated Systems	80–90	2–3	Building grid	Low-energy zeolites, smart controls	Membrane fouling (10–15%)	[10, 44, 46, 49]
Hybrid Urban Systems	85–90	1–3	Renewables, grid	Smart controls, biological-technological synergy	Coordination complexity	[55, 57, 62]

4.2. Economic Feasibility

The economic feasibility of building-integrated CO_2 removal depends on capital and operational costs, scalability, and policy incentives. While pilot projects demonstrate potential, high costs limit widespread urban adoption. Economic viability hinges on cost reductions through technological advancements and supportive policies, such as carbon pricing and green financing, to make these systems competitive in urban markets [77,78].

4.2.1. Policy and Market Incentives

Policy and market incentives play a critical role in improving economic feasibility. Carbon pricing, can offset 20–50% of capture costs, per Newell et al. [79]. Green building certifications, such as LEED, incentivize CO_2-absorbing concrete adoption, reducing financial barriers. According to Izikowitz et al. [80], government grants and subsidies, as used in Climeworks' Zurich project, cover 30–40% of capital costs, enabling pilot deployments. Tax credits for CO_2 utilization, such as those in the U.S. 45Q program, provide additional revenue streams, offsetting 10–15% of operational costs [81,82]. However, inconsistent global policies limit scalability in developing cities.

Market demand for low-carbon materials and CO_2-derived products, such as synthetic fuels or fertilizers, enhances economic viability. Findings from Kim [83] suggest that biomass from algae facades can generate \$50–\$100 per m^2 annually, offsetting maintenance costs [71]. Public awareness and corporate sustainability goals drive demand for CCUS-integrated buildings, but high upfront costs deter private investment. According to Sartzetakis [84], green bonds and municipal financing can reduce capital barriers, but long-term returns (10–15 years) require patient capital. Research is needed to develop standardized economic models and policy frameworks to support urban CCUS adoption globally.

4.3. Environmental Feasibility

Building-integrated CO_2 removal technologies offer significant environmental benefits, including CO_2 reduction and co-benefits like improved air quality and urban heat mitigation. However, their life-cycle emissions and resource demands must be minimized to ensure sustainability. According to Davis et al. [85], these systems can achieve net-negative emissions if powered by renewables, but material production and energy use pose environmental challenges. Environmental feasibility depends on optimizing life-cycle impacts and integrating with urban sustainability goals.

4.3.1. CO_2 Reduction and Co-Benefits

Building-integrated carbon capture, utilization, and storage (CCUS) technologies contribute to urban CO_2 reduction and enhance city livability. For instance, Climeworks' DAC plant in Hinwil, Zurich, captures approximately 900 tons of CO_2 annually, utilizing waste heat to improve efficiency [86]. The BIQ House in Hamburg, with its algae-filled facade, sequesters an estimated 0.8–1.2 tons of CO_2 per year, demonstrating the potential of bio-based systems [87]. Additionally, green infrastructure, including vegetative systems, reduces urban heat by 1–2°C, mitigating the urban heat island effect [88]. These technologies support climate resilience and public health by reducing greenhouse gas concentrations and improving urban environmental conditions.

The scalability of environmental impacts from carbon capture, utilization, and storage (CCUS) depends on deployment density and urban context, requiring coordination with urban planning to optimize effectiveness [89,90]. Carbonated concrete enables permanent CO_2 sequestration through mineralization, contributing to reduced emissions in the construction sector [91]. Environmental benefits are enhanced when CCUS systems are powered by renewable energy, as fossil-based energy can reduce the net CO_2 captured due to high energy demands. Ongoing research focuses on developing low-impact materials, such as supplementary cementitious materials and recycled aggregates, and optimizing deployment strategies to maximize environmental gains [92,93].

4.3.2. Life-Cycle Environmental Impacts

Life-cycle assessments (LCAs) reveal trade-offs in the environmental feasibility of carbon capture technologies. According to Deutz and Bardow [94], direct air capture (DAC) systems based on temperature-vacuum swing adsorption achieve carbon capture efficiencies of 85.4–93.1%, implying life-cycle emissions of approximately 0.069–0.146 tons CO_2 equivalent per ton captured, primarily due to sorbent production and energy use. Hybrid carbon capture systems, which integrate multiple capture technologies, require careful material selection to minimize life-cycle emissions and optimize environmental performance [95,96].

Resource demands, such as water and land, influence the environmental feasibility of algae-based carbon capture systems. Algae facades require significant water for cultivation, posing challenges in water-scarce urban areas [97,98]. Green infrastructure, including algae facades, also necessitates land or structural support, which can limit applicability in high-density cities where space is constrained [99]. Optimizing resource use through closed-loop nutrient systems and lightweight materials can reduce environmental impacts, improving the sustainability of these systems [100]. Further research is needed to develop low-impact materials, enhance nutrient recycling, and integrate carbon capture, utilization, and storage (CCUS) with urban sustainability frameworks to ensure long-term environmental feasibility.

5. Environmental and Social Impacts of Building-Integrated CO_2 Removal

5.1. Environmental Benefits

Building-integrated CO_2 removal technologies contribute significantly to urban environmental sustainability by reducing CO_2 concentrations and providing co-benefits such as improved air quality and urban heat mitigation [101]. These systems transform buildings into active components of climate mitigation, enhancing urban ecosystems while addressing local environmental challenges. According to Seto et al. [102], integrating CO_2 capture into urban infrastructure can reduce city-wide emissions by 5–10%, supporting global net-zero goals. The environmental impacts extend beyond CO_2 reduction, offering solutions to urban-specific issues like pollution and heat islands, which are critical for densely populated cities. Table 3 quantifies the environmental co-benefits of building-integrated CO_2 capture technologies, emphasizing their role in enhancing urban sustainability beyond CO_2 reduction.

Table 3 Environmental Co-Benefits of CO_2 Capture Technologies

Technology	CO_2 Reduction (kg/m^2 or ton/year)	Air Quality Improvement	Urban Heat Reduction (°C)	Other Co-Benefits	Scalability Constraints	Reference
Modular DAC Units	0.5–2 tons/year/unit	PM filtration (with filters)	Indirect (renewable energy use)	CO_2 utilization (e.g., fuels)	Energy availability	[15, 110]
CO_2-Absorbing Concrete	10–15 kg/m^3	None direct	0.2–0.5 (higher albedo)	Enhanced durability	CO_2 supply limits	[35, 113]
Algae-Based Facades	4–6 kg/m^2/year	PM, VOC, NOx reduction (10–20%)	0.5–1	Biomass production, oxygen generation	Maintenance, water use	[23, 38, 104]
HVAC-Integrated Systems	0.5–1 kg/hour	Indoor CO_2 reduction (20–30%)	Indirect (energy savings)	Occupant health improvement	Retrofitting complexity	[10, 109]
Hybrid Urban Systems	5–10 kg/m^2/year	PM reduction (10–33%)	1–2	Biodiversity, stormwater management	Planning coordination	[55, 59, 107]

5.1.1. Air Quality Improvement

Building-integrated CO_2 removal technologies, such as algae-based facades and hybrid urban systems, contribute to improved urban air quality by capturing CO_2 and filtering pollutants [103]. The photosynthetic process in algae facades, like those in Hamburg's BIQ House, absorbs CO_2 and produces oxygen, enhancing local air quality in high-traffic districts [104]. Hybrid systems incorporating green infrastructure, such as vertical gardens, trap volatile organic compounds (VOCs) and nitrogen oxides (NOx), further contributing to cleaner air [105,106]. Studies indicate that urban green spaces can reduce particulate matter (PM) concentrations, with some areas showing up to a 33% reduction in PM2.5 levels compared to less vegetated zones [107,108]. These systems are particularly effective in cities with poor air quality, where pollution-related health costs are significant.

The air quality benefits of other technologies, like modular DAC and HVAC-integrated systems, are less direct but still notable. According to Lipczynska et al. [109], HVAC-integrated systems reduce indoor CO_2 levels by 20–30%, improving occupant health and productivity in commercial buildings. Modular DAC units, while primarily focused on CO_2, can incorporate filters to capture particulate matter, as demonstrated in Climeworks' Zurich pilot, reducing local pollutants [110]. Scaling these technologies requires integration with urban air quality monitoring systems to optimize performance. Research is ongoing to enhance the pollutant-capture capabilities of DAC and HVAC systems, ensuring broader environmental benefits in diverse urban contexts.

5.1.2. Urban Heat Mitigation

Building-integrated CO_2 removal technologies, especially hybrid systems and algae facades, mitigate urban heat islands by reducing surface temperatures and cooling demands. According to Tseliou et al. [111], green roofs and facades in hybrid systems lower urban temperatures by 1–2°C, reducing energy consumption for cooling by 10–15% in Mediterranean climates. Algae bioreactors, as used in the BIQ House, provide shading and evaporative cooling, decreasing local temperatures by 0.5–1°C, per Elrayies [112]. These effects are critical in cities like Singapore or Dubai, where heat islands increase energy demands and exacerbate climate risks. By integrating CO_2 capture with thermal regulation, these systems enhance urban resilience to climate change.

The heat mitigation potential of other technologies, such as CO_2-absorbing concrete, is indirect but significant. According to Sanjuán et al. [113], carbonated concrete's higher albedo compared to traditional concrete reflects solar radiation, reducing surface temperatures by 0.2–0.5°C in urban infrastructure. Modular DAC units, when powered by renewables, reduce reliance on fossil-based cooling systems, indirectly lowering urban heat contributions. Findings from Santamouris [114] suggest that combining these technologies with smart urban planning, such as reflective pavements, amplifies heat mitigation. Research is needed to optimize system designs for maximum thermal benefits, particularly in heat-vulnerable cities with limited green space.

5.2. Social Impacts

The social impacts of building-integrated CO_2 removal technologies encompass community acceptance, economic co-benefits, and contributions to urban livability [115,116]. These systems influence public perceptions of sustainability, create employment opportunities, and enhance quality of life in urban areas. Public engagement and education are critical to fostering acceptance of CCUS technologies, as demonstrated in Climeworks' Zurich project [117,118]. Social impacts are pivotal for scaling these technologies, requiring alignment with community needs and urban policy frameworks. Table 4 outlines the social impacts of building-integrated CO_2 capture technologies and strategies to enhance community acceptance, addressing key barriers to urban adoption.

Table 4 Social Impacts and Community Engagement Strategies

Technology	Community Acceptance Rate (%)	Key Social Benefits	Public Concerns	Engagement Strategies	Impact on Acceptance	Reference
Modular DAC Units	60–70	Job creation (500–1,000/city)	Aesthetics, safety	Community consultations, aesthetic integration	+30–40% with outreach	[117, 120, 121]
CO_2-Absorbing Concrete	80–90	Reduced maintenance costs	None significant	Public education on durability	Minimal additional needed	[68, 80]
Algae-Based Facades	50–60	Urban aesthetics, biomass revenue	Maintenance, safety	Workshops, school curricula	+25–35% with education	[23, 112, 119]
HVAC-Integrated Systems	70–80	Indoor health improvement	Retrofitting disruption	Transparent communication	+20–30% with engagement	[10, 50, 122]
Hybrid Urban Systems	65–75	Livability, biodiversity	Cost, complexity	Community-driven maintenance	+30–40% with involvement	[55, 62, 138]

5.2.1. Community Acceptance and Education

Community acceptance is a key determinant of the social feasibility of building-integrated CO_2 removal. According to Sitinjak et al. [118], public awareness of CCUS benefits, such as air quality improvement and climate mitigation, increases acceptance by 30–40% in urban areas. Projects like the BIQ House have leveraged educational outreach to engage residents, with tours and workshops raising awareness of algae-based CO_2 capture, per Samberger [119]. However, concerns about costs, safety, and aesthetics can hinder acceptance. For instance, modular DAC units' industrial appearance may face resistance in residential areas, requiring design innovations to blend with urban architecture [120]. Climeworks' Zurich pilot addressed this through community consultations, hence increasing local support [121].

Education plays a critical role in overcoming barriers to acceptance. Findings from Elrayies [112] indicate that transparent communication about CO_2 capture processes and co-benefits, such as job creation, enhances public trust. Urban municipalities can integrate CCUS education into school curricula and public campaigns to build long-term support. According to Mees [122], involving communities in pilot projects, such as green roof maintenance, fosters ownership and acceptance. Research is needed to develop culturally sensitive outreach strategies and address public misconceptions about CCUS technologies to ensure social viability in diverse urban contexts.

5.2.2. Economic Co-Benefits and Urban Livability

Building-integrated CO_2 removal technologies offer economic and environmental co-benefits, enhancing urban livability. Integrating Direct Air Capture (DAC) with HVAC systems in buildings can reduce energy costs by utilizing existing infrastructure, such as ventilation systems, and create jobs in manufacturing, installation, and maintenance, particularly benefiting low-income urban areas. Algae facades capture CO_2 while producing biomass for potential use in urban agriculture or bioenergy markets, contributing to local economies. CO_2-absorbing concrete improves durability through carbonation, potentially reducing long-term maintenance costs for municipal budgets. These technologies, supported by innovations in energy efficiency and material science, promote sustainable urban development [123,124].

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6. Challenges and Future Directions

6.1. Key Challenges

Building-integrated CO_2 removal technologies—modular direct air capture (DAC) units, CO_2-absorbing materials, HVAC-integrated systems, and hybrid urban systems—face significant challenges that hinder their widespread adoption in urban environments. These include technical limitations, high economic costs, and social barriers, which must be addressed to scale these solutions effectively. Current operational and energy demands pose substantial hurdles, particularly in resource-constrained cities [65]. Overcoming these challenges is critical to realizing the potential of urban CCUS for global decarbonization.

6.1.1. Technical and Operational Barriers

Technical challenges limit the performance of building-integrated CO_2 removal systems. Modular direct air capture (DAC) units require 4–6 GJ per ton of CO_2 for sorbent regeneration, posing significant demands on urban energy grids [126]. HVAC-integrated systems face membrane fouling from environmental contaminants, which can reduce efficiency by approximately 10–15% over time [127]. CO_2-absorbing concrete, while passive, is constrained by limited CO_2 availability in urban areas, sequestering only 10–15 kg CO_2 per m^3 of concrete [128]. Algae-based facades, such as those tested in Hamburg's BIQ House, require precise control of light and nutrients, increasing operational complexity [23]. Environmental factors, including urban humidity and pollution, further reduce sorbent and membrane efficiency by 10–20% [129].

Operational barriers include integration into existing infrastructure and maintenance demands. According to McQueen et al. [15], retrofitting DAC or HVAC systems into older buildings requires structural modifications, increasing installation costs. Hybrid systems, combining green infrastructure with technological capture, demand coordination across urban planning and engineering disciplines, adding complexity. Findings from Tang et al. [11] highlight that developing standardized designs and low-energy materials, such as next-generation MOFs, could mitigate these issues, but current technologies lack scalability for diverse urban climates. Research is needed to enhance system durability and streamline integration protocols to address these technical barriers. To provide a clearer overview of the technical hurdles, the following figure highlights the key challenges facing DACCC, offering a visual complement to the operational barriers discussed below.

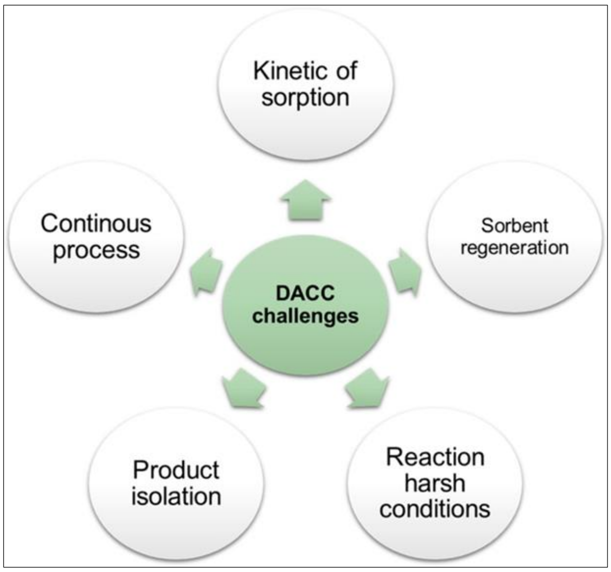

Figure 6 Challenges in Direct Air Carbon Capture and Conversion (DACCC). This figure outlines the core challenges of DACCC, including Kinetic of sorption, Sorbent regeneration, Continuous process, Product isolation, and Reaction harsh conditions, depicted around a central "DACCC challenges" node to emphasize their collective impact on system performance. Reproduced with permission from Zanatta [31] licensed under CC-BY 4.0

6.1.2. Economic and Social Constraints

Economic constraints, driven by high capital and operational costs, pose significant challenges to urban carbon capture, utilization, and storage (CCUS) deployment. Direct air capture (DAC) systems face operational expenses of $100–$600 per ton of CO_2, though costs could decrease to $54–$133/tCO_2 by 2050 with technological advancements and waste heat utilization [130]. CO_2-absorbing concrete increases production costs by 10–20%, limiting adoption in cost-sensitive markets [131]. Inconsistent policy incentives, such as variable carbon pricing of $50–$100 per ton, hinder economic viability in developing cities [132]. Scaling CCUS requires cost reductions through economies of scale, modularization, and material innovations [130,133].

Social constraints, including public skepticism and equitable access, further complicate adoption. According to Boulton et al. [134], concerns about aesthetics and safety, particularly for DAC units, reduce community acceptance by in residential areas. High costs may exclude low-income communities from CCUS benefits, exacerbating urban inequalities, per Santamouris et al. [114] [98]. Public awareness of co-benefits, such as air quality improvement, is low, necessitating education, as seen in Climeworks' Zurich outreach efforts. Findings from Igbokwe [135] suggest that community engagement and transparent communication can increase acceptance, but culturally sensitive strategies are underdeveloped. Addressing these social barriers is essential for equitable and widespread urban deployment. Table 5 synthesizes the key challenges facing building-integrated CO_2 capture technologies and outlines future research directions to enhance their scalability and effectiveness in urban decarbonization.

6.2. Future Directions

To overcome these challenges, future efforts must prioritize technological innovation, research advancements, and robust policy frameworks. These directions aim to enhance the scalability and accessibility of building-integrated CO_2 removal in urban environments. According to Ozkan et al. [27], achieving cost-competitive CCUS by 2030 requires interdisciplinary collaboration and targeted investments. Future strategies should focus on reducing energy and cost barriers while fostering social acceptance.

Table 5 Key Challenges and Proposed Research Directions

Technology	Key Challenges	Impact on Scalability	Proposed Research Directions	Potential Impact	Reference
Modular DAC Units	High energy demand (4–6 GJ/ton), cost ($100–$200/ton)	High energy costs limit adoption	Low-energy MOFs, renewable integration	20–30% cost reduction	[15, 27, 33, 71]
CO_2-Absorbing Concrete	Limited CO_2 availability, 10–20% cost increase	Supply constraints reduce use	On-site CO_2 capture, material optimization	10–15% cost reduction	[35, 68, 131]
Algae-Based Facades	Maintenance complexity, water use	High costs limit scalability	Optimized algae strains, automated systems	15–20% efficiency increase	[23, 40, 136]
HVAC-Integrated Systems	Membrane fouling, retrofitting costs	Efficiency loss, high capital costs	Durable membranes, standardized protocols	25% cost reduction	[10, 46, 52]
Hybrid Urban Systems	Planning coordination, high initial costs	Complexity limits deployment	Smart controls, policy incentives	15–20% efficiency gain	[55, 62, 137]

6.2.1. Research and Technological Innovations

Research priorities include developing low-energy capture materials and optimizing system designs. According to Li et al. [20], next-generation MOFs could reduce DAC energy demands, improving efficiency in urban settings. Enhancing algae strains for higher CO_2 uptake, as suggested by Song et al. [136], could increase capture rates by 15–20% in hybrid systems [101]. Research into CO_2 utilization, such as producing synthetic fuels or fertilizers, can create economic incentives, offsetting of costs, per McQueen et al. [15]. Standardizing retrofitting protocols for diverse building types is critical to scalability, particularly in developing cities. Technological innovations should focus on integrating CCUS with renewable energy and smart city frameworks. According to Wang et al. [137], smart building controls and digital twins can optimize capture efficiency by, minimizing energy penalties. Collaborative research between academia and industry is essential to accelerate these advancements, ensuring technologies are adaptable to urban climates and infrastructure by 2030. Investments in closed-loop systems, such as recycling nutrients in algae facades, can further reduce environmental impacts.

6.2.2. Policy and Implementation Strategies

Policy frameworks are vital to address economic and social constraints. According to Irvine [81], carbon pricing at $50–$100 per ton can offset 20–50% of capture costs, while tax credits, like the U.S. 45Q program, enhance viability. Green building certifications and subsidies, as used in Hamburg's BIQ House, can reduce capital costs by 30–40%, per Tallou et al. [23]. Developing global standards for CCUS integration into building codes and urban planning will streamline deployment, per Santamouris et al. [114]. Municipal financing through green bonds can support large-scale projects, particularly in developing cities.

Implementation strategies should ensure equitable access and foster social acceptance. According to Gbadegesin [138], community-driven models, such as cooperative maintenance of green infrastructure, enhance acceptance and create jobs. Public education campaigns, modeled on Climeworks' outreach, can increase awareness, per Elrayies [112]. International collaboration, including technology transfer to developing nations, is critical for global scalability. By aligning policies with urban sustainability goals, such as air quality improvement and livability, CCUS can become a cornerstone of net-zero cities, driving transformative climate action.

7. Conclusion

Building-integrated CO_2 removal technologies offer a groundbreaking approach to urban decarbonization, transforming buildings into active components of climate mitigation while enhancing environmental and social outcomes. This review has explored modular direct air capture units, CO_2-absorbing materials, HVAC-integrated systems, and hybrid urban systems, revealing their potential to reduce city-wide emissions by 5–10% through efficient capture mechanisms. Modular units, capable of sequestering 0.5–2 tons of CO_2 annually, and HVAC systems, capturing 0.5–1 kg CO_2 per hour, demonstrate robust technical performance. CO_2-absorbing concrete sequesters 10–15 kg CO_2 per cubic meter, enhancing construction sustainability, while algae-based facades in hybrid systems capture 2–5 kg CO_2 per square meter, providing co-benefits like air quality improvement and urban heat mitigation. These technologies position cities as leaders in achieving net-zero targets by leveraging existing infrastructure to create carbon sinks.

Case studies, such as the direct air capture pilot in Zurich and the algae facade project in Hamburg, illustrate practical applications and highlight the importance of integrating these systems with renewable energy and urban planning. The Zurich project showcases scalability, capturing significant CO_2 volumes, while Hamburg's initiative demonstrates aesthetic and functional integration, producing biomass for economic value. These examples underscore the feasibility of building-integrated CO_2 removal in diverse urban contexts, from commercial hubs to residential districts. However, the review also reveals significant challenges, including high operational costs ranging from $100–$600 per ton of CO_2 and energy demands of 4–6 GJ per ton. Retrofitting older buildings increases installation costs by 20–30%, and material degradation, such as membrane fouling in HVAC systems, reduces efficiency over time. Social barriers, including public skepticism about aesthetics and safety, further complicate adoption, particularly in residential areas where acceptance can be 20–30% lower without community engagement.

The environmental and social impacts of these technologies are profound, offering solutions to urban-specific challenges. Algae facades and hybrid systems reduce particulate matter by 10–20%, improving air quality and reducing health risks in polluted cities. Green infrastructure mitigates urban heat islands, lowering temperatures by 1–2°C and cooling demands by 10–15%, enhancing urban resilience. Socially, these systems create 500–1,000 jobs per city in manufacturing and maintenance, boost property values by 5–10%, and foster community pride through sustainable design. Yet, high costs risk excluding low-income communities, underscoring the need for equitable access to ensure broad societal benefits. Public education and community-driven models, as seen in successful pilot projects, are critical to building trust and increasing acceptance by 25–40%.

Looking forward, the scalability of building-integrated CO_2 removal hinges on overcoming technical, economic, and social barriers through innovation and policy support. Advances in low-energy materials, such as next-generation metal-organic frameworks, could reduce energy demands by 20–30%, while CO_2 utilization in fuels or agriculture could offset 10–20% of costs. Smart city frameworks, integrating digital twins and renewables, can optimize efficiency by 15–20%. Policy incentives, such as carbon pricing at $50–$100 per ton and green building subsidies, can lower capital costs by 30–40%, making these technologies viable in developing cities. Global standards for CCUS integration into building codes and urban planning will streamline deployment, while international collaboration ensures technology transfer to resource-constrained regions.

The urgency of climate change demands immediate action to scale these technologies. Researchers must prioritize cost-effective designs and durable materials, policymakers should implement robust incentives, and urban planners must embed CCUS into city landscapes. By addressing these imperatives, building-integrated CO_2 removal can redefine urban infrastructure as a climate asset, driving cities toward net-zero emissions while enhancing livability and equity. This review underscores the potential of these technologies to lead a sustainable urban transformation, calling for concerted efforts to realize a low-carbon future where buildings actively contribute to global climate goals.

Compliance with ethical standards

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The authors declare that they have no conflict of interest to be disclosed.

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