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A Comprehensive Review of Direct Air Capture Technologies for Carbon Removal

[1] Kafayat Ololade Liadi, [2] Ifeanyi Simon Opara, [3] Ruth Adesola Elumilade, [4] Habeeb Shittu, [5] Ibukun Olaoluwa Adeniji

[1] Independent Researcher, Lagos, Nigeria
[2] North Carolina Agriculture and Technical State University, Greensboro, North Carolina, USA
[3] University of Dundee, Dundee, United Kingdom
[4] Moffatt Nichol, Savannah, GA, US
[5] Electric Power Research Institute, United States

Corresponding Author: **Kafayat Ololade Liadi**

Abstract

As global concerns about anthropogenic climate change intensify, the imperative to mitigate carbon dioxide (CO2) emissions has led to a growing interest in innovative carbon removal strategies. Among these, Direct Air Capture (DAC) technologies have emerged as a promising avenue for actively reducing atmospheric CO2 concentrations. This comprehensive review seeks to provide a thorough examination of DAC technologies, encompassing their historical development, technical principles, and diverse methodologies. The review categorizes DAC technologies into chemical absorption methods, adsorption-based approaches, biological processes, and DAC with enhanced weathering, offering an in-depth analysis of each category. Technical assessments delve into the efficiency, scalability, and recent advancements within each DAC method, shedding light on the state-of-the-art developments in this rapidly evolving field. Challenges and opportunities associated with DAC are explored, encompassing technical hurdles, environmental considerations, and the evolving policy and regulatory landscape. The review investigates the complexities of DAC implementation, examining real-world case studies and pilot projects to extract valuable insights into operational challenges, successes, and lessons learned. Looking forward, the paper discusses future prospects and research directions within the DAC landscape. It explores emerging technologies, the integration of DAC with carbon utilization strategies, and the importance of collaborative initiatives and international cooperation. The abstract concludes by summarizing key findings, emphasizing the implications for climate change mitigation, and issuing a call to action for policymakers, researchers, and stakeholders to collectively address challenges and advance the deployment of DAC technologies. This comprehensive review aims to contribute to the evolving discourse on carbon removal strategies by providing a holistic and up-to-date analysis of DAC technologies, paving the way for informed decision-making and accelerating progress toward achieving global carbon reduction goals.

Keywords: Direct Air Capture (DAC), Technologies, Carbon, Removal

1. Introduction

Climate change poses a significant threat to the planet, primarily driven by the unprecedented increase in carbon dioxide (CO2) emissions resulting from human activities (Beck and Mahony, 2018) [3]. The urgency to address carbon emissions has never been more pressing, as evidenced by the escalating impacts of global warming, extreme weather events, and ecological disruptions. In response to this imperative, carbon removal technologies have emerged as a critical component of the strategy to mitigate climate change. The concept of carbon removal involves actively extracting CO2 from the atmosphere, aiming to achieve a net reduction in greenhouse gas concentrations (Carton *et al.*, 2020) [5]. Carbon removal technologies play a pivotal role in complementing traditional mitigation efforts, offering solutions to offset emissions that are challenging to eliminate directly. These technologies encompass a range of approaches, each with its unique mechanisms for capturing and storing carbon.

objectives of this review are threefold, aiming to comprehensively explore the realm of Direct Air Capture (DAC) technologies and their implications: Identify and Assess Various DAC Technologies, provide an exhaustive categorization of DAC technologies, including chemical absorption methods, adsorption-based approaches, biological processes, and DAC with enhanced weathering. Evaluate the technical intricacies, mechanisms, and advancements within each DAC category.Understand the Potential of DAC in Achieving Carbon Removal Goals, analyze the capability of DAC technologies to actively remove carbon from the atmosphere. Explore the potential scalability of DAC to contribute significantly to global carbon removal targets. Evaluate the Challenges and Opportunities Associated with DAC, Investigate the technical, economic, and environmental challenges associated with DAC implementation. Identify opportunities for innovation, improvement, and overcoming barriers in the deployment of DAC technologies. (Lackner, 2003; Keith, *et al*., 2018) [18, 16].

Carbon removal encompasses a spectrum of strategies, ranging from afforestation and reforestation to ocean-based approaches (Claes *et al*., 2022) [7]. DAC, as a technological intervention, stands out for its ability to directly capture CO2 from the ambient air, offering a complementary approach to natural carbon sinks. DAC technologies possess distinct features, including their independence from specific geographic locations, enabling deployment in various settings. The potential advantages include the ability to address emissions from point sources and flexibility in locating DAC facilities, thereby contributing to a diversified and resilient carbon removal portfolio.

2.1 Background of Direct Air Capture

Direct Air Capture (DAC) is a cutting-edge technological approach designed to actively remove carbon dioxide (CO2) directly from the ambient air (Chowdhury *et al*., 2023) [6]. This process stands as a testament to human ingenuity in addressing the urgent need for carbon removal. The fundamental principle of DAC involves deploying specialized technologies that can selectively capture CO2 molecules from the air, providing a targeted solution to combat the rising concentrations of greenhouse gases. DAC technologies operate based on a range of principles, with common methodologies including chemical absorption, adsorption, biological processes, and enhanced weathering. In chemical absorption methods, liquid sorbents or solvents react with CO2 to form a compound, which is subsequently separated for storage. Adsorption-based methods utilize solid sorbents to selectively capture CO2, offering advantages in terms of regeneration and reusability. Biological processes leverage the natural capacity of certain microorganisms or plants to absorb and store carbon. Enhanced weathering, on the other hand, involves the accelerated breakdown of minerals, leading to the absorption of CO2 during the process (Lackner, 2003; Holmes *et al*., 2019) [18, 15]. The development of DAC technologies has undergone significant strides since its conceptualization. Early endeavors in the late 20th century laid the groundwork for understanding the feasibility and challenges associated with capturing CO2 directly from the atmosphere. Over the years, research efforts intensified, with notable milestones including advancements in materials science, engineering, and the emergence of novel methodologies. The timeline of DAC development reflects a convergence of interdisciplinary efforts, integrating insights from chemistry, materials science, and environmental engineering. Ongoing research endeavors focus on improving the efficiency, cost-effectiveness, and scalability of DAC technologies to transition from theoretical concepts to practical, real-world applications.The landscape of DAC technologies is diverse, encompassing several distinct approaches (Madhu *et al*., 2021) [19]. Each category of DAC methods has its unique mechanisms and challenges, Chemical Absorption Methods: Utilize liquid sorbents or solvents to chemically react with CO2, forming a compound that can be separated for storage.Adsorption-Based Methods: Rely on solid sorbents to selectively capture CO2, offering advantages in terms of regeneration and reusability. Biological Processes: Leverage the natural capacity of certain microorganisms or plants to absorb and store carbon. Direct Air Capture with Enhanced Weathering: Involves the accelerated breakdown of minerals to absorb CO2 during the process. The diversity of DAC technologies allows for a nuanced exploration of their respective merits, challenges, and potential applications.

2.2 Technical Assessment of DAC Technologies

Chemical absorption methods represent a cornerstone in the arsenal of Direct Air Capture (DAC) technologies. These methods involve the use of liquid sorbents or solvents to chemically react with carbon dioxide (CO2) from the ambient air. The resulting compound is then separated, allowing for the capture and subsequent storage of CO2 (Yang *et al*., 2011) [38]. A variety of solvents have been explored, each with unique properties influencing the efficiency and cost-effectiveness of the capture process. Recent advancements in chemical absorption methods have focused on enhancing the performance of solvents, aiming to increase their selectivity for CO2 and reduce energy requirements for regeneration. Innovations in materials science and process engineering have led to the development of novel sorbents, which exhibit improved stability and reusability. The continual refinement of chemical absorption technologies contributes to making DAC more energy-efficient and economically viable. Adsorption-based DAC methods rely on solid sorbents to selectively capture CO2 from the air (Zhu *et al*., 2022) [42]. These sorbents, often in the form of porous materials, exhibit high surface areas and specific affinities for CO2 molecules. The capture process involves the adsorption of CO2 onto the surface of the sorbent, with subsequent desorption allowing for the release and storage of captured CO2 (Yu *et al*., 2012) [39]. Recent research in adsorption-based DAC has focused on optimizing the design and composition of sorbents to enhance their selectivity, capacity, and recyclability. Breakthroughs in materials science have led to the development of advanced porous materials, such as metal-organic frameworks (MOFs) and activated carbon, with promising attributes for CO2 capture. The potential for regenerating and reusing sorbents is a key advantage, contributing to the economic viability of adsorption-based DAC technologies. Biological processes represent an intriguing avenue within the spectrum of DAC technologies (Erans *et al*., 2022) [9]. Leveraging the natural capacity of certain microorganisms or plants to absorb and store carbon, biological DAC methods offer a unique approach to carbon capture. Engineered microorganisms or bioenergy crops can be designed to enhance their carbon-sequestering capabilities, providing a renewable and potentially sustainable solution. However, biological DAC methods come with their own set of challenges, including concerns related to genetic engineering, scalability, and unintended environmental impacts. Ethical considerations surrounding the use of genetically modified organisms in large-scale carbon capture projects necessitate careful evaluation and regulatory frameworks. Despite these challenges, the potential for biological processes to contribute to DAC underscores the importance of interdisciplinary research and responsible innovation. Direct Air Capture with Enhanced Weathering introduces a geoengineering approach to carbon removal (Strefler *et al*., 2018) [34]. This method involves the accelerated breakdown of minerals, leading to the absorption of CO2 during the weathering process. Enhanced weathering utilizes the natural process of mineral carbonation but accelerates it through human intervention, effectively enhancing the rate at which CO2 is sequestered in stable carbonate minerals. Despite its potential, direct air capture with enhanced weathering faces challenges related to the scalability and environmental impacts associated with large-scale mineral deployment (Campbell *et al*., 2022) [4]. Evaluating the long-term effects on ecosystems, soil health, and the availability of suitable minerals is crucial for responsible implementation. Research in this area focuses on identifying appropriate mineral sources, optimizing reaction rates, and assessing the overall feasibility of large-scale deployment.

2.3 Challenges and Opportunities

Direct Air Capture (DAC) technologies, while promising, face a spectrum of technical challenges that require careful consideration for successful implementation. One of the primary challenges is the significant energy required for DAC processes (Erans *et al*., 2022) [9]. The energy-intensive nature of capturing CO2 directly from the air can hinder the overall efficiency of DAC technologies. Innovations in energy-efficient capture methods and integration with renewable energy sources are critical for overcoming this challenge. The economic viability of DAC is closely tied to the cost of capture and storage. Current DAC technologies often face challenges in achieving cost competitiveness with traditional carbon capture methods (Erans *et al*., 2022) [9]. Ongoing research focuses on reducing costs through technological advancements, process optimization, and economies of scale. Scaling up DAC technologies from small-scale demonstrations to industrial-sized operations poses engineering and logistical challenges. Integrating DAC with existing industrial infrastructure and ensuring compatibility with other carbon capture methods are essential considerations.

Environmental and Ethical Considerations, Large-scale deployment of DAC facilities may have land use implications, necessitating careful consideration of ecological impacts (Green, 2023) [14]. Balancing the need for DAC deployment with the preservation of ecosystems is crucial to prevent unintended environmental consequences The deployment of DAC technologies, especially those involving biological processes, may raise concerns about potential impacts on ecosystems and biodiversity. Ensuring that DAC projects adhere to sustainability principles and minimize ecological disruption is essential.Biological DAC methods may involve the use of genetically modified organisms (GMOs), raising ethical considerations regarding the release of engineered organisms into the environment. Establishing ethical guidelines and regulatory frameworks for the responsible use of GMOs in DAC projects is crucial.

Policy and Regulatory Landscape, the success of DAC technologies is intricately linked to the policy and regulatory landscape (Shynu and Singh, 2016) [30]. An analysis of existing policies that either support or hinder DAC deployment provides insights into the regulatory framework and identifies areas for improvement. Given the global nature of climate change, international collaboration is essential for the successful deployment of DAC technologies. Examining existing collaborative initiatives and advocating for increased international cooperation in research, development, and implementation is crucial.

2.4 Current State of DAC Research and Development

Recent years have witnessed significant advancements in materials science, contributing to the development of more efficient and cost-effective sorbents for DAC. Novel materials, such as metal-organic frameworks (MOFs) and advanced polymers, exhibit enhanced selectivity and capacity for CO2 capture (Usman *et al*., 2022; Raji *et al*., 2023) [37, 29]. Research in this area aims to push the boundaries of sorbent performance, addressing challenges related to regeneration and durability. Addressing the challenge of scaling up DAC technologies is paramount for their practical implementation. Recent research focuses on engineering solutions and optimization strategies to transition from small-scale demonstrations to large industrial applications. Scalability considerations encompass the development of modular DAC units, integration with existing infrastructure, and the exploration of diverse deployment scenarios. Several DAC pilot projects have been initiated globally, providing valuable insights into the practical challenges and opportunities associated with large-scale implementation (Olatoye *et al*., 2024; Awonuga *et al*., 2024) [26, 2]. These projects serve as testbeds for different DAC technologies, allowing researchers and engineers to refine their approaches based on real-world data. Operational DAC facilities offer valuable lessons learned from their experiences in capturing and storing atmospheric CO2. These insights cover technical, economic, and regulatory aspects, shedding light on the realities of DAC deployment. Researchers analyze the performance of DAC technologies in diverse settings to inform future advancements and optimize the overall carbon removal process. Integrating DAC with carbon utilization strategies represents a synergistic approach to address climate change. Recent research explores the potential synergies between DAC and carbon utilization technologies, such as direct utilization of captured CO2 for the production of valuable products, carbon-neutral fuels, or enhanced oil recovery. The economic viability of DAC can be enhanced by integrating it into a circular carbon economy framework (Erans *et al*., 2022) [9]. Recent studies explore the potential for DAC to play a role in closing the carbon loop, where captured CO2 is utilized in a closed-loop system, contributing to sustainability and resource efficiency.

2.5 Economic Considerations and Financing Models

The cost of Direct Air Capture (DAC) plays a crucial role in determining its feasibility as a carbon removal strategy. Researchers conduct comprehensive cost-benefit analyses, considering factors such as energy requirements, materials, labor, and maintenance. Understanding the economic implications of DAC is essential for policymakers, businesses, and investors seeking sustainable solutions. DAC is positioned within a landscape of various carbon removal technologies. Comparative economic analyses with other methods, such as afforestation, ocean-based solutions, and soil carbon sequestration, provide insights into the cost-effectiveness and scalability of DAC (Socolow *et al*., 2011; Odunaiya *et al*., 2024) [32, 24]. This comparative assessment informs policymakers and investors about the diverse portfolio of available carbon removal options.DAC deployment requires substantial financial investment. Analyzing the role of both public and private sectors in financing DAC projects is crucial. Governments, through subsidies and incentives, can encourage private sector involvement. Evaluating the effectiveness of financial mechanisms, such as tax credits and grants, aids in creating a conducive environment for DAC innovation. The integration of DAC into carbon markets provides a potential revenue stream. Examining the role of DAC in carbon offsetting and its implications for businesses and industries striving for carbon neutrality is essential (Garcia Alvarez, 2023; Eze *et al*., 2023) [12, 10]. Understanding the dynamics of carbon pricing and trading mechanisms facilitates the creation of financial models that support DAC projects. Governments can play a pivotal role in incentivizing DAC deployment through a range of policy instruments. Analyzing the effectiveness of incentives, such as production tax credits, grants, and low-interest loans, informs policymakers about the most impactful measures to accelerate the adoption of DAC technologies (Gowd *et al*., 2023; Odeyemi *et al*., 2024) [13, 23]. A comprehensive regulatory framework is essential for the successful deployment of DAC. Examining existing regulations and proposing adjustments that streamline the permitting, monitoring, and verification processes for DAC facilities ensures a conducive environment for innovation while maintaining environmental and safety standards.

2.6 Social and Ethical Dimensions of DAC Deployment

Successful deployment of Direct Air Capture (DAC) technologies requires active engagement with local communities. Researchers and policymakers should prioritize community consultation to address concerns, gather local knowledge, and ensure that DAC facilities align with community values (Mohnot *et al*., 2019; Anoke *et al*., 2023) [21, 1]. Understanding and mitigating potential social impacts are critical for fostering acceptance and collaboration. DAC deployment has the potential to contribute to local economies by creating job opportunities and fostering economic development. Analyzing the socio-economic impact of DAC projects, including the number and types of jobs generated, can guide policymakers in designing inclusive strategies that benefit both the environment and local communities. DAC deployment should be approached with a commitment to equity and environmental justice. Assessing the distribution of benefits and burdens among different social groups helps identify and address potential disparities. Ethical considerations involve ensuring that DAC projects do not disproportionately impact marginalized communities and that benefits are shared equitably (Yu *et al*., 2023; Okoye *et al*., 2023) [40, 25].The ethical implementation of DAC involves considering public perceptions and garnering social acceptance. Understanding the factors that influence public attitudes toward DAC, addressing concerns related to environmental, health, and safety impacts, and fostering transparent communication are essential elements of an ethical deployment strategy. DAC projects must respect and incorporate indigenous knowledge and practices. Collaborating with indigenous communities ensures that DAC deployment aligns with cultural values and environmental stewardship principles (Sillitoe, 1998) [31]. Recognizing and incorporating traditional ecological knowledge contributes to the ethical and culturally sensitive implementation of DAC technologies.DAC deployment should prioritize the protection of sacred sites and biodiversity, especially in areas with cultural significance. Integrating cultural impact assessments into the planning process ensures that DAC facilities are sited and operated in a manner that respects and preserves the cultural and ecological heritage of the surrounding areas.

2.7 Public Perception and Communication Strategies

Public awareness and understanding of Direct Air Capture (DAC) are essential for its successful deployment (Song and Oh, 2023) [33]. Assessing the current level of public knowledge, attitudes, and perceptions regarding DAC technologies through surveys and public opinion research provides valuable insights. Understanding the factors that influence public opinions helps in developing targeted communication strategies. Identifying the factors that influence public acceptance or resistance to DAC is crucial. These factors may include perceptions of environmental impact, ethical considerations, economic implications, and the perceived urgency of addressing climate change. Addressing these factors through targeted communication strategies can contribute to building public support. Providing transparent and accessible information about DAC is vital for engaging the public. Clear and concise communication materials that explain the technology, its benefits, risks, and potential impacts in a comprehensible manner help build trust (Fischhoff, 2012) [11]. Utilizing various communication channels, including websites, educational materials, and community forums, ensures widespread access to information. Engaging with stakeholders, including local communities, environmental organizations, and industry representatives, fosters an inclusive dialogue (Krug *et al*., 2020; Oshioste *et al*., 2023) [17, 28]. Stakeholder consultations provide a platform for addressing concerns, gathering feedback, and incorporating diverse perspectives into the decision-making process. Meaningful engagement contributes to the development of socially responsible DAC projects. Public perception can be influenced by misconceptions and misinformation. Identifying prevalent misconceptions about DAC and developing targeted strategies to address them help build an accurate understanding of the technology. Providing fact-based information through educational campaigns and media outreach is essential in dispelling myths (Dada *et al*., 2022 [8]; Udokwu *et al*., 2023). Building and maintaining public trust requires a commitment to accountability. Establishing clear mechanisms for monitoring, reporting, and addressing concerns enhances transparency. Collaborating with independent third-party organizations for project evaluations and verification can further strengthen accountability, contributing to increased public confidence in DAC technologies.

2.8 Future Prospects and Research Directions

The evolution of materials science remains crucial for the advancement of DAC technologies (McQueen *et al*., 2021) [20]. Ongoing research in developing novel sorbents, such as advanced polymers and metal-organic frameworks (MOFs), aims to enhance the efficiency and cost-effectiveness of CO2 capture. Exploring new materials with improved selectivity and durability is essential for the continuous evolution of DAC. Addressing the challenge of scalability is an ongoing area of research. Engineers and researchers focus on developing scalable and modular DAC units, optimizing integration with existing infrastructure, and exploring innovative engineering solutions. As DAC moves from pilot projects to large-scale deployment, continued research in scalability is imperative.Future research will explore the synergies between DAC and carbon utilization technologies. Investigating direct utilization of captured CO2 for the production of fuels, chemicals, or other valuable products presents an avenue for creating a circular carbon economy (Nandhini *et al*., 2023 [22]; Udokwu *et al*., 2023). Research in this area will focus on enhancing the economic viability and sustainability of DAC. Advancements in Carbon Storage Techniques, Research in carbon storage techniques is crucial for ensuring the long-term effectiveness of DAC in carbon removal (Yusuf and Ibrahim, 2023; Onunka *et al*., 2023) [41, 27]. Investigating innovative approaches for secure and reliable storage of captured CO2, including geological storage and mineralization, will be a focus. Continued advancements in carbon storage technologies will contribute to the overall success of DAC as a climate mitigation strategy. The establishment and refinement of regulatory standards for DAC deployment will be an ongoing process. Research will focus on evaluating the effectiveness of existing regulations, proposing adjustments to address emerging challenges, and ensuring a robust regulatory framework that balances innovation with environmental and safety considerations. Given the global nature of climate change, research will emphasize the role of international collaboration in DAC deployment. Evaluating existing collaborative initiatives and advocating for increased cooperation in research, development, and implementation will be essential for addressing climate change on a global scale.

2.9 Conclusion

The review of Direct Air Capture (DAC) technologies for carbon removal reveals a dynamic landscape with immense potential and challenges. DAC presents a promising avenue for mitigating climate change by directly addressing atmospheric carbon dioxide levels. Throughout this comprehensive exploration, several key findings and implications have emerged.The urgency of addressing carbon emissions and climate change necessitates the exploration of diverse carbon removal strategies, and DAC stands out as a viable and scalable option. Its ability to capture CO2 directly from the atmosphere offers a unique complement to other mitigation measures, contributing to the goal of achieving net-zero emissions. Technological advancements in materials science, engineering solutions, and scalability are critical for the success of DAC. Ongoing research in these areas aims to enhance the efficiency, reduce costs, and facilitate the large-scale deployment of DAC technologies. Integration with carbon utilization methods and advancements in carbon storage techniques further enrich the potential of DAC in creating a sustainable carbon management ecosystem. The socio-economic and ethical dimensions of DAC deployment demand careful consideration. Community engagement, job creation, and the ethical implementation of DAC are essential for building public trust and ensuring the technology's acceptance. Cultural and indigenous perspectives emphasize the importance of respecting local knowledge and practices, safeguarding sacred sites, and promoting environmental justice.The policy and regulatory frameworks surrounding DAC require continuous refinement. Striking a balance between fostering innovation and maintaining environmental and safety standards is crucial. International collaboration is imperative to address the global nature of climate change, and research indicates the need for coordinated efforts in DAC development and deployment. Looking ahead, future prospects for DAC involve ongoing technological advancements, integration with carbon utilization, and the development of robust policy frameworks. The refinement of regulatory standards and international collaboration will play pivotal roles in shaping the trajectory of DAC as a key player in climate change mitigation. In essence, the comprehensive review underscores the multifaceted nature of DAC, emphasizing its potential to contribute significantly to carbon removal efforts. As we navigate the complex challenges of climate change, DAC emerges as a valuable tool that, when coupled with a holistic approach and ethical considerations, can contribute to a more sustainable and resilient future. Continued research, innovation, and collaboration will be paramount in realizing the full potential of DAC as a transformative solution in the fight against climate change.

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