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| RESEARCH ARTICLE

The Convergence of AI and Nature: Advancing Carbon Dioxide Capture, Removal, and Storage Technologies through Integrated Ecosystem-Based Strategies

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| ABSTRACT

This paper examines the critical integration of Artificial Intelligence (AI) and Nature-Based Solutions (NbS) to enhance Carbon Dioxide Capture, Removal, and Storage (CCRS) technologies. Recognizing the limitations of current approaches, the study proposes that combining AI's analytical power with natural ecosystems' carbon sequestration potential offers a transformative pathway for achieving significant negative emissions and sustainable carbon storage. The research details AI's role in optimizing the entire carbon management lifecycle. This includes AI-driven advancements in material design and process control for technological carbon capture, and data-driven management for improved biological carbon removal through optimal NbS deployment. Specifically, the paper highlights AI techniques like machine learning and predictive modeling for enhanced monitoring of blue carbon ecosystems (e.g., salt marshes, seagrass beds), utilizing remote sensing to maximize their sequestration potential. Additionally, the study explores AI-driven precision agriculture for optimizing soil carbon sequestration via advanced fertilization and tailored soil management. It also assesses AI's application in species and site selection for large-scale afforestation and reforestation, considering factors like growth rates and climate resilience. The integration of AI-powered Measurement, Reporting, and Verification (MRV) systems is also discussed to bolster the credibility of carbon credits from NbS. The paper includes relevant case studies, such as AI-powered process automation in industrial carbon capture and AI's emerging use in the built environment for emission prediction. Crucially, the work addresses ethical considerations and potential challenges, including AI's energy consumption, data quality, and algorithmic biases. Through a comprehensive review, this study identifies critical research directions and proposes a robust framework for ethical and sustainable integrated AI-NbS CCRS systems. It concludes that the judicious fusion of AI with the natural benefits of NbS provides a potent and economically viable strategy for achieving substantial reductions in atmospheric carbon dioxide, thereby contributing significantly to global net-zero emissions targets and fostering a sustainable future.

| KEYWORDS

Artificial Intelligence (AI), Carbon Capture and Storage (CCS), Carbon Dioxide Removal (CDR), Climate Change Mitigation, Machine Learning, Nature-Based Solutions (NbS), Sustainable Development.

| ARTICLE INFORMATION

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1. Introduction

Although they are similar, CCR (Carbon Capture and Removal) and CCS (Carbon Capture and Storage) are not the same. The process of extracting carbon dioxide (CO_2) from the atmosphere and storing it for decades or centuries in plants, soils, rocks, saline aquifers, depleted oil wells, or long-lasting goods like cement is called carbon removal, often referred to as carbon dioxide removal (CDR) or carbon drawdown. Scientists have proposed numerous techniques for removing carbon. While some are still in the early phases of research and development, others are currently being used comparatively limitedly. Negative emissions technologies, or NETs, are methods and technologies used to remove carbon (Institute for Carbon Removal Law and Policy & American University, n.d.). Climate change and global warming are currently the world's top concerns. However, this issue has contributed to floods in some nations and deserts in others, and ignoring these changes would pose a serious threat to the sustainability of the ecosystem. Research has demonstrated that the primary source of this problem is the rise in the atmospheric concentration of carbon dioxide (CO_2). As a result, researchers are actively looking for suitable ways to either minimize the negative impacts of CO_2 emissions or reduce them. Global warming has been addressed through several measures, such as enhancing the efficiency of current operations through waste heat recovery in energy-intensive industries like cement, steel, aluminum, ceramics, and so forth. Also being used are environmentally friendly and efficient energy conversion technologies, such as fuel cells that run on renewable energy. Furthermore, using renewable energy sources has little to no negative effects on the environment. The process of capturing CO_2 from power plants, industrial operations, and other point sources and storing it underground or using it in other ways is known as carbon capture and storage, or CCS. One important factor influencing CCS's efficacy and cost-efficiency is how soluble CO_2 is in the capture solvent (Nassef, 2023). Because between 15 and 40 percent of the carbon dioxide that humans emit will stay in the atmosphere for up to 1,000 years, with around 10 to 25 percent of its remaining for tens of thousands of years, carbon removal is important. By delaying or even stopping climate change, removing and sequestering that carbon dioxide could lower climate risk indefinitely (Institute for Carbon Removal Law and Policy & American University, n.d.).

A comprehensive approach that includes both the active management of carbon dioxide already present in the atmosphere and considerable reductions in greenhouse gas emissions is necessary to address the urgency of climate change (IPCC, 2021). Carbon dioxide removal (CDR), carbon storage, and carbon capture methods and procedures are all included in carbon management. According to Wikipedia editors (2025a), carbon capture methods actively remove CO_2 from the atmosphere, whereas carbon capture technologies prevent CO_2 emissions from point sources. For long periods, captured or removed CO_2 is kept out of the atmosphere thanks to durable carbon storage (IPCC AR6 WGIII, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), CDR is necessary to control global warming and reach net-zero emissions targets. One essential pathway for CDR is provided by nature-based solutions (NbS), which sequester carbon through natural processes. These include soil carbon sequestration, afforestation, and reforestation, and they frequently offer other advantages like increased biodiversity. Artificial intelligence (AI) offers a revolutionary chance to improve all aspects of carbon management systems, from streamlining capture procedures to enhancing storage monitoring and verification. This study investigates how NbS and AI may be integrated into various aspects of carbon management, looking at how they could be able to develop a more efficient and sustainable strategy for combating climate change. An overview of the several technologies used for CO_2 capture is given in Figure 01 below, with an emphasis on those that particularly address the solubility element of CO_2 capture.

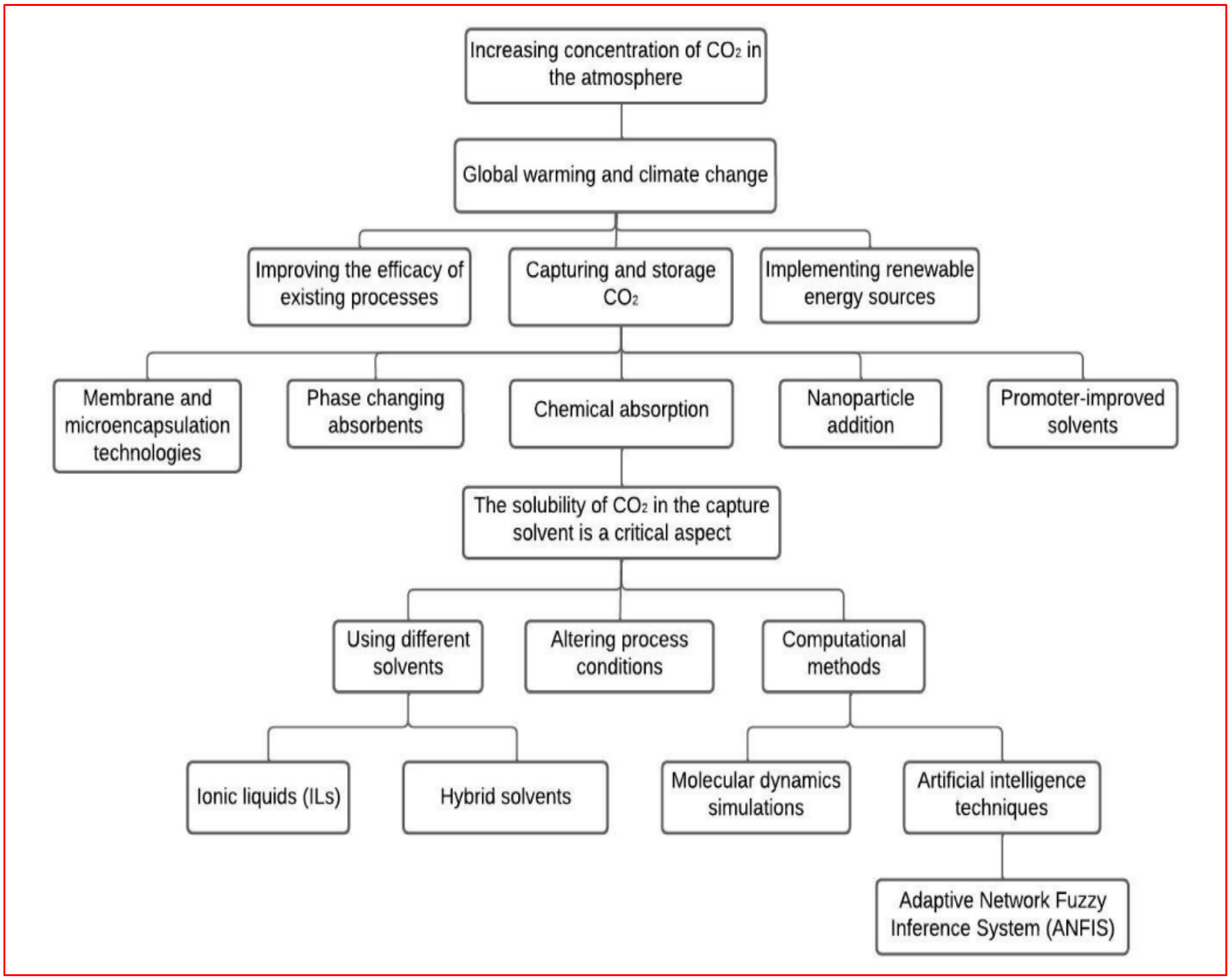

Figure 01: Schematics of solubility-based systems for visualizing CO_2 capture (Source: Nassef, 2023).

AI has a significant impact on reducing CO_2 emissions, as seen in Figure 02 below. A cycle of GHG sequestration based on AI is represented by the left scheme. In the right framework, the function of AI software is described.

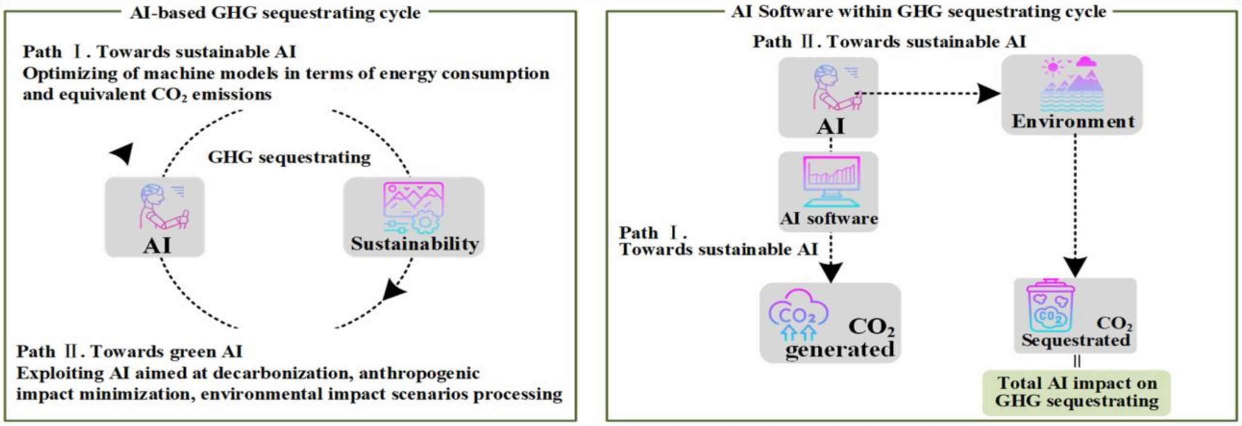

Figure 02: high-level AI-based GHG sequestration solutions (Source: G. Li et al., 2024).

A multifaceted strategy is required to reduce greenhouse gas emissions due to the growing climate catastrophe, and this strategy includes removing, storing, and capturing carbon dioxide (CO_2) from the atmosphere. The merging of artificial intelligence (AI) with nature-based solutions (NbS) to improve these vital processes is examined in this research. Utilizing ecosystems for carbon sequestration, nature-based solutions provide accessible, affordable solutions with a host of additional advantages. Both technical and nature-based approaches to carbon management can be made much more accurate, efficient, and scalable with the use of artificial intelligence's sophisticated analytical and predictive powers. Throughout the whole carbon management lifecycle, this study explores the many technologies used in carbon collection, removal, and storage, emphasizing the function of NbS and the revolutionary potential of AI. It looks at how AI and NbS operate together, how difficult and morally complex it is to integrate, what is being done now, and what legislative frameworks are required to encourage their broad use for a sustainable future.

2. Literature Review

A significant study into strategies for controlling atmospheric carbon dioxide (CO_2) has been prompted by the growing threat posed by climate change. The present status of research on carbon dioxide capture, removal, and storage (CCRS) technologies is examined in this review of the literature, with an emphasis on the combination of artificial intelligence (AI) and nature-based solutions (NbS). The review provides a thorough overview of the topic by synthesizing findings from current scholarly articles, reports, and projects. According to the Intergovernmental Panel on Climate Change (IPCC), carbon dioxide removal (CDR) is essential to achieving net-zero emissions and containing global warming, underscoring the significance of successful CCRS techniques. With a focus on its crucial significance in climate research and politics, the scientific literature on CDR has grown dramatically. Land-based techniques, including afforestation and reforestation (FAQ Chapter 4-Global Warming of 1.5 OC, n.d.), soil carbon sequestration (Lück et al., 2024), and biochar production (Wikipedia contributors, 2025c) are among the different approaches to CDR that are being investigated. Additionally, ocean-based CDR techniques like blue carbon management and ocean alkalinity augmentation are becoming more popular (Carbonregistry.com, n.d.). Technological solutions like Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) represent other key areas of research. Since nature-based solutions (NbS) offer quick and reliable ways to remove carbon while also bringing co-benefits like increased biodiversity and ecosystem resilience, their promise in carbon sequestration is becoming more widely acknowledged. According to the IPCC, NbS is essential for reducing carbon emissions and includes forest restoration and better land management (Nature-based Solutions for Climate, 2025). Initiatives for reforestation are essential NbS for boosting soil and biomass carbon storage. Another major possibility is the sequestration of soil carbon through techniques such as conservation tillage and cover crops (Nature-based Solutions for Climate, 2025b).

Artificial intelligence (AI) is becoming a game-changing technology in several areas of carbon management and climate change mitigation (United States Government, 2023). Real-time analysis of massive datasets by AI improves environmental monitoring, allowing for more precise predictions and risk reduction (Columbia University & Bezos Earth Fund, 2024). AI can optimize energy systems that use carbon capture technology in the context of CCRS and offer real-time facility monitoring for CDR (Bezos Earth Fund et al., 2023). AI is also being used to improve the efficacy and efficiency of nature-based carbon removal, such as tracking forests with drones and satellite imaging, and improving farming methods for sequestering carbon in the soil. The advancement of CCRS technologies can be greatly aided by the combination of AI and NbS. AI can optimize NbS management plans and site selection to optimize carbon sequestration (G. Li et al., 2024b). AI helps choose species, choose sites, and track the health and growth of trees in afforestation and reforestation (Alejo et al., 2025). AI offers suggestions for precision farming, intelligent plant selection, and data analysis on soil health in the context of soil carbon sequestration. AI is also essential to the management and observation of blue carbon ecosystems, for carbon removal initiatives to be credible, accurate monitoring, reporting, and verification (MRV) are essential. Through the study of satellite images, machine learning, and sensor data processing, artificial intelligence (AI) can completely transform MRV for NbS and provide more precise and scalable carbon sequestration verification. Numerous projects, like those by Pachama, Boo Mitra, Meta and WRI, and MORFO (Morfo, n.d.), show how AI may be used practically to improve MRV for nature-based carbon removal operations.

Notwithstanding its potential, the integration of AI and NbS for CCRS is fraught with difficulties, including the energy consumption of AI technologies and the carbon footprint of data centers, as well as issues with data accessibility, quality, and availability for AI-driven applications (United States Government, 2023). The use of AI in natural ecosystems raises ethical concerns, such as algorithmic bias and potential ecological disruption, which must be carefully considered. Current projects are investigating the possibility of combining AI with NbS for CCRS. AI is used by AstraZeneca's AZ Forest program to track reforestation in Africa. AI and drone planting technology are combined with ReForest Latam to restore ecosystems (MIT Solve, n.d.). AI was used for watershed management in the Muskoka Integrated Watershed Management project (Capodaglio & Callegari, 2025). Ocean-based CDR is the focus of several businesses, such as Ebb Carbon (Cowls et al., 2021), Captura, and Planetary Technologies (REM Web Solutions - WebWiz@rd, n.d.). AI is being used by Agri Sense Carbon and Net Carbon to improve soil health and sequester carbon. Google and Microsoft are investing in nature-based carbon reduction projects and supporting AI businesses. In the future, research should concentrate on building ethical frameworks for AI in ecological applications, reducing the environmental impact of AI technologies ("Green AI") (S, 2024), and refining AI algorithms for carbon accounting and environmental monitoring. Additionally, more research is required to determine how AI and particular NbS might work together in various ecosystems. The substantial potential of combining artificial intelligence (AI) with natural solutions to improve carbon dioxide capture, removal, and storage technologies is highlighted in this research. AI overcomes many of the drawbacks of conventional techniques by providing strong tools for NbS optimization, monitoring, and verification. Even though issues with energy use, data quality, and moral ramifications need to be handled cautiously, further research and cooperative projects are opening the door to a more efficient and sustainable method of managing carbon emissions.

2.1 Carbon Dioxide Removal (Cdr) In the Context of Climate Change Mitigation

There is now widespread scientific agreement that effective mitigation measures are urgently needed due to the growing frequency and severity of climate change impacts, which are directly linked to rising global temperatures. One of the primary conclusions of climate science is that a fundamental change in our relationship with carbon dioxide (CO_2) is required to stabilize global temperatures at levels that avoid the most disastrous effects of climate change. In particular, to achieve this equilibrium, CO_2 emissions from human activity must be offset by an equal amount of CO_2 extracted from the atmosphere. Net-zero carbon dioxide (CO_2) emissions are the definition of this crucial equilibrium. Emissions reductions alone may not be enough to meet the required temperature stabilization targets, even though aggressive and sustained reductions in anthropogenic (human-caused) CO_2 emissions are the cornerstone of any climate change mitigation strategy. This acknowledgement is partly due to the inherent difficulties of totally eradicating emissions from every area of the world economy. Decarbonization is severely hampered by a few important economic sectors that are distinguished by intricate manufacturing processes. Complete emissions eradication is particularly challenging with existing technologies since industries like steel and cement manufacturing, for instance, entail chemical reactions that inherently generate CO_2. Often referred to as "residual emissions," the emissions from these difficult-to-decarbonize industries are likely to continue even after significant attempts to reduce emissions.

Approaches to actively remove CO_2 from the environment are becoming more popular to offset these inevitable residual emissions and to address the historical buildup of CO_2 in the atmosphere. Scientists are currently exploring and improving a variety of methods intended to increase the Earth's land surface and seas' inherent ability to absorb CO_2. The goal of these strategies is to support the role of natural "carbon sinks." At the same time, substantial research and development are being focused on creating and implementing innovative technology techniques designed especially for CO_2 removal. The term Carbon Dioxide Removal (CDR) refers to both the technology and nature-based techniques. The fact that practically every climate scenario evaluated by the Intergovernmental Panel on Climate Change (IPCC) that successfully keeps the rise in global temperatures to particular stabilization levels depends, in one way or another, on the application of CDR to remove more CO_2 from the atmosphere than is released highlights the significance of CDR. It is important to recognize that there are other greenhouse gases (GHGs) besides CO_2 that contribute to the greenhouse effect and consequent global warming. CO_2 and a variety of other non-CO_2 GHGs contribute to the total effect of GHGs on global temperatures. Several other greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs), are released as a result of human activity, and all contribute to global warming. There are currently no large-scale, commercially feasible techniques for eliminating these non-CO_2 GHGs directly from the atmosphere. Therefore, additional removals of CO_2 from the atmosphere beyond those needed to offset CO_2 emissions are required to fully balance the warming potential of non-CO_2 GHG emissions that are difficult to abate at the source. This demonstrates how important CDR is to reaching complete climate neutrality.

The diverse landscape of CDR methods can be broadly categorized into several distinct approaches:

- **Terrestrial Carbon Sequestration:** The goal of these CDR techniques is to increase the land surface's absorption of CO_2. Because forests are important carbon sinks, afforestation and reforestation initiatives are common tactics to increase wooded areas. This also includes initiatives to enhance soil carbon sequestration through modified land management or agricultural methods.
- **Ocean-Based Carbon Dioxide Removal:** This group includes techniques aimed at enhancing the oceans' capacity to absorb CO_2. These techniques can be further separated into two categories: chemical (such as raising ocean alkalinity to increase the ocean's capacity to absorb CO_2) and biological (such as boosting the productivity of marine ecosystems to increase phytoplankton uptake of CO_2).
- **Technical Carbon Dioxide Removal:** This group includes engineering-based techniques for CO_2 direct capture. Examples include the chemical extraction of CO_2 from ambient air by direct air capture (DAC) and the utilization of bioenergy crops in conjunction with the geological storage and capture of CO_2 emitted during burning (BECCS).

Although CDR is a key element in the vast majority of climate scenarios that meet temperature stabilization targets, it is vital to recognize that some academics have voiced legitimate concerns about a high dependence on CDR for mitigating climate change. Uncertainties about the efficacy, technical and financial viability, scalability, and possible unforeseen negative consequences of the widespread use of specific CDR techniques are the main focus of these worries.

Specific concerns include:

- **Reversibility of Carbon Storage:** Natural disturbances like forest fires or modifications to land management techniques like tillage can cause carbon to be released back into the atmosphere. This is a problem for CDR techniques that depend on biological carbon storage, such as forestry and soil carbon enrichment. This possibility of reversibility calls into question how long-lasting carbon storage will be.
- **Competition with Other Land Uses:** Agriculture and other vital land uses may face competition from forestry and biofuel-based CDR techniques, which demand large land expanses. The competition may have consequences for biodiversity and food security.
- **Ecological Side Effects:** There is a chance that ocean-based CDR techniques will have unforeseen ecological effects. Marine ecosystems could be disrupted by changing ocean chemistry or promoting biological activity, necessitating careful study and observation.

On the other hand, studies also highlight possible co-benefits linked to specific CDR methodologies. The overall sustainability and appeal of CDR implementation may be improved by these co-benefits. Among the examples are:

- **Enhanced Agricultural production:** Soil fertility, water retention, and overall agricultural production can all be improved by increasing soil organic matter using soil carbon sequestration techniques.
- **Mitigation of Ocean Acidification:** The oceans' absorption of excess atmospheric CO_2 poses a serious threat to marine species, and some techniques for increasing ocean alkalinity may be able to mitigate this effect.

3. Methodology

This paper employs a mixed-methods approach, integrating a comprehensive literature review with a critical synthesis of existing research and emerging applications in the domain of Carbon Dioxide Capture, Removal, and

Storage (CCRS) technologies, with a specific focus on the integration of Artificial Intelligence (AI) and Nature-Based Solutions (NbS).

1) **Literature Review:** A systematic and extensive review of peer-reviewed scientific literature, technical reports, and policy documents was conducted using relevant databases (e.g., Web of Science, Scopus, Google Scholar). The search strategy incorporated keywords including "carbon capture," "carbon removal," "carbon storage," "nature-based solutions," "ecosystem-based strategies," "artificial intelligence," "machine learning," "remote sensing," "environmental monitoring," and combinations thereof. The review aimed to:

    - Establish the current state-of-the-art in CCRS technologies and the individual contributions of NbS and AI.
    - Identify existing research on the integration of AI with various NbS for carbon management.
    - Analyze the reported efficacy, scalability, and cost-effectiveness of these integrated approaches.
    - Examine the methodologies employed in previous studies, including data sources, analytical techniques, and validation methods.
    - Identify the challenges, ethical considerations, and knowledge gaps in the field.

2) **Synthesis and Critical Analysis:** The information gathered from the literature review was synthesized and critically analyzed to:

    - Evaluate the potential of AI to enhance the different stages of CCRS when applied to NbS, including site selection, species optimization, monitoring of carbon sequestration, and verification of carbon credits.
    - Assess the methodological rigor and limitations of existing studies on AI-NbS integration for carbon management.
    - Identify common themes, contrasting findings, and areas of consensus and divergence in the literature.
    - Develop a conceptual framework illustrating the synergistic relationship between AI and NbS in advancing CCRS technologies.
    - Highlight the scientific methods and data sources currently employed in AI-driven analysis of NbS for carbon management (e.g., analysis of satellite imagery using convolutional neural networks, time-series analysis of sensor data using recurrent neural networks, predictive modeling using regression and classification algorithms).

3) **Case Study Analysis (Illustrative):** While this paper primarily focuses on a review and synthesis, illustrative case studies of existing projects and research initiatives that successfully integrate AI and NbS for carbon management were examined. These case studies provided practical examples of the methodologies and outcomes of such integrated approaches, highlighting the scientific methods used for data acquisition, processing, and analysis in real-world applications.

4) **Identification of Research Directions:** Based on the literature review and critical analysis, key research gaps and promising future directions for methodological development in the integration of AI and NbS for CCRS were identified. This involved considering:
    - A need for standardized methodologies for data collection, processing, and validation in AI-driven NbS carbon management.
    - The development of robust and transparent MRV frameworks leveraging AI technologies.
    - The application of advanced AI techniques (e.g., explainable AI, federated learning) to address challenges such as data bias and privacy.
    - The development of integrated models that couple ecological processes with AI algorithms to optimize carbon sequestration outcomes.

This methodology provides a structured approach to analyze the current landscape of AI and NbS integration in CCRS, identify methodological strengths and weaknesses, and propose avenues for future research to advance this critical field. The emphasis is on a scientific and evidence-based evaluation of the potential of this convergence to contribute significantly to climate change mitigation efforts.

3.1 The Need for Carbon Management

A comprehensive approach that includes both the active management of carbon dioxide already present in the atmosphere and considerable reductions in greenhouse gas emissions is necessary to meet the urgency of climate change. Carbon dioxide removal (CDR), carbon storage, and carbon capture methods and procedures are all included in carbon management. According to Wikipedia editors (2025d), carbon capture methods actively remove CO_2 from the atmosphere, whereas carbon capture technologies prevent CO_2 emissions from point sources. Long-lasting carbon storage guarantees that the CO_2 that has been removed or captured stays out of the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), CDR is necessary to limit global warming and reach net-zero emissions targets (Carbon Gap, 2025). One essential pathway for CDR is provided by nature-based solutions (NbS), which sequester carbon through natural processes. These include soil carbon sequestration, afforestation, and reforestation, and they frequently offer other advantages like increased biodiversity. Artificial intelligence (AI) offers a revolutionary chance to improve all aspects of carbon management systems, from streamlining capture procedures to enhancing storage monitoring and verification. The integration of NbS and AI across the carbon management spectrum is examined in this research, along with their potential to develop a more effective and sustainable strategy for combating climate change.

3.2 Recognizing Technologies for Carbon Dioxide Capture, Removal, and Storage

- **Carbon Dioxide Capture Technologies:** To mitigate climate change, carbon dioxide capture technologies are essential since they stop CO_2 emissions from entering the atmosphere (Yu et al., 2023b). Both direct CO_2 capture from the atmosphere and big stationary sources such as power plants and industrial sites can be addressed by these methods (Lebling, n.d.; British Geological Survey, 2022). Post-combustion capture is a significant strategy that involves extracting CO_2 from flue gases following the burning of fossil fuels (British Geological Survey, 2022). This technique, which can be used on already-existing power plants, frequently entails using chemical solvents, such as amines, to cleanse the gas (Wikipedia authors, 2024). The removal of CO_2 before the fuel's burning is another method known as pre-combustion capture (Pre-combustion Capture - (Intro to Climate Science)- Vocab, Definition, Explanations, Fiveable, n.d.). This is frequently combined with gasification procedures, which turn fuel into syngas and remove CO_2 before the combustion of the hydrogen-rich gas (British Geological Survey, 2022). The greater CO_2 concentration makes this technique more effective (Pre-Combustion Carbon Capture Research, n.d.). Third, fuel is burned in an environment with almost pure oxygen, a process known as "oxy-fuel combustion" (9.2. Carbon Dioxide Capture Approaches, n.d.). This produces a flue gas that is mostly composed of CO_2 and water vapor, which facilitates the capture of CO_2 following the condensing of the water (British Geological Survey, 2022b; GLOBAL CCS INSTITUTE et al., 2012). Lastly, systems known as direct air capture (DAC) extract CO_2 straight from the surrounding air. This is crucial to handling distributed emissions and historical CO2. CO_2 can be captured by DAC using either liquid solvents or solid sorbents (Pre-combustion Capture - (Intro to Climate Science) - Vocab, Definition, Explanations, Fiveable, n.d.-b). The CO_2 that has been caught can subsequently be transferred and stored in deep underground geological formations or used in a variety of ways. These carbon dioxide capture technologies are vital instruments in the fight against global warming and the shift to a low-carbon future, despite obstacles like cost and energy requirements (Pre-combustion Capture - (Intro to Climate Science) - Vocab, Definition, Explanations, Fiveable, n.d.-b; Lebling, n.d.-b). The National Energy Technology Laboratory of the U.S. Department of Energy states that Carbon dioxide (CO_2) capture systems may be classified into three categories (9.2. Carbon Dioxide Capture Approaches, n.d.-b): post-combustion, pre-combustion, and oxy-combustion.

- **Carbon Dioxide Removal (CDR) Technologies:** The term Carbon Dioxide Removal (CDR) refers to a group of methods and technologies used to remove carbon dioxide (CO_2) straight from the atmosphere. The method of directly removing carbon dioxide (CO_2) from the surrounding air by chemical or physical means is known as direct air capture (DAC). The entire process of removing carbon dioxide is known as direct air carbon capture and sequestration (DACCS), provided that the removed CO_2 is subsequently stored in a secure location for an extended period of time. Negative emissions technologies (NETs) are systems that participate in this process (Wikipedia contributors, 2025g). An example of the potential appearance and functionality of direct air capture is shown in Figure 03 below.

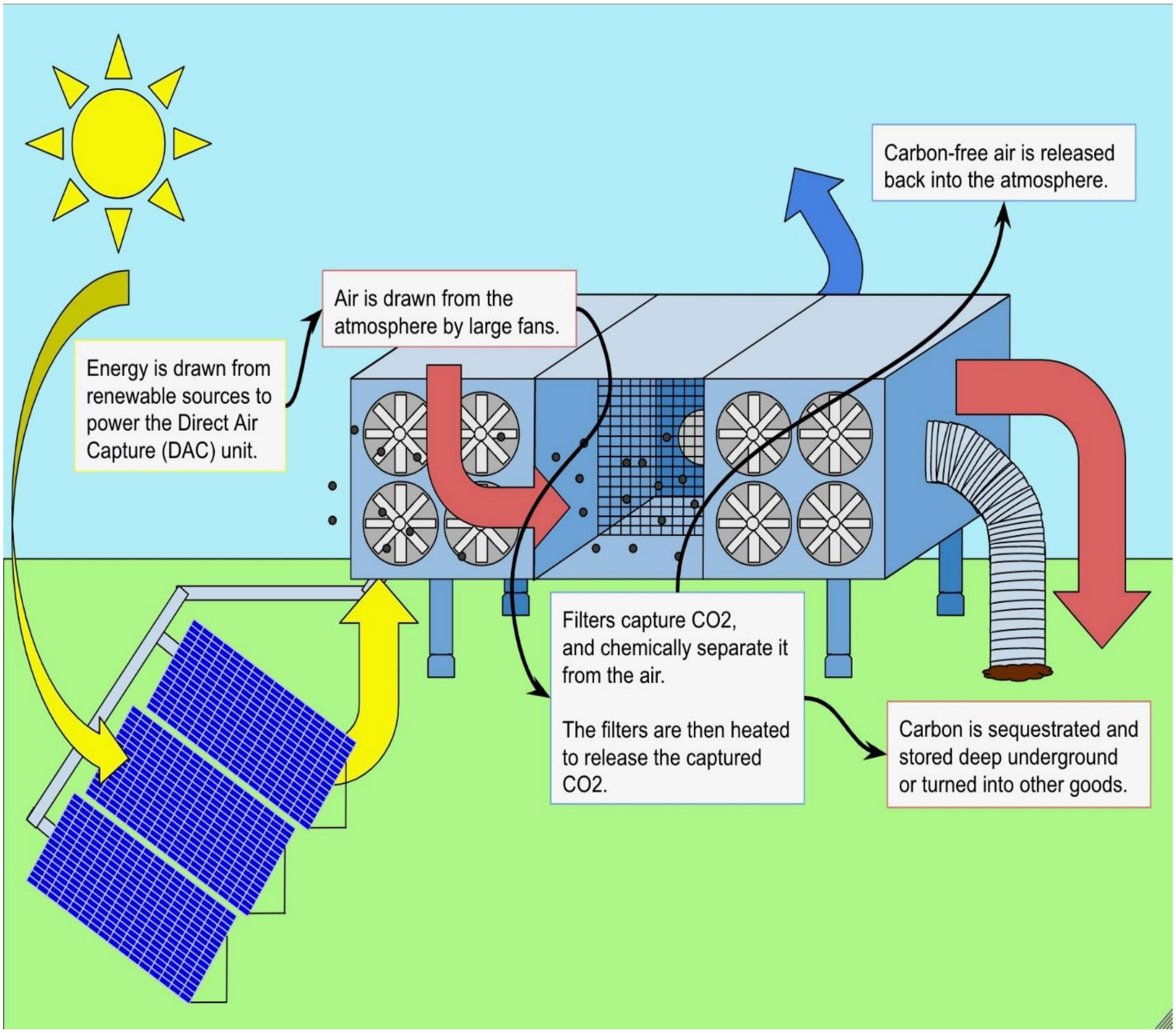

Figure 03: An illustration of the possible appearance and operation of direct air capture (Source: Wikipedia contributors, 2025g).

In contrast, carbon capture and storage (CCS) aims to capture CO_2 emissions at their source, such as industrial sites or power plants. The importance of CDR technology in climate change mitigation measures is becoming more widely acknowledged, especially when it comes to addressing historical emissions and those from industries whose emissions are difficult to reduce (Wikipedia contributors, 2025h). The importance of CDR in accomplishing climate goals in conjunction with notable decreases in greenhouse gas emissions has been emphasized by the Intergovernmental Panel on Climate Change (IPCC) and other scientific organizations. It is crucial to remember that CDR is meant to support current efforts to reduce emissions to create a sustainable future, not to take the place of them (Burtka, 2023).

Several CDR technology categories are now being developed and put into use. Utilizing natural processes and land-based techniques eliminates CO_2. Planting trees to store carbon in their biomass and the nearby soils is known as reforestation or afforestation. This practice has co-benefits like improved biodiversity and ecosystem restoration

(Carbonregistry.com, n.d.-b). However, the amount of land available may restrict how large these techniques may grow, and harvesting or fires may cause the stored carbon to be released. Agricultural methods that enhance soil resilience and health by increasing carbon storage in soils are the focus of soil carbon sequestration. However, the soil can only hold so much carbon, and if the soil is disturbed, it can be released (Nature-Based Carbon Dioxide Removal- En-ROADS User Guide, n.d.). Using finely ground silicate rocks spread across agricultural land speeds up natural chemical reactions that transform atmospheric CO_2 into stable bicarbonate ions, which are then carried to the ocean as part of enhanced weathering (Relying on Large-scale Carbon Dioxide Removal Risks Damaging the Biosphere, n.d.). This technique can also improve soil fertility, although there are still issues with limiting possible trace element release and tracking its efficacy (Fact Sheet: Soil Carbon Sequestration, n.d.). Heating biomass in an oxygen-limited environment produces biochar, a stable, carbon-rich substance that can be put into the soil for improved soil quality and long-term carbon storage (Cherlinka, 2024). Although biochar provides long-lasting carbon storage, its scalability is contingent upon the availability of sustainable biomass feedstocks. CO_2 emissions from biomass-based energy production are captured using Bioenergy with Carbon Capture and Storage (BECCS) and stored permanently, frequently underground (Enhanced Rock Weathering - UNDO Carbon, 2025). Although BECCS can provide energy and may have negative emissions, there are issues with land use, rivalry with food production, and the sustainability of biomass supplies. The designed, closed-system techniques and technologies for eliminating carbon dioxide are depicted in Figure 04 below.

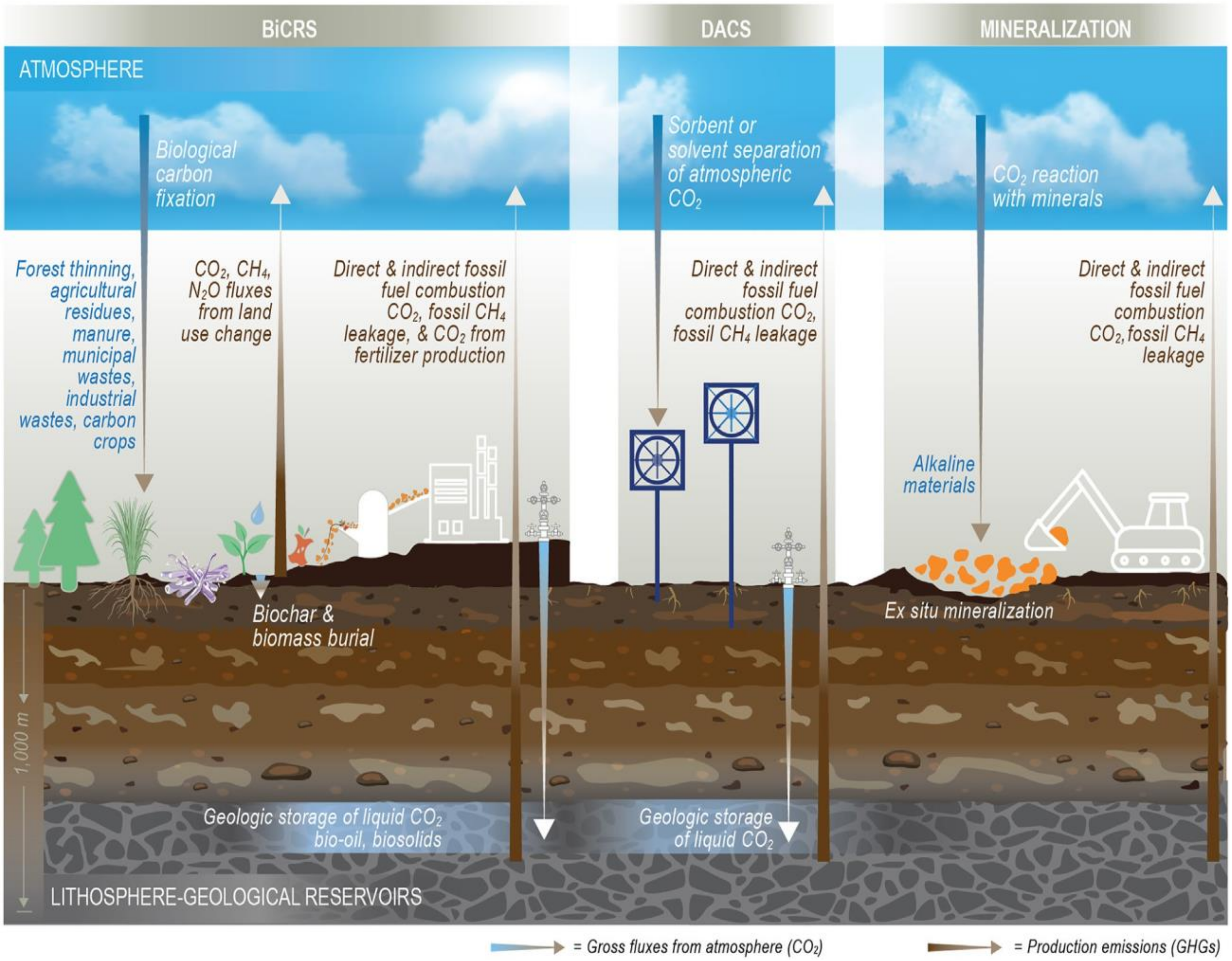

Figure 04: Designed, closed-system methods and technologies for removing carbon dioxide (Source: Nordahl et al., 2024).

Ocean-based CDR techniques take advantage of the ocean's enormous CO_2 absorption and storage capability. Adding alkaline minerals to seawater to boost its capacity to store CO_2 and possibly reverse ocean acidification is known as ocean alkalinity enhancement (NOAA Ocean Acidification Program, 2025). However, more research is needed to determine the scalability and long-term effects on marine ecosystems (Keith, 2025). By adding nutrients like iron, ocean fertilization seeks to increase phytoplankton growth and improve the uptake of CO_2 from the atmosphere (NOAA Ocean Acidification Program, 2025b). While possibly eliminating substantial amounts of carbon, questions regarding unforeseen ecological impacts linger (Lebling, n.d.-c). Blue carbon management focuses on maintaining and restoring coastal ecosystems such as mangroves and seagrasses, which are extremely effective carbon sinks and give co-benefits like biodiversity protection (McClain et al., 2021). Coastal pollution and industrialization, however, pose a threat to these ecosystems. Although direct ocean capture and electrochemical techniques use electricity to remove CO_2 from seawater or raise ocean alkalinity, they are energy-intensive and present difficulties for open-ocean monitoring. However, they provide the possibility of long-term storage and hydrogen co-production.

CO_2 is directly extracted from the atmosphere using technological means. By using physical or chemical methods, Direct Air Capture and Storage (DACCS) removes CO_2 from the surrounding air and stores it for a long time, usually in geological formations. Due to the diluted nature of CO_2 in the atmosphere, DACCS can now capture emissions from any place, but they are expensive and energy-intensive. Utilizing industrial wastes, carbon mineralization is the process of reacting collected CO_2 with minerals to create stable carbonates, which may provide a permanent and safe storage solution (Wikipedia authors, 2025). Although CDR technologies have great potential to reduce climate change by eliminating CO_2 from the atmosphere, their widespread implementation is fraught with difficulties. Since the majority of technologies are still in their infancy and must be greatly expanded to reach the gigaton levels necessary to accomplish climate targets, scalability continues to be a major obstacle. Many CDR technologies, especially designed solutions, are expensive, which prevents them from being widely used (The 2024 State of CDR Report: Scaling up CO_2 Removal to Meet Paris Targets, n.d.).

Furthermore, rigorous assessment and management are necessary due to the potential for unforeseen environmental consequences from large-scale deployment, such as changes in land use and impacts on ecosystems. To ensure fair and just implementation, social issues, including food security and property rights, must also be adequately considered (Policies for Scaling up Carbon Dioxide Removal in the United States, n.d.). The reliability and efficacy of CDR technologies hinge on the establishment of robust and consistent monitoring, reporting, and verification (MRV) procedures. Technologies for carbon dioxide removal represent a broad and evolving field with significant promise to help mitigate climate change and dramatically reduce emissions. Numerous land-based, ocean-based, and technological approaches are under investigation; each presents its advantages, disadvantages, and mechanisms. To enhance effectiveness, reduce costs, and ensure the sustainability of these technologies, ongoing research, development, and demonstration efforts are crucial. Effectively addressing the climate crisis will likely require a diverse array of CDR strategies supported by strong legislation, global cooperation, and continuous innovation.

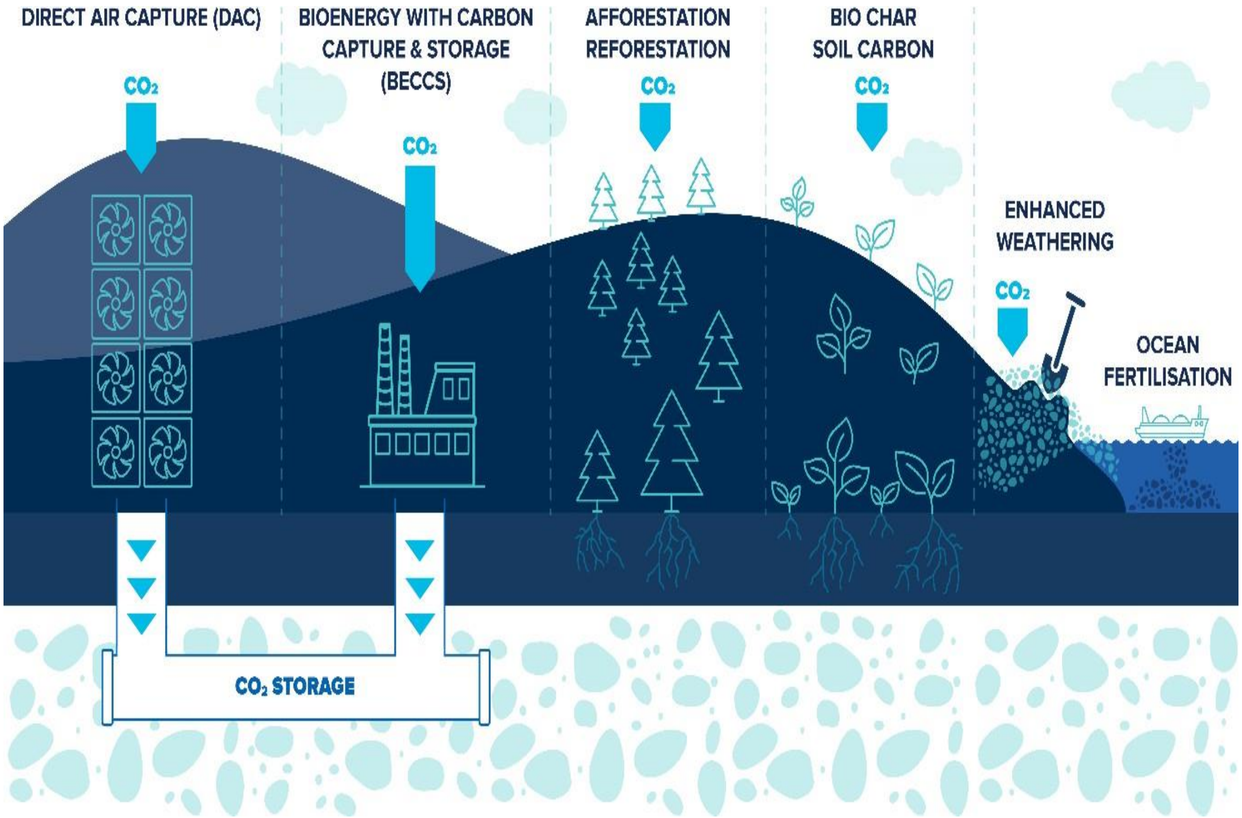

Figure 05: Carbon removal approaches (Source: Tamme, 2021).

Both technological and natural methods can be used to remove carbon (Figure 05). These provide a variety of methods for storing CO_2, from deep geological formations to biomass, soils, and oceans. A combination of natural and technical methods can be found in some strategies, such as biochar and bioenergy with carbon capture and storage (BECCS). Every carbon removal strategy has its own set of drawbacks and difficulties, whether they are connected to cost, permanence, scalability, the effect on biodiversity and/or land use change, or other factors (Tamme, 2021). According to Fuss et al. (2018), no single strategy is expected to be able to sustainably fulfill the rates of carbon uptake outlined in integrated assessment pathways that are consistent with 1.5 ◦C of global warming.

- **Carbon Dioxide Storage Technologies:** Carbon storage technologies are essential for mitigating climate change by capturing carbon dioxide (CO_2) from the atmosphere or preventing its release from industrial sources. These technologies fall into two main categories: biological and geological storage.

  i. **Biological carbon storage:** Utilizing carbon sinks- natural areas such as grasslands, wetlands, forests, and oceans- to absorb and store CO_2 is known as biological carbon storage. The quantity of carbon captured can be increased by improving these natural sinks through reforestation, afforestation, and better land management. Particularly, coastal wetlands have a large capacity to store carbon.
  ii. **Geological carbon storage:** The process of removing CO_2 from massive stationary sources and depositing it deep down into appropriate geological formations is called geological carbon storage, or geo-sequestration. Depleted oil and gas reservoirs and deep saline aquifers, which have the greatest known storage potential, are examples of possible storage locations. Many processes, including structural, residual, solubility, and mineral trapping, can trap injected CO_2, which is frequently in a supercritical fluid state (Global Carbon Capture and Storage Institute Ltd, 2018; Carbon Storage FAQs, n.d.). One use for CO_2 injection into oil reservoirs is enhanced oil recovery (EOR), which increases oil production while storing the gas underground. New technologies also investigate the use of CO_2 in goods like chemicals or concrete,

which can provide long-term storage options. However, depending on the product, storage permanence differs. Implementing carbon storage technologies is essential to reaching net-zero emissions goals, and their safe and efficient long-term storage necessitates ongoing research, development, and supportive legislation (British Geological Survey, 2022c).

3.3 Carbon Removal Methods and Technologies

There are numerous methods for removing and storing carbon dioxide from the atmosphere. To fit their unique needs, several nations are likely to implement varying combinations of these technologies and techniques. Several of the most popular methods are described in this section.

- **Direct Air Capture (DAC):** Chemical sorbents or membranes are used in DAC technology to directly collect carbon dioxide from ambient air. Power plants, industrial sites, and even the atmosphere itself are some of the places where DAC can be installed. Possible Drawbacks: Energy consumption, affordability, and scalability are issues that DAC technology must deal with. Research is still being done on creating economical and effective sorbents and streamlining the capture procedure. For CO direct air capture, the levelized cost estimates for 2050 are displayed in Figure 06 (G. Li et al., 2024). The term "direct air capture and carbon storage" (DACCS) describes methods that use specially designed equipment to capture CO_2 and store it in the same types of geological reservoirs or durable materials as are used for BECCS. These devices use a variety of chemical processes to extract CO_2 from the surrounding air, which is subsequently separated for sequestration. The main input in DACCS is energy, whereas the main input in other carbon removal technologies is natural resources like biomass or rocks. Currently, three businesses are operating direct air capture plants, most of which are modest facilities that reuse the CO_2 instead of sequestering it. Carbon Engineering's site in Texas will supply CO_2 for enhanced oil recovery, which sequesters the captured CO_2 but enhances the output of fossil fuels, while Clime Works' facility in Iceland would sequester CO_2 in rock. These two larger-scale DACCS projects are presently being developed (Institute for Carbon Removal Law and Policy & American University, n.d.).

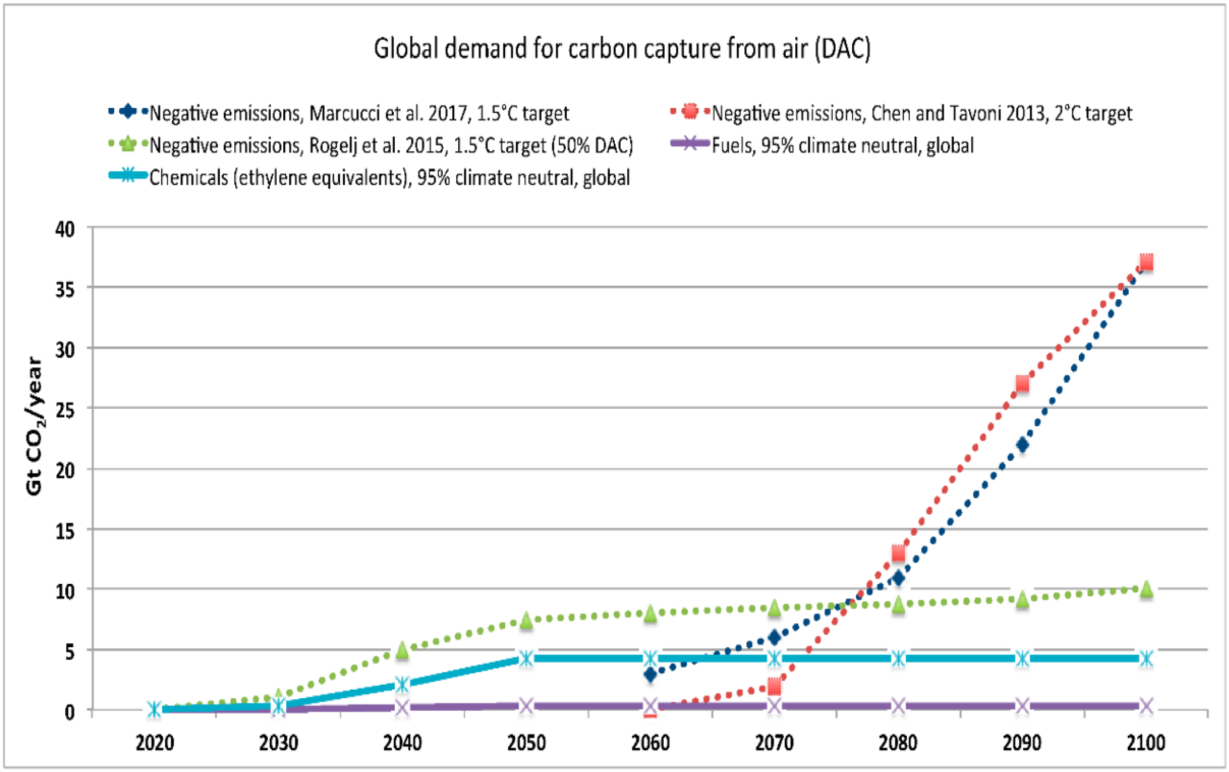

Figure 06: Global Direct Air Capture (DAC) demand for achieving negative emissions from 2060 in comparison with globally required climate-neutral CO for Power-to-Liquids and Power-to-Chemicals in Gt CO/year (Source: G. Li et al., 2024).

- **Bioenergy with Carbon Capture and Storage (BECCS):** BECCS, or bioenergy with carbon capture and storage, is the process of cultivating or harvesting biomass, processing it, turning it into energy or biofuels, absorbing the carbon dioxide that is produced, and storing it underground or in durable items. BECCS can be implemented in a variety of ways, depending on whether the biomass is collected from forest residues, agricultural wastes, or other sources, or if it is purpose-grown, converted to liquid or gaseous fuels, or pelletized and burned to produce heat or electricity. Other factors that affect BECCS' climate impact and overall sustainability include whether the biomass is stored in saline aquifers, depleted oil fields, basalt formations, or long-lasting products (Institute for Carbon Removal Law and Policy & American University, n.d.).

BECCS integrates carbon capture and storage with the generation of biomass energy. Figure 07's process flow diagram shows the harvest season operations, which comprise CCS and steam extraction for industrial processes. CO emissions from energy generation are captured by biomass plants and stored underground (Mishra et al., 2020). BECCS can be used in industrial facilities, power plants, or facilities specifically designed to produce biomass. A sustainable supply of biomass feedstock, process energy balance optimization, and potential environmental effects of large-scale biomass production are among the challenges (G. Li et al., 2024).

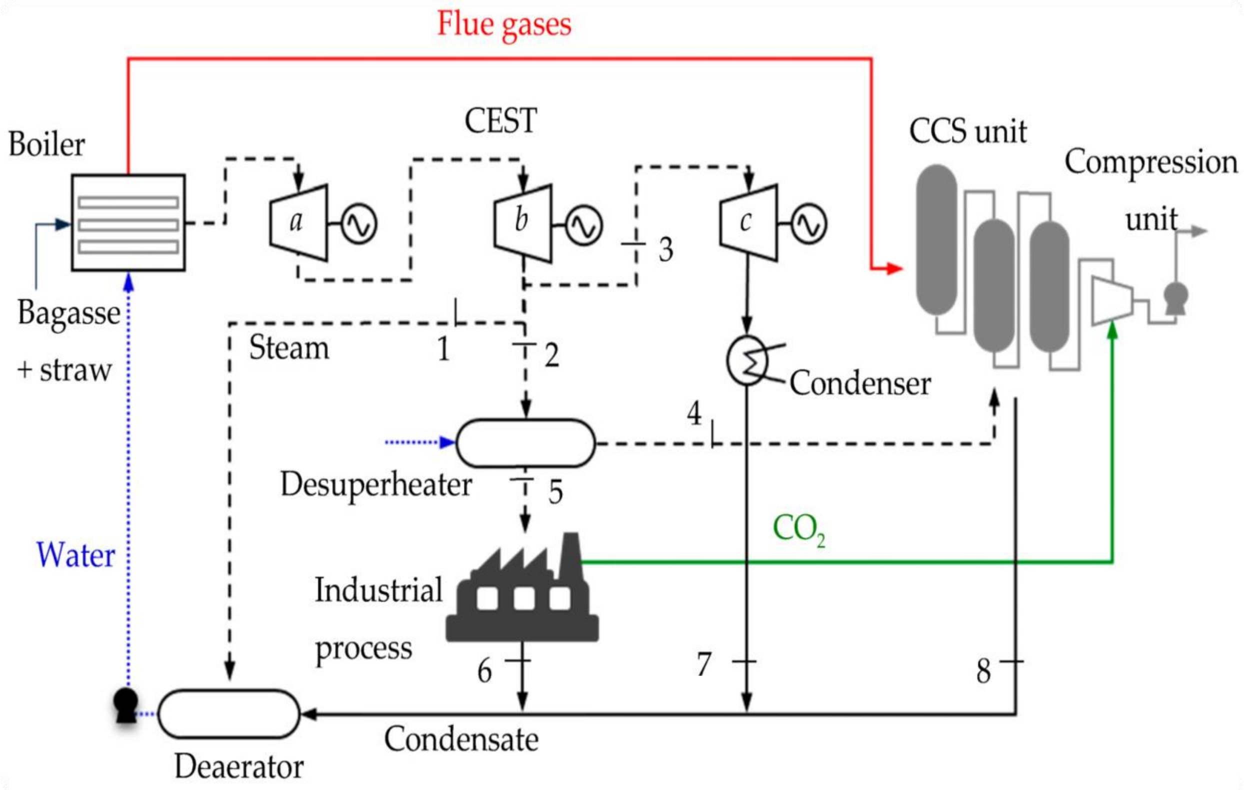

Figure 07: BECCS process flow diagram (harvest season) (Source: G. Li et al., 2024).

- **Improved Weathering**: Accelerating natural weathering processes to absorb and store carbon dioxide is known as enhanced weathering (Goll et al., 2021).

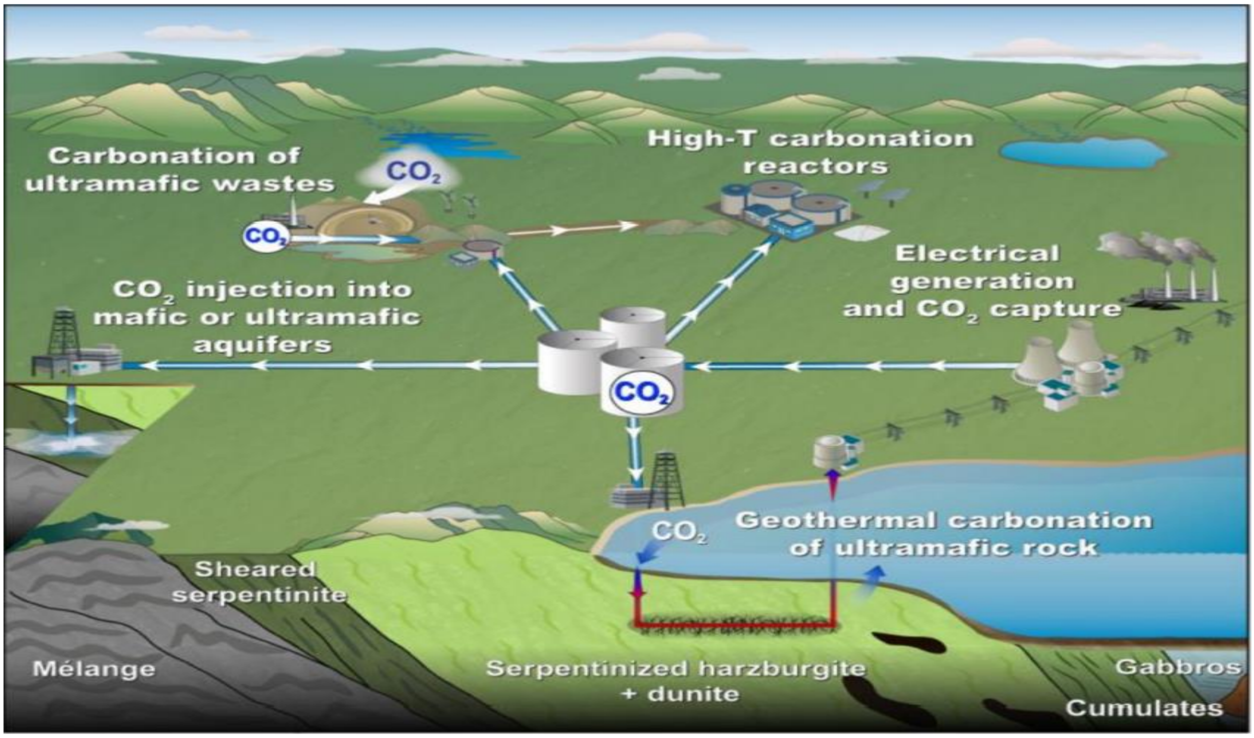

Figure 08: Improved weathering processes in visual form (Source: G. Li et al., 2024).

It usually entails applying rocks or minerals that react with CO_2 to permanently sequester it. The strategies of CCS using mineral carbonation are presented in a conceptual diagram in Figure 08. Certain carbon capture facilities, coastal regions, and agricultural lands can all benefit from enhanced weathering. Understanding the long-term stability of carbon storage, determining appropriate mineral supplies, and evaluating the environmental effects of extensive mineral deployment are among the difficulties (G. Li et al., 2024).

- **Sequestration of Carbon:** In geological formations such as deep saline aquifers or depleted oil and gas reserves, carbon sequestration entails absorbing and storing carbon dioxide emissions (Mosleh et al., 2019). A variety of emission sources, such as power plants and industrial sites, can benefit from carbon sequestration. The challenges include addressing public perception and regulatory issues regarding the permanency and safety of storage, choosing appropriate storage locations, and guaranteeing the long-term integrity of the storage reservoirs (G. Li et al., 2024).
- **Coastal Blue Carbon:** Carbon stored in coastal wetlands and seagrass meadows through restoration and improved management is known as "blue carbon." At the moment, these regions contain significant amounts of carbon in their sediments and biomass. Along with offering significant co-benefits, restoring or establishing new seagrass meadows or wetlands could boost the overall quantity of carbon dioxide they absorb from the atmosphere. Additionally, some scientists have suggested cultivating seaweed and using different methods to store the carbon that has been gathered. The global potential for using blue carbon to remove carbon has not yet been estimated (Institute for Carbon Removal Law and Policy & American University, n.d.).
- **Enhanced Mineralization:** The process by which different minerals naturally absorb CO_2 from the environment is called enhanced mineralization. Mining particular types of rock, like basalt or olivine, is the first step in the process. Grinding such rocks into powder and distributing the resulting powder over soils, where it would react with the air to generate carbonate minerals, is one well-known implementation idea. Soil quality may be improved by the minerals released throughout the process. Alternatively, powdered rock can be scattered throughout the ocean or exposed to CO_2-rich liquids. Although enhanced mineralization is still in its infancy, it has a lot of potential in the long run (Institute for Carbon Removal Law and Policy & American University, n.d.).
- **Soil Carbon Sequestration:** The term "soil carbon sequestration" describes a variety of techniques used to increase the amount of carbon retained in soils, particularly agricultural soils. Manuring, cover crop rotation, and no-till farming are notable examples. These methods help protect fields from drought and floods and can increase agricultural yields because they improve soil quality. Although soil carbon sequestration techniques are already operational and prepared for expansion, there are still several significant obstacles to overcome, such as promoting broad adoption and guaranteeing the practices' long-term upkeep to keep the carbon in the ground (Institute for Carbon Removal Law and Policy & American University, n.d.).
- **Biochar:** One type of charcoal made by heating biomass in a low-oxygen atmosphere is called biochar. It improves soil quality and locks carbon away for decades or millennia when it is buried or ploughed into the soil. Although it would compete with BECCS for biomass inputs, it can thus supplement the majority of other land-based carbon removal methods. The type of biomass utilized, how it is sourced and cooked, whether the soils are subsequently disturbed, and other process variables all affect how much carbon is eventually removed using biochar, much like with BECCS. Although biochar is currently generated on a limited scale, estimations of its potential, co-benefits, and side effects need to be refined through large-scale field studies (Institute for Carbon Removal Law and Policy & American University, n.d.).
- **Ocean Alkalinization:** Alkaline materials are added to the water to absorb CO_2, a process known as ocean alkalinization. Spreading materials like lime across the water is the most direct method, while other strategies have also been suggested by scientists. Although this is frequently categorized as a form of accelerated mineralization, it also has the advantage of immediately reducing ocean acidification by raising seawater's pH. Ocean alkalinization research is still in its infancy, much like increased mineralization research in general (Institute for Carbon Removal Law and Policy & American University, n.d.).
- **Forestation and forest restoration:** Forestation is the process of planting trees over a lot of land or letting forests grow back on their own. Reforestation is the process of planting trees on land that has recently been covered by forest; afforestation is the process of planting trees on land that has not recently been covered by forest. Assisting degraded forests in regaining their native structure, biodiversity, and biological processes is

known as forest restoration. As the trees and soil mature, these newly created or rehabilitated forests would absorb carbon, with the rates and consequences varying according to the type of trees planted and whether the forest regains its native biological functions. As with other biological techniques of removing carbon, the climate advantages of forestation are reversible since forests would sequester the captured carbon for as long as they are standing. For instance, the carbon that has been absorbed is released back into the atmosphere if the forest burns down (Institute for Carbon Removal Law and Policy & American University, n.d.).

3.4 Nature-Based Solutions for Carbon Dioxide Removal: Mechanisms and Opportunities

Nature-based solutions (NbS) offer substantial and frequently affordable potential for mitigating climate change by utilizing the innate ability of natural ecosystems to extract carbon dioxide (CO_2) from the atmosphere (Griscom et al., 2020). In addition to meeting the pressing demand for Carbon Dioxide Removal (CDR), these solutions offer numerous other advantages, such as boosting ecosystem services, biodiversity, and promoting sustainable development (Nature-based Solutions, n.d.).

- **Afforestation and Reforestation:** Fundamental NbS for CDR include reforestation, which is the re-establishment of forests in regions that have been deforested or degraded, and afforestation, which is the planting of forests on land that has not been vegetated for a significant amount of time (at least 50 years). The main process is photosynthesis, in which trees create biomass and release oxygen by absorbing CO_2, water, and sunshine from the atmosphere. According to Fawcett et al. (2011), a sizable amount of the carbon that is captured is long-term stored in the biomass of the trees (trunks, branches, leaves, and roots) and the soil as organic matter. Afforestation and reforestation's capacity to sequester carbon is impacted by several variables, including the choice of tree species (taking lifetime and growth rate into account), planting density, site circumstances (soil type and climate), and management techniques.

The stability of stored carbon depends on sustainable forest management, which includes prudent harvesting and defense against disturbances like pests and wildfires (Griscom et al., 2017). These programs provide significant co-benefits in addition to CDR. By establishing and repairing habitats, they play a critical role in the conservation of biodiversity (Secretariat of the Convention on Biological Diversity, 2009). According to Mills et al. (2016), forests are essential for controlling hydrological cycles, lowering soil erosion, enhancing water quality, and influencing local climate regulation through evapotranspiration and shading. Additionally, local people may benefit economically from sustainably managed forestry ("The State of the World's Forests 2020," 2020). The conversion of other important habitats, including wetlands and grasslands, into monoculture tree plantations must be avoided, too, as this can have a detrimental effect on ecosystem services and biodiversity.

- **Soil Carbon Sequestration (The Undiscovered Carbon Store):** According to Reece et al. (2011), soil is a significant global carbon storage that surpasses the carbon stored in the atmosphere and terrestrial vegetation. Using land management techniques that improve the soil's ability to store organic carbon is known as soil carbon sequestration. The use of organic amendments (Zomer et al., 2017), cover crops, managed grazing, agroforestry, no-till farming (Soil Texture Calculator, Natural Resources Conservation Service, n.d.), and the restoration of degraded lands (Land Matters for Climate: Reducing the Gap and Approaching the Target, 2015) are important practices. Improving soil health, water retention, nutrient cycling, and ultimately agricultural productivity and resilience are all benefits of increasing soil carbon, which also helps mitigate climate change (Taylor et al., 2014). However, the rate and amount of carbon sequestration in soils depend on several factors, and precise monitoring and verification can be difficult (2nd State of the Carbon Cycle Report (SOCCR2), n.d.).
- **Coastal Ecosystems as Effective Carbon Sinks for Blue Carbon Management:** Seagrass meadows (Seagrass Meadows, n.d.), saltmarshes (About Coastal Wetlands, US EPA, 2025), and mangroves (Resources, n.d.) are examples of coastal ecosystems that are remarkably effective at sequestering and storing carbon, frequently at rates that are several times higher than those of terrestrial forests (Brecher & Fisher, 2013). This "blue carbon" can be sequestered for millennia in their biomass and, more importantly, in the carbon-rich sediments beneath them (Team, n.d.). Because mangroves retain large amounts of organic matter and silt, their anaerobic, wet soils

accumulate a tremendous amount of carbon. Additionally, they sustain fisheries, safeguard coasts, and offer vital habitat (Resource Collections, n.d.). Seagrass meadows improve water quality, sustain biodiversity, stabilize coastal areas, and effectively trap and store carbon in their biomass and sediments. Because salt marshes are so good at capturing organic matter and silt, their anoxic soils store a lot of carbon. Additionally, they protect interior regions from coastal floods and offer crucial habitat (Library Collections, U.S. Fish & Wildlife Service, n.d.). In addition to releasing large amounts of stored carbon back into the atmosphere, human activity-induced deterioration and loss of these blue carbon ecosystems also remove their priceless co-benefits (Lee et al., 2012). Therefore, preserving and rehabilitating these habitats is an essential NbS for coastal resilience and CDR (Blue Carbon, n.d.).

- **Additional Nature-Based Remedies (Increasing the Toolkit):** In addition to these well-established NbS, additional intriguing strategies are coming into focus. To create stable carbonate minerals, enhanced weathering speeds up the weathering of silicate rocks. Soil fertility can be increased and carbon sequestered by applying biochar. Wetland and peatland restoration can help these carbon-rich ecosystems sequester carbon and reduce carbon emissions (Wetlands and Climate Change, n.d.).
- **Possibilities and the Way Ahead:** NbS provide a compelling and frequently economical CDR pathway with a host of co-benefits that complement more general sustainability objectives (Overview of Nature-based Solutions, n.d.). Compared to solely technological techniques, they frequently provide more ecologically friendly and socially acceptable solutions that may be used in a variety of land and water management strategies (Vidal et al., 2023). Further highlighting their significance is the fact that they have helped achieve several Sustainable Development Goals (SDGs) (Sustainable Development Goals, n.d.). However, resolving important issues, including permanence, additionality, scalability, co-benefits and trade-offs, and reliable monitoring, reporting, and verification (MRV) systems, is necessary to fully realize NbS's promise for CDR (Nature-based Solutions Initiative, n.d.).

A thorough plan for mitigating the effects of climate change must include nature-based solutions. We can significantly reduce carbon dioxide while also increasing biodiversity, boosting ecosystem services, and promoting sustainable development by utilizing ecosystems' power. Unlocking NbS's full potential in the fight against climate change requires ongoing research, innovation, supportive legislation, and cooperative initiatives.

CDR Method	Maturity Level	Estimated Cost per Ton of CO_2 (USD)	Storage Timescale	Mitigation Potential	Key Co-benefits	Key Risks and Trade-offs
Afforestation/ Reforestation	High	0-240	Decades to centuries	Medium	Biodiversity enhancement, soil health improvement, and watershed protection.	Land competition, potential for carbon release (e.g., fires).
Soil Carbon Sequestration	Medium	-45-100	Decades to centuries	Medium	Improved soil health, increased agricultural productivity, and enhanced water retention.	Reversibility, saturation limits.
Blue Carbon Management	Medium	50-500	Decades to centuries	Low to Medium	Coastal protection, habitat for marine life.	Vulnerability to degradation, long timescales for maximum benefits.
Direct Air Capture and Storage	Low	100-300	10,000+ years	High (potential)	Can be located independently of emission sources.	High energy requirement, high cost, and water usage in some processes.
Bioenergy with	Medium	100-300	10,000+	High	Renewable energy	Land competition for

CCS			years	(potential)	source.	biomass production, potential for increased GHG emissions from biomass production, and transport.
Ocean Alkalinity Enhancement	Low	40-260	10,000+ years	High (potential)	Potential to mitigate ocean acidification.	Potential for increased GHG emissions from material production and transport, impacts on marine ecosystems not fully understood.

Table 01: Key Carbon Dioxide Removal Technologies.

Table 01 compares several CDR techniques in several important areas. A technology's maturity level is determined by its establishment and use; reforestation and direct air capture and storage have the highest levels of maturity, while ocean alkalinity enhancement and direct air capture and storage have the lowest levels. Bioenergy and Soil Carbon Sequestration using CCS are in a moderate stage. There are wide variations in the estimated cost per ton of CO_2 (USD). Afforestation/reforestation and soil carbon sequestration are examples of nature-based solutions that can be economical, even exhibiting negative costs in some soil carbon situations. The price range for Blue Carbon Management is larger. At the moment, Ocean Alkalinity Enhancement is in the moderate price range, whereas Direct Air Capture and Storage and Bioenergy with CCS are more costly. The term "storage timeline" describes how long CO_2 is stored. The longest-lasting storage over thousands of years is provided by geological storage combined with Direct Air Capture and Storage (DCCS), bioenergy with CCS, and improved ocean alkalinity. Although less permanent and reversible, nature-based alternatives provide storage for decades to centuries. The magnitude of the contribution to CO_2 reduction is indicated by the mitigation potential. The scalability of technology makes Direct Air Capture and Storage and Bioenergy with CCS very promising. Due to land and management constraints, reforestation and soil carbon sequestration have medium potential, while blue carbon management has lower to medium potential because of the size of coastal ecosystems. Ocean Alkalinity Enhancement has a lot of promise, but further research is needed. Principal Co-benefits draw attention to benefits beyond carbon reduction. Ecological advantages of nature-based solutions include improved soil health, coastal protection, and biodiversity. Direct Air Capture and Storage provides flexibility in terms of location. CCS combined with bioenergy can produce renewable energy. Enhancing ocean alkalinity may help slow down ocean acidification. Important Risks and Trade-offs: List possible disadvantages. Nature-based remedies may be vulnerable to carbon emissions and land competition. The energy requirements and prices of bioenergy and direct air capture and storage with CCS are significant. More research is needed to fully comprehend the effects of ocean alkalinity enhancement on marine ecosystems. Reversible soil carbon sequestration is possible with saturation limitations.

Table 01 analysis shows that there is no one CDR technology that is always better. Different approaches have different advantages and disadvantages in terms of co-benefits, scalability, and cost persistence. Though they may have limited mitigation potential and shorter storage durations, nature-based solutions are typically well-established, reasonably priced, and offer substantial co-benefits. Ocean-based CDR, especially Ocean Alkalinity Enhancement, shows promise for high mitigation and ocean acidification mitigation, but needs more research on environmental impacts. Engineered solutions like Direct Air Capture and Storage and Bioenergy with CCS offer high mitigation potential and long-term storage, but they are currently expensive and energy-intensive.

Nature-Based Solution	Specific AI Application	Key Benefits of AI Integration
Afforestation/ Reforestation	Site Selection Optimization	Identifies optimal planting locations based on environmental factors.
Afforestation/ Reforestation	Species Optimization	Determines suitable tree species based on site conditions and predicts growth patterns.
Afforestation/ Reforestation	Monitoring Tree Growth and Health	Analyzes drone and satellite imagery to track tree development and health.
Soil Carbon Sequestration	Precision Agriculture Recommendations	Recommends optimal irrigation, fertilization, and soil management for enhanced carbon uptake.
Soil Carbon Sequestration	Smart Plant Selection	Suggests plants best suited for maximum carbon capture based on local conditions.
Blue Carbon Management	Understanding Ocean Carbon Uptake	Processes data from oceanographic sensors to improve understanding of carbon dynamics.
Blue Carbon Management	Predicting Impacts of Interventions	Analyzes data to forecast the effects of ocean-based CDR activities.
Blue Carbon Management	Automated Ecosystem Monitoring	Uses video and satellite data for efficient assessment of coastal ecosystem health and changes.
Multiple NbS	Monitoring and Verification (MRV)	Provides accurate, efficient, and transparent methods for tracking and verifying carbon removal.
Forestry	Emissions Auditing and Carbon Stock Monitoring	Supports asset owners in accurately assessing emissions and tracking carbon within forests.

Table 02: Applications of AI in Enhancing Nature-Based Carbon Dioxide Removal.

Table 02 shows particular applications of AI to enhance Nature-Based Solutions. AI is used in site selection optimization for reforestation and afforestation to choose the best planting sites based on environmental criteria. In reforestation and afforestation, species optimization predicts growth trends and chooses appropriate tree species based on site conditions. Tracking Tree Development and Health in Afforestation/Reforestation uses satellite and drone data to monitor tree growth and health. For improved carbon uptake, Precision Agriculture Recommendations for Soil Carbon Sequestration recommend the best possible soil management, fertilization, and irrigation practices. Based on regional conditions, Smart Plant Selection for Soil Carbon Sequestration recommends plants that will collect the most carbon. Oceanographic sensor data is processed to enhance comprehension of carbon dynamics in Blue Carbon Management's Understanding Ocean Carbon Uptake. Data analysis is used in Predicting Impacts of Interventions in Blue Carbon Management to predict the outcomes of ocean-based CDR initiatives. Blue Carbon Management's Automated Ecosystem Monitoring effectively evaluates the health and changes of coastal ecosystems using satellite and video data. Carbon removal may be tracked and verified with precision, efficiency, and transparency using Monitoring and Verification (MRV) across Multiple NbS. Accurate evaluation of emissions and carbon tracking within forests is supported by emissions auditing and carbon stock monitoring in forestry.

By optimizing different project stages, AI has the potential to greatly increase the efficacy and scalability of Nature-Based CDR, according to Table 02 analysis. The capacity of AI to handle a variety of massive datasets yields insightful information for well-informed decision-making. Applications cover a variety of NbS kinds, demonstrating AI's wide range of applications. AI-enhanced MRV is essential for project effectiveness and legitimacy.

Challenge/Consideration	Description	Potential Mitigation Strategies
AI Energy Consumption	Training and running AI models require significant energy, often from fossil fuels.	Optimize AI algorithms for energy efficiency, and use renewable energy sources for AI infrastructure.
Data Availability and Quality	AI models need large, high-quality, unbiased, and accessible datasets for effective performance.	Invest in data collection and sharing initiatives, develop data standards, and address data biases.
Ethical Considerations	Use of AI in natural ecosystems raises concerns about authenticity, equity, long-term effects, and bias.	Develop ethical guidelines and frameworks, ensure transparency and accountability in AI deployment.
Bias and Inaccuracies in AI Models	AI models can perpetuate biases from training data, leading to unfair or inaccurate outcomes.	Implement rigorous testing and validation procedures, ensure diverse and representative training data, and incorporate human oversight.
AI Infrastructure Gap	Demand for AI infrastructure, particularly data centers, is rapidly increasing and may outpace clean energy.	Invest in expanding clean energy capacity to meet the growing demands of AI infrastructure.

Table 03: Challenges and Considerations in the Integration of AI and Nature-Based CDR.

Table 03 lists the difficulties and moral issues with AI in nature-based CDR. AI Power Usage The carbon footprint of developing and executing AI models can be substantial. Availability and Quality of Data Large, high-quality, objective, and easily accessible datasets are necessary for AI models to function well. Moral Aspects to Take into Account The use of AI in natural ecosystems raises questions around bias and authenticity, equity's long-term repercussions. Bias and Inaccuracies in AI Models. Biases can be reinforced by AI models, producing unfair or erroneous results. The gap in AI Infrastructure Resources for sustainable energy may be strained by the growing need for AI infrastructure.

Analysis of Table 03 shows that integrating AI with NbS faces challenges. Addressing AI's energy consumption and ensuring data quality are vital Ethical considerations, and potential biases in AI models need careful attention. AI deployment should align with broader sustainability goals, including clean energy for AI infrastructure.

The overall analysis shows a varied CDR landscape, with Nature-Based Solutions providing established, reasonably priced solutions with co-benefits but limits in terms of scalability and permanence. The effectiveness and monitoring of nature-based CDR could be greatly improved by integrating AI. However, to ensure truly sustainable and equitable climate solutions, it is imperative to address the ethical implications and data quality of AI's energy footprint. In an ideal world, the "Relevant Snippet IDs" would offer more context from a longer document.

3.5 Ocean-Based Carbon Removal:

Our climate is greatly influenced by the ocean, which makes up more than 70% of the planet's surface. Approximately 30% of all carbon dioxide (CO_2) emissions created by humans have been absorbed by it, making it a huge natural carbon sink (Ocean Conservancy, 2024). Marine habitats are at risk, though, as this absorption is also contributing to ocean acidification (What Is Ocean Acidification? n.d.). Exploring and sustainably implementing ocean-based carbon dioxide removal (CDR) strategies is becoming more and more important to effectively solve the climate issue in conjunction with drastic emission reductions (Cape, 2024). The term "ocean-based CDR," or "marine CDR" (mCDR), refers to a variety of methods intended to improve the ocean's inherent capacity to absorb and store CO_2 from the atmosphere or to extract dissolved CO_2 directly from saltwater (Klima, 2025). These techniques fall into two general categories: biotic (biological) and abiotic (non-biological).

1) **Biotic Approaches:** Through photosynthesis, these techniques take advantage of the ability of marine life to absorb CO_2 (Lebling, n.d.-d).

- **Microalgae Cultivation:** Growing microalgae, or phytoplankton, may absorb large amounts of CO_2, much like seaweed. Several approaches are being investigated, such as growing algae in controlled systems and subsequently burying the biomass or using it for bio-products with long-term carbon storage, or improving natural blooms by adding nutrients (ocean fertilization) (Ashour et al., 2024). Nonetheless, there are worries about the unforeseen ecological effects of extensive ocean fertilization.
- **Blue Carbon Ecosystem Restoration:** One well-established mCDR method is the preservation and restoration of coastal habitats, such as salt marshes, seagrass meadows, and mangrove forests (The Ultimate Guide to Blue Carbon, Cloverly, n.d.). Often at rates far higher than those of terrestrial forests, these "blue carbon" environments are remarkably effective at storing and sequestering carbon in their biomass and underlying sediments. Additionally, they provide a host of co-benefits, such as enhanced water quality, habitat availability, and coastal protection (Understanding Blue Carbon, 2022).
- **Macroalgae (Seaweed) Cultivation and Sinking:** Growing seaweed quickly and then releasing the biomass into the deep ocean is another interesting biotic strategy. CO_2 from surface waters is absorbed by seaweed as it grows. According to Mapping Seaweed Farming Potential - Carbon Plan (n.d.), the carbon stored in its tissues can be sequestered for long periods when sunk to the deep sea, preventing its return to the atmosphere. This approach requires careful evaluation of scalability and ecological effects.

2) **Abiotic Approaches:** These techniques improve CO_2 uptake and storage by taking advantage of the physical and chemical characteristics of the ocean (Marine Carbon Dioxide Removal: What It Is and How It Works, Carbon Direct, n.d.).

- **Direct Ocean Capture (DOC):** DOC methods seek to directly extract dissolved CO_2 from saltwater for long-term storage or use, much as direct air capture on land. There are issues with this strategy's cost-effectiveness and energy efficiency.
- **Ocean Alkalinity Enhancement (OAE):** This method includes introducing minerals such as crushed limestone or olivine to the ocean to increase its alkalinity (Zhu et al., 2024). Oceans with higher alkalinity are better able to absorb CO_2 from the atmosphere and transform it into stable bicarbonate ions, which might effectively store the gas for extended periods and possibly reverse ocean acidification (Kessler, 2024).
- **Electrochemical Ocean CDR:** Seawater is separated into basic and acidic solutions using electricity in these techniques (Marine Carbon Dioxide Removal: What It Is and How It Works, Carbon Direct, n.d.-b). While the basic stream can increase ocean alkalinity and encourage additional atmospheric CO_2 absorption, the acidic stream can be employed to collect dissolved CO_2 for storage (Keith, 2025a).

The ocean's enormous capacity to store carbon and its current natural carbon cycle make ocean-based CDR extremely promising (Lebling, n.d.-d). Additionally, reducing ocean acidification and improving biodiversity are two benefits that several mCDR techniques, such as OAE and blue carbon restoration, provide (Carbon Dioxide Removal: NOAA State of the Science Factsheet, 2024). The field is still in its infancy, though, and much more study and research are required to completely comprehend the usefulness, scalability, affordability, and possible social and environmental effects of these strategies. Ocean-based CDR must be developed and implemented responsibly, taking into account potential dangers and establishing strong frameworks for monitoring, reporting, and verification to guarantee its efficacy and safety as a component of a larger climate action plan (Lebling, n.d.-c).

3.6 CDR+AI Integration: Enhancing Carbon Emissions Assessment

The combination of artificial intelligence (AI) with carbon dioxide removal (CDR) technology offers a revolutionary chance to improve our comprehension and control of carbon emissions. We can achieve previously unheard-of levels of precision in emissions assessment by combining the strengths of both disciplines, opening the door to more potent climate mitigation techniques. A more detailed and dynamic understanding of emission sources and trends is one of the main benefits of this integration.

Revolutionizing Carbon Emissions Assessment with AI-Powered CDR: One of the first steps in combating climate change is accurately estimating and measuring carbon emissions. Our capacity to achieve this accuracy is greatly increased by the combination of AI and CDR technologies. Large and complicated datasets from a variety of sources, including data streams from CDR facilities themselves, complex industrial processes, and dynamic energy consumption patterns, are easily processed and analyzed by AI algorithms (Inventory of U.S. Greenhouse Gas Emissions and Sinks, US EPA, 2025). Compared to conventional techniques, this thorough study makes it possible to produce carbon emission estimates that are more precise and faster. Such improved precision is essential for pinpointing high-emission industries and geographical areas, closely monitoring advancement toward predetermined emission reduction goals, and supplying solid statistics to support important policy choices. Because of AI's analytical capabilities, data from several sources can be seamlessly integrated and processed to create a comprehensive picture of emissions across industries and regions. These sources can include:

- **Industry-Specific Operational Data:** AI may be trained to directly measure emissions linked to various processes and activities by analyzing operational data from certain industries, such as manufacturing, transportation, and energy production. Inefficiencies and chances for focused emission reductions can be found using this fine-grained data (De Pee et al., 2018).
- **Comprehensive Emissions Inventories:** AI can identify major contributing industries and individual emission sources within those sectors by analyzing comprehensive national and regional emissions inventories (Total GHG Emissions and Removals in the EU, 2025).
- **Real-time Sensor Networks and IoT Devices:** Continuous, real-time monitoring of emissions at different sizes, from individual industrial facilities to metropolitan surroundings, is made possible by the growth of sensor networks and Internet of Things (IoT) devices (Smart Grid Group, NIST, 2023). This high-frequency data can be ingested and analyzed by AI algorithms, which will help identify emission spikes, persistent high-emission zones, and the efficacy of mitigation measures (September 2019 - IEEE Internet of Things, n.d.).
- **High-Resolution Satellite Imagery:** Satellite data provide crucial information about changes in land use (such as deforestation, a major source of emissions), industrial operations that emit pollutants, and atmospheric concentrations of greenhouse gases. These enormous datasets can be processed and interpreted by AI algorithms, which can then be used to identify areas with high emissions and monitor how they change over time (NASA Earth Observatory, n.d.-a). The identification of particular emission plumes and their origins is made possible by sophisticated methods such as spectral analysis and pattern recognition (Sentinel-5P, n.d.).

AI can identify complex spatial and temporal patterns of emissions by examining a wide range of emissions-related data. This entails locating emission hotspots, which are geographically concentrated regions with noticeably higher emission rates, as well as regions that show notable variations in emissions over time, such as spikes caused by events or seasonal variations. Identifying these high-emission regions is essential for focusing interventions and allocating resources for reduction. Additionally, AI models may learn from past emissions data thanks to machine learning techniques, which allow them to identify recurrent emission patterns and forecast future emission trends (Climate.gov Home, n.d.). By proactively identifying regions that are more likely to develop into high-emission zones in the future, this predictive capability makes preventative intervention easier. The comprehensible spatial visualization of emissions data is made possible by the combination of AI and geospatial analysis techniques (What Is GIS?, Geographic Information System Mapping Technology, n.d.). AI can give stakeholders and policymakers clear and intelligible representations of high-emission regions and their surroundings by using geospatial statistics and interactive maps to display emissions data. This visual clarity makes it easier to identify areas that need targeted mitigation techniques and makes it easier for various stakeholders to communicate with one another. In conclusion, AI algorithms provide a potent toolkit for transforming the evaluation of carbon emissions by utilizing these sophisticated analytical skills. Our progress towards a sustainable, low-carbon future will be accelerated by the precise and insightful data produced by this integration, which enables policymakers to prioritize areas for mitigation efforts, create more focused and effective interventions, and carry out emission reduction measures with greater accuracy.

3.7 The Role of Artificial Intelligence in Climate Change Mitigation and Carbon Management

Artificial intelligence (AI), which provides strong instruments for comprehending and combating climate change, is becoming more and more important in environmental monitoring and climate science. AI improves our ability to observe, predict, and intervene by analyzing large datasets in real-time.

- **AI in Climate Science:** AI makes it possible to perform complex climate modeling and simulation, which aids researchers and decision-makers in evaluating the effects of various measures. Artificial intelligence (AI) has the potential to optimize renewable energy systems, boost conservation efforts, and improve forecasts of climate trends and extreme weather events. The strategies for using AI to increase the efficiency of carbon capture and storage (CCS) are depicted in Figure 09 below.

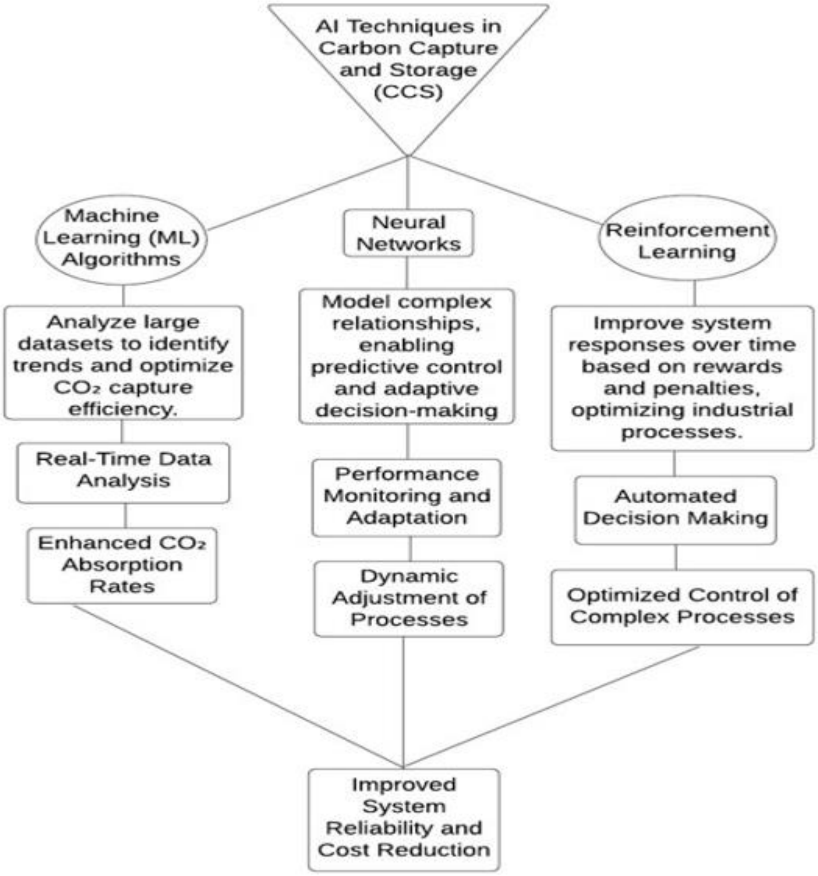

Figure 09: Strategies for Increasing the Efficiency of Carbon Capture and Storage (CCS) Using AI (Source: Anyebe et al., 2024).

- **AI in Environmental Monitoring:** AI is used to gather and analyze data in real time from a variety of sources, including sensors, drones, and satellites, to follow wildlife, identify deforestation, monitor air and water quality, and predict changes in the climate. This makes it possible to make quicker and better-informed judgments about environmental protection.
- **AI in Carbon Management:** AI can precisely measure carbon emissions, optimize energy systems that include carbon capture, and provide real-time monitoring of CDR facilities. These capabilities are particularly pertinent to carbon management. Additionally, AI is essential for improving the efficacy and efficiency of different carbon removal methods, such as nature-based solutions (G. Li et al., 2024). AI is utilized, for example, to map forests, track reforestation initiatives, evaluate tree health and carbon sequestration, and improve agricultural methods to increase soil carbon. AI can analyze oceanographic sensor data in ocean-based CDR to enhance our comprehension of ocean carbon uptake. By evaluating geological data and forecasting the behavior of CO_2

plumes, AI also plays a critical role in maximizing carbon storage (Carbon Gap, 2025b; IPCC Climate Change Mitigation Report Released, n.d.).

AI offers significant potential to overcome the limitations of traditional carbon management methods by providing more efficient, accurate, and scalable solutions.

3.8 Ai-Driven Optimization of Energy Systems for Enhanced Carbon Dioxide Removal (Cdr)

To achieve deep decarbonization and lessen the effects of climate change, Carbon Dioxide Removal (CDR) technologies must be successfully integrated into current and future energy systems. Although CDR has the potential to remove CO_2 from the atmosphere, its implementation is closely related to the energy industry as a potential energy consumer, and as a result of better energy management. By optimizing energy system configurations to enhance the performance and cost-effectiveness of CDR integration, artificial intelligence (AI) plays a critical role in navigating this complex interaction. Artificial intelligence algorithms are capable of analyzing the complex dynamics of energy systems by processing large datasets that include patterns of energy demand, the sporadic nature of renewable energy output, the grid infrastructure that is currently in place, and several other relevant elements. Through the analysis of this data, artificial intelligence (AI) models can create complex representations of energy systems that capture the intricate interactions between a variety of energy sources, such as nuclear, renewables, and fossil fuels, changing demand, and the carbon emissions that come from these interactions. Energy planners and operators can find economical and effective configurations for integrating CDR technologies thanks to these AI-driven models, which facilitate scenario analysis and optimization.

This optimization process involves a holistic consideration of several key factors:

- **Energy Demand:** To foresee future requirements and guarantee that CDR processes may be incorporated without jeopardizing energy security, AI algorithms examine past and projected energy demand.
- **Availability of Renewable Energy:** AI models predict the availability of renewable energy sources like solar, wind, and hydropower because it is crucial to power CDR with clean energy to optimize its net carbon removal capacity. In order to schedule CDR activities to align with times when renewable energy output is at its peak, forecasting is essential.
- **Energy Storage Capabilities:** To mitigate the intermittent nature of renewable energy sources and offer a steady energy supply for CDR facilities, artificial intelligence (AI) optimizes the deployment and management of energy storage solutions (such as batteries and pumped hydro).
- **Carbon Removal Targets:** AI algorithms can be constrained by specific carbon removal targets, optimizing energy system configurations to achieve desired levels of atmospheric CO_2 reduction.

AI makes it easier to find the best solutions that not only maximize the use of renewable energy sources and reduce overall carbon emissions, but also meet particular energy and carbon removal goals by modeling and assessing various system configurations under these limitations. Additionally, AI helps to optimize demand-side management (DSM) tactics, which are essential for integrating CDR and balancing energy supply and demand. To find chances for demand response, AI systems that make use of machine learning techniques examine patterns in energy usage. This entails anticipating times of high energy demand and planning energy-intensive operations, both in buildings and industrial processes, as efficiently as possible. A more favorable environment for CDR operation and a reduction in carbon emissions are the results of effective DSM, which lessens dependency on fossil fuel-based power to satisfy peak demand. Another area where AI offers substantial advantages is in forecasting the accuracy of renewable energy. Artificial intelligence (AI) algorithms can produce more accurate projections of renewable energy availability by examining historical weather data, statistics on renewable energy generation, and other pertinent variables (such as weather forecasts). By matching their energy need with times of high renewable energy generation and low grid demand, these precise forecasts allow CDR facilities to be scheduled and operated optimally, thus reducing the carbon emissions linked to CDR.

Beyond demand management and the integration of renewable energy, AI algorithms optimize the configurations of the entire energy system by examining a variety of historical and real-time data, such as:

- Energy supply and demand data.
- Market prices for energy.
- Weather conditions.
- Grid stability parameters.

This comprehensive analysis enables AI to identify opportunities for:

- Strategic deployment of energy storage.
- Demand-shifting initiatives.
- Smart grid management.

Grid stability, the intermittent nature of renewable energy sources, and the development of an energy infrastructure that can efficiently support and improve CDR technologies all depend on these efficiencies. A low-carbon energy system schematic is shown in Figure 10.

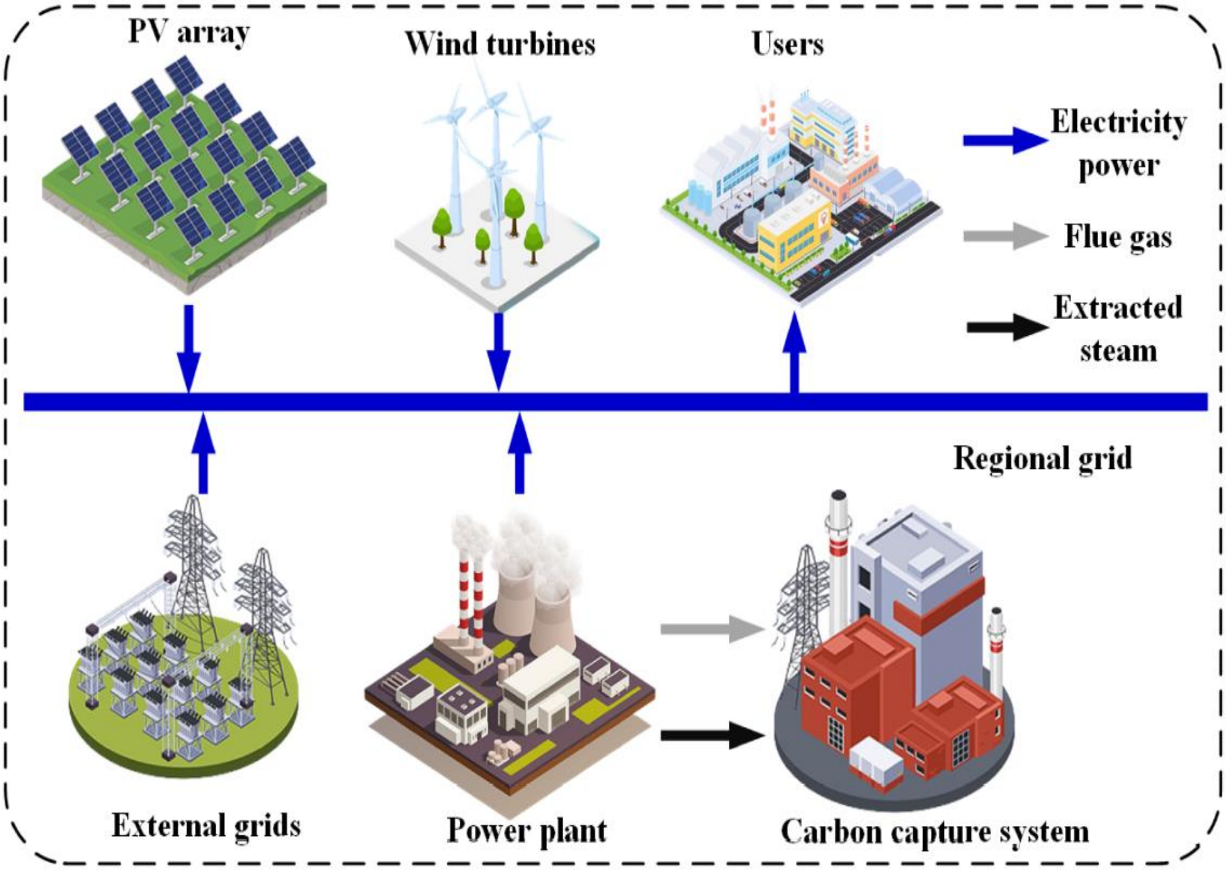

Figure 10: An illustration of a system for low-carbon energy (Source: G. Li et al., 2024).

Connecting to Nature-Based Solutions (NbS): It is crucial to take into account the links with Nature-Based Solutions (NbS), especially in the context of bioenergy with carbon capture and storage (BECCS), even though the discussion above mostly focuses on how AI interacts with conventional energy infrastructure. BECCS is a CDR technology that combines carbon capture and storage with biomass as an energy source to produce net-negative emissions. For BECCS, the sustainability of biomass feedstocks is a crucial factor, which is where NbS comes into play. By reducing ecological effects and optimizing carbon sequestration in the energy system and the biomass source, artificial intelligence (AI) can help manage forests and other biomass sources (NbS) to guarantee a sustainable supply for BECCS. AI can be utilized, for instance, to:

- Optimize forest management practices for sustainable biomass production.
- Monitor and predict biomass yields.
- Assess the carbon sequestration potential of forest ecosystems.

The successful integration of CDR technology depends on AI-driven energy system optimization. By improving CDRs and the energy sector's overall sustainability, cost-effectiveness, and efficiency, this optimization helps to mitigate the effects of climate change. Additionally, when combined with NbS principles, AI can guarantee that CDR solutions such as BECCS are implemented sustainably.

3.9 Advancements in Artificial Intelligence for Building Carbon Emission Calculation and Management

Many sectors are under a lot of pressure to lower their carbon footprints as the urgency of tackling anthropogenic climate change increases. One of the most significant contributors to global carbon emissions is the construction industry, which calls for a fundamental change to more sustainable practices and a significant cut in carbon output to fulfill ever-tougher carbon reduction targets (Hua et al., 2025). Numerous industries, such as manufacturing, retail, and telecommunications, have already seen the revolutionary potential of AI. Since its deployment, automation has improved noticeably, streamlining production processes and greatly increasing accuracy and efficiency (Abioye et al., 2021). Similarly, in the 1960s, when the "intelligent building" concept first emerged, the construction sector started to see the first penetration of this ground-breaking technology (Alanne & Sierla, 2021). Today's AI in construction mostly focuses on the advancement and synergistic convergence of blockchain technology, machine learning, the Internet of Things (IoT), and other cutting-edge digital solutions. A key element of artificial intelligence, machine learning algorithms are being used more and more for crucial tasks like improving construction risk management, maximizing building design for energy efficiency, and producing more precise project cost estimates, all of which eventually result in increased accuracy and cost effectiveness (Hashemi et al., 2020).

Additionally, AI's integration with smart sensors and real-time data analytics allows for precise maintenance demand prediction, ongoing structural health monitoring, and the guarantee of long-term building infrastructure safety and durability (Sofi et al., 2021). The use of AI technology in the construction industry has advanced due to its continued rapid evolution, especially in the critical areas of estimating and forecasting building carbon emissions. The potential of artificial intelligence technologies to offer data-driven insights for the development of sustainable buildings is impressive. AI-powered systems can precisely estimate current carbon emissions and, more crucially, forecast future emission trends by utilizing their capacity to handle and analyze large datasets of building energy consumption. This capacity for prediction offers a strong scientific foundation for creating and putting into practice efficient plans meant to maximize energy efficiency and drastically lower carbon emissions in buildings (Gaur et al., 2023). At the same time, advanced AI optimization algorithms may examine a wide range of building attributes and consumption needs to produce tailored energy-saving suggestions and all-inclusive plans. In order to determine the best practices for attaining sustainable and carbon-efficient building operation, these customized solutions can take into account variables including building materials, occupancy patterns, HVAC system efficiency, and local climate conditions (Hu et al., 2023). Building owners and managers are empowered to make well-informed decisions and carry out focused interventions that optimize energy savings and reduce environmental impact thanks to this individualized approach.

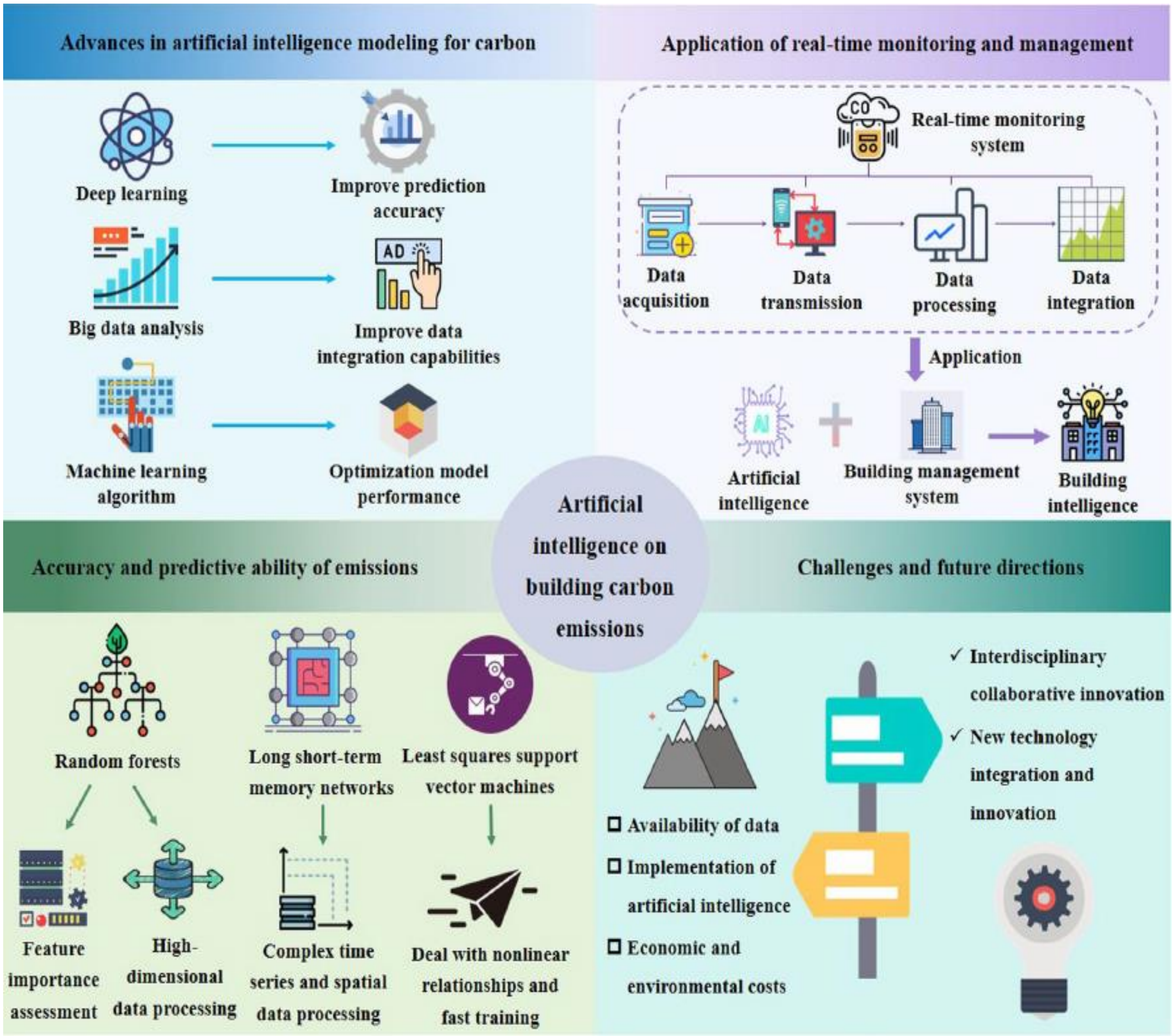

Figure 11: Artificial intelligence used to control building carbon emissions (Source: Hua et al., 2025).

Four major areas of artificial intelligence research advancements about building carbon emissions are highlighted in Figure 11 (Hua et al., 2025): real-time monitoring system applications, capabilities for improving emissions management and forecasting accuracy, and the difficulties and potential paths for future development. The benefits of artificial intelligence technology in areas like data processing and analysis are emphasized through an overview of its application in carbon emissions management. This opens the door for a later discussion of how artificial intelligence may enhance emissions management and forecasting accuracy. The entire picture of artificial intelligence technology in reducing carbon emissions is depicted in this graphic, including research advancements, real-world applications, and potential obstacles and paths forward. An illustration of the various uses of AI in controlling carbon emissions from buildings can be found in Figure 11. Four crucial areas of research advancement within this sector are strategically highlighted in the figure. First of all, it demonstrates how AI can be used in real-time monitoring systems, highlighting its capacity to continuously monitor energy use and related carbon emissions, offering instantaneous insights into the environmental performance of a building. Second, the figure highlights how AI can improve forecasting accuracy and emissions management. This includes AI's capacity to examine past data, spot trends, and forecast future emission patterns, allowing for proactive emission reduction measures and well-informed decision-making. Thirdly, Figure 11 recognizes the obstacles that now stand in the way of the broad implementation and advancement of AI in building carbon management. Data accessibility, model interpretability, interaction with current building management systems, and the requirement for strong standardization are a few examples of these difficulties. The figure concludes by outlining future research and development directions in this quickly developing field, possibly emphasizing areas like the application of AI to support circular economy principles in the building industry, the development of more complex and context-aware AI models, and the integration of AI with emerging sustainable technologies. Figure 11 provides an effective summary of the present and future directions of AI in building carbon emissions control by graphically depicting these important topics. It emphasizes the inherent benefits of AI technology, especially its ability to process and analyze large, complex datasets, which lays the groundwork for its potential to greatly improve emissions control procedures and raise the precision of carbon emission projections. The groundwork for a more thorough investigation of the particular uses of AI in attaining carbon-efficient and sustainable growth in the built environment is laid out by this thorough overview.

3.10 Enhancing Carbon Capture and Storage: A Deep Dive into the Transformative Benefits of Artificial Intelligence Integration

Carbon Capture and Storage (CCS) technologies are at the forefront of international efforts to decarbonize industrial processes and lower atmospheric CO_2 concentrations due to the urgent need to address the worsening climate change catastrophe. However, maximizing CCS's effectiveness, affordability, safety, and general sustainability is essential to its broad and successful implementation. To achieve this optimization, artificial intelligence (AI) has become a potent catalyst, providing several revolutionary advantages that have the potential to fully realize CCS's potential. Anyebe et al. (2024) offer a critical foundation for comprehending these advantages, and this section explores each in greater detail, building on their findings and elaborating on the implications for carbon management going forward.

1) Efficiency Improvement (The Cornerstone of AI-Driven CCS Optimization):

A key component of AI's contribution to CCS is efficiency enhancement, which tackles the dynamic and inherently complex nature of carbon capture operations. Conventional CCS techniques frequently struggle with a wide range of interrelated factors that might seriously reduce the efficacy of capture. The operational environment is always changing due to changes in temperature, pressure, gas and liquid flow rates, solvent concentrations, and flue gas stream composition. For traditional control systems, maintaining ideal conditions in this changing environment is a difficult task. AI offers a paradigm change in tackling this issue because of its ability to do complex data analysis and adaptive control. The flood of real-time data produced by sensors and monitoring devices dispersed throughout the CCS system may be processed and analyzed by AI algorithms powered by machine learning, deep learning, and other cutting-edge methodologies. This data offers a comprehensive picture of the continuous capture process by encompassing a large number of factors. AI models can create incredibly accurate depictions of the behavior of the system by spotting complex patterns and connections in this complicated dataset. These models provide a more sophisticated view of how changes in one parameter impact others by capturing the non-linear relationships and dynamic interactions between many variables, going beyond simple correlations.

Equipped with this profound comprehension, artificial intelligence algorithms can modify operational settings in real-time, optimizing capture circumstances with previously unheard-of accuracy. By optimizing CO_2 capture and reducing energy and resource waste, this adaptive control makes sure the CCS system runs as efficiently as possible. AI, for example, can adjust solvent flow rates to correspond with the flue gas's fluctuating composition, lowering solvent losses and improving capture selectivity. In a similar vein, AI can adjust the capture unit's pressure and temperature parameters to reduce energy consumption without sacrificing capture rates. Furthermore, AI has the potential to significantly improve the general layout and setup of CCS facilities. Artificial intelligence (AI) algorithms can determine the best equipment configuration, capture unit size, and integration with current industrial processes by modeling various operating scenarios and examining historical data. AI-driven efficiency improvement that takes a comprehensive approach can drastically lower capital and operating costs, increasing CCS's viability and appeal for widespread implementation.

2) Accuracy Improvement (Ensuring Precision and Reliability in CO_2 Management):

The integrity and long-term efficacy of carbon control initiatives depend critically on accuracy, which is not just a desired aspect of CCS. Significant inefficiencies, higher operating costs, and—most concerning—possible environmental hazards related to CO_2 leakage or insufficient storage can result from inaccurate measurements, imprecise forecasts, or unreliable control. From capture to storage, artificial intelligence (AI) is essential to improving accuracy along the CCS chain. The accuracy of measurements in CCS facilities can be greatly improved using AI-powered monitoring systems. Manual readings or less advanced sensors may be used in traditional monitoring techniques, which can lead to inaccuracies and data collection limitations. In contrast, AI-driven systems use a network of extremely fine sensors and advanced data collecting systems to deliver accurate and continuous measurements of important parameters. At different phases of the capture process, these parameters include CO_2 flow rates, concentrations, and purity levels. AI is also incredibly accurate at monitoring pressure gradients, temperature profiles, and energy consumption. A thorough and trustworthy picture of the CCS system's performance is provided by this granular level of data capture, facilitating better control and decision-making.

In addition to monitoring, AI greatly increases the precision of CO_2 storage forecasts. By facilitating the creation of extremely complex models of subsurface formations, artificial intelligence (AI) helps to ensure the long-term safety and security of geological storage locations. These models predict the behavior of injected CO_2 over long periods by combining injection settings, seismic surveys, and geological data. Patterns of CO_2 migration, variations in reservoir pressure, and the possibility of leakage through faults or cracks can all be predicted by AI algorithms. To guarantee the durability of CO_2 sequestration, these forecasts are essential for choosing appropriate storage locations, refining injection techniques, and putting in place efficient monitoring programs. AI can also improve the precision of process control in CCS plants. AI algorithms can apply more accurate and responsive control techniques by evaluating real-time data and forecasting future system behavior. This lessens errors in CO_2 capture and processing as well as departures from ideal operating circumstances. The increased accuracy made achievable by AI leads to a greater level of confidence in the effectiveness and reliability of CCS as a climate change mitigation strategy.

3) Cost Reduction (Paving the Way for Economically Viable CCS Deployment):

One of the key determinants of CCS's broad acceptance and effective incorporation into the world energy scene is its economic feasibility. One of the main obstacles to the widespread use of CCS has frequently been identified as the high initial and ongoing expenses involved. AI provides a potent toolkit to tackle these financial issues and reduce the costs of CCS at every stage. One of the main ways to cut costs is through AI-driven energy consumption optimization. Energy is a key component in CCS operations, especially when it comes to CO_2 capture and compression. AI systems can examine trends in energy use, spot inefficiencies, and put plans in place to reduce energy use. This may entail combining CCS plants with renewable energy sources, recovering waste heat, and optimizing process parameters. AI directly lowers operating costs and increases the economic competitiveness of CCS by lowering energy needs.

AI-enabled predictive maintenance offers yet another important way to cut costs. In industrial settings, unscheduled downtime brought on by equipment failures can be quite expensive. To identify early indicators of deterioration or imminent failure, artificial intelligence (AI) systems can examine sensor data from pumps, compressors, and other vital equipment. This makes preventative maintenance possible, reducing production losses, averting expensive malfunctions, and increasing equipment lifespan. Predictive maintenance powered by AI improves the availability and dependability of CCS systems while lowering maintenance expenses. Additionally, AI can reduce construction expenditures by optimizing the layout and configuration of CCS facilities. To find the most economical solutions, AI algorithms can examine a variety of design criteria, including the number and kind of capturing units, pipeline arrangement, and building materials. To maximize system performance and minimize the overall footprint of CCS infrastructure, AI can also simulate various operational situations. It is feasible to increase the economic appeal of CCS and hasten its broad implementation as a crucial technology for mitigating climate change by utilizing AI to optimize both capital and operating expenses.

4) High CO_2 Sequestration Rate (Scaling Up CCS for Maximum Impact):

CCS technology must function at a scale appropriate for the size of the problem if they are to significantly aid in climate change mitigation. To successfully remove significant amounts of greenhouse gases from the atmosphere, it is necessary to have the capacity to collect and store CO_2 at large rates. To maximize and enable CO_2 sequestration rates, artificial intelligence is essential. Achieving high sequestration rates requires AI-driven capture process optimization. AI enables CCS facilities to function closer to their maximum capacity by dynamically modifying operating settings and preserving peak efficiency. Additionally, by optimizing the material flow inside the system, AI algorithms can decrease bottlenecks and boost throughput. The overall sequestration rate is increased by these modifications, which guarantee that the most CO_2 is caught per unit of time.

To optimize the impact of CCS infrastructure on reducing atmospheric CO_2, AI can also help with its strategic placement. To find the best places for CCS facilities, AI algorithms can examine data on the distribution of the main emission sources, the availability of appropriate geological storage sites, and the current transportation networks. Higher overall sequestration rates are a result of this strategic placement, which guarantees that CCS is installed where it can most effectively collect the highest amounts of CO_2. AI can also maximize the integration of CCS with other carbon management techniques, such as direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS). AI can significantly improve the overall sequestration rate and efficacy of the carbon management portfolio by coordinating the operation of various technologies and optimizing resource allocation.

5) Safety and Reliability (Ensuring Secure and Dependable CCS Operations):

CCS systems must operate safely and dependably for the sake of public trust and environmental preservation. A CCS infrastructure event, accident, or failure might have serious repercussions, from public outcry to financial losses and environmental harm. AI is essential for reducing risks and guaranteeing predictable performance, which improves the safety and dependability of CCS operations. Monitoring systems with AI capabilities offer a strong foundation for quickly identifying irregularities and possible threats. Throughout the CCS process, these systems continuously monitor vital parameters using a network of sensors and data collection tools. To detect possible issues like leaks, equipment failures, or unstable operating parameters, AI algorithms examine this data for departures from typical operating conditions. Artificial intelligence (AI) systems can set off automated alerts, start emergency shutdown protocols, or give operators prompt warnings and instructions when they identify an issue. By taking a proactive approach to safety, the likelihood of mishaps is reduced, and worker and environmental protection is guaranteed.

Predictive maintenance, as previously discussed, also significantly contributes to the reliability of CCS systems. By anticipating equipment failures and scheduling maintenance proactively, AI reduces the likelihood of unplanned downtime and ensures the continuous operation of CCS facilities. This enhanced reliability is essential for maintaining consistent CO_2 capture rates and ensuring the long-term effectiveness of the technology. The intricate control systems that regulate the functioning of CCS facilities can also be optimized by AI. Even in the face of disruptions or uncertainty, AI algorithms can maintain stable and seamless operation by learning from past data and adapting to changing circumstances. The entire dependability of the CCS infrastructure is improved, and the chance of operational errors is reduced thanks to this optimized control.

6) Environmental Sustainability (Aligning CCS with Broader Sustainability Goals):

CCS's ultimate goal is to mitigate climate change by lowering CO_2 emissions, which will support environmental sustainability. AI is essential to optimizing CCS's environmental advantages and making sure that its implementation is in line with more general sustainability objectives. AI maximizes the quantity of CO_2 captured and permanently stored, improving the environmental sustainability of CCS. AI makes the guarantee that CCS efficiently lowers atmospheric CO_2 concentrations by maximizing capture efficiency, raising sequestration rates, and limiting leakage.

Additionally, AI encourages CCS operations to adopt more environmentally friendly procedures. AI systems, for instance, can optimize energy use, lowering the need for fossil fuels to power CCS installations. To further reduce

CCS's carbon footprint, AI can help integrate it with renewable energy sources. AI can also help reduce the negative environmental effects of developing CCS infrastructure. To minimize land use conflicts, minimize habitat impact, and encourage responsible resource management, AI algorithms can evaluate ecological data, social aspects, and land use trends to optimize the location of CCS facilities. By keeping an eye out for possible environmental effects at storage locations, AI can also help ensure the long-term viability of CO_2 storage. To find any indications of leakage or other negative effects, AI systems can examine data on soil conditions, seismic activity, and groundwater quality. This proactive monitoring minimizes the environmental impact of CO_2 storage by ensuring that it is carried out safely and responsibly.

A thorough and revolutionary method of improving the efficacy, efficiency, and sustainability of these vital technologies is provided by the incorporation of AI into CCS. AI enables us to absorb and store CO_2 more efficiently, responsibly, and sustainably by tackling major obstacles and enabling new performance levels, opening the door to a future that is cleaner, healthier, and more resilient. Anyebe et al.'s (2024) views are a useful manual for comprehending and utilizing AI's enormous potential in the quest for a sustainable carbon management paradigm.

3.11 Combining Artificial Intelligence with Nature-Based Carbon Dioxide Removal to Improve It

The combination of Nature-Based Solutions (NbS) with Artificial Intelligence (AI) produces a potent synergy to improve carbon sequestration. AI can optimize NbS management plans and site selection to optimize carbon sequestration.

- **Blue Carbon Management:** By analyzing data from satellite altimetry and oceanic sensors to comprehend carbon uptake, artificial intelligence (AI) plays a critical role in monitoring and managing blue carbon ecosystems. AI can forecast the effects of different ocean-based CDR activities and calculate the potential for carbon storage in particular habitats (Bax et al., 2025).
- **Soil Carbon Sequestration:** AI improves soil carbon sequestration by using precision agricultural methods to analyze data and suggest the best fertilization, irrigation, and soil management strategies. To optimize carbon capture, artificial intelligence (AI) technologies can recommend plant species that are most suitable for particular soil types and climates. To suggest exact combinations of cover crop species, AI systems can also decipher the findings of soil tests. Artificial intelligence (AI) gives farmers practical insights to improve carbon sequestration by evaluating soil health data from IoT sensors and satellite photos.
- **Afforestation and Reforestation:** Artificial intelligence (AI) algorithms are able to examine environmental elements such as topography and soil composition in order to determine the best places to plant and the best kinds of trees. Selecting locally suitable tree species for reforestation is made easier by AI-powered algorithms that can also correctly identify tree species from photos. Additionally, AI is utilized to track the health and growth of trees through drone and satellite imagery.

3.12 Artificial Intelligence for Nature-Based Carbon Removal Monitoring, Reporting, and Verification (Mrv)

For nature-based carbon removal operations to be credible and effective, accurate Monitoring, Reporting, and Verification (MRV) is crucial. AI has the potential to completely transform MRV for NbS, incorporating machine learning and satellite imagery processing. Large datasets from remote sensing technologies can be analyzed by AI algorithms to more accurately and spatially resolve carbon stocks and fluxes. Subtle alterations in vegetation health or patterns of land use that suggest carbon sequestration can be detected using machine learning algorithms. AI is also capable of processing sensor network data for ongoing observation and early anomaly detection. AI can also improve the traceability and transparency of carbon credits produced by sequestration projects.

Case Studies: To track reforestation efforts and assess tree health, MORFO uses drones and AI-powered tools. A worldwide tree canopy map driven by AI was created by Meta and WRI to enhance forest monitoring and verify carbon credits. Pachama optimizes the MRV of nature-based carbon projects by using AI analytics and satellite data. Tierra Foods collaborated with the University of Huddersfield to develop an AI-powered forestry-based CDR monitoring system. Boomitra measures and validates soil carbon credits using AI and satellite technology. To provide soil organic carbon with satellite-based carbon credit verification, Taranis and Albo Climate collaborated. MRV data and carbon removal activities are audited by Charm Industrial using AI (Crimmins, 2025).

3.13 Considerations and Difficulties in Combining AI with Nature-Based CDR

While the integration of AI and NbS for CDR offers significant potential, several challenges and considerations must be addressed.

- **Bias and Inaccuracies in AI Models:** Biases may be reinforced or amplified by AI models that were trained on biased data. Policy actions must be carefully considered in light of the uncertainty in AI-driven climate predictions. Predictions with incomplete data may be less accurate. Complex AI models' "black box" phenomena can erode confidence and make it difficult to spot errors.
- **Data Availability and Quality:** For efficient training, AI models need a lot of high-quality data. Data gaps, noise, and biases can all affect how accurate verification results are. It's also critical to guarantee data security and privacy.
- **AI Energy Consumption:** Complex AI models demand a lot of processing power to train and operate, which results in significant energy consumption and greenhouse gas emissions. AI's energy requirements may surpass the growth of sustainable energy sources. The goal of "green AI" techniques is to lessen the carbon footprint of AI technologies (S, 2024b; AI-Powered Soil Carbon Project Launched in East Africa to Support Smallholder Farmers – Farm to Market Alliance, n.d.).
- **Ethical Concerns:** Including AI in natural ecosystems presents ethical questions, including long-term ecological implications, stakeholder influence, and ecological balance disruption. Vulnerable groups may suffer as a result of algorithmic bias in resource distribution. In the creation and application of AI, accountability and transparency are crucial. Long-term repercussions and sustainable actions must be given top priority in ethical frameworks.

4. Future Research Directions

Building on the combined knowledge of AI and NbS integration in CCRS, the following important future research avenues demand careful examination to develop this exciting area further:

- **Resolving Data Gaps, Bias, and Accessibility:** To resolve current data gaps, biases, and accessibility difficulties that impede the broad use of AI in NbS for CCRS, substantial research is needed. This entails funding extensive data collection projects, creating methods for identifying and reducing bias in ecological datasets, and investigating federated learning strategies that support cooperative research while protecting data privacy.
- **Creation of Standardized Procedures and Performance Standards:** Standardized procedures and performance standards are desperately needed to assess the effectiveness and scalability of AI-driven NbS for carbon sequestration. Clear processes for data collection, preprocessing, model training and validation, and uncertainty quantification across various ecosystems and AI algorithms must be established.
- **Improving the Robustness and Transparency of AI-Driven MRV:** The creation of more resilient, transparent, and economical AI-powered MRV frameworks for NbS should be the top priority of future research. To improve the interpretability of AI models used for carbon accounting, this involves investigating explainable AI (XAI) methodologies and creating strategies for integrating multi-scale data (such as satellite, drone, and in-situ sensors) with increased accuracy and decreased uncertainty.
- **Strategies for Scaling and Deployment:** Future studies should focus on the difficulties in regionally and internationally implementing AI-enhanced NbS for CCRS. This includes looking into the infrastructure needs for broad adoption, policy ramifications, and economic viability.
- **Examining the Socio-Ecological Consequences and Ethical Frameworks:** To completely comprehend the wider socio-ecological ramifications and create strong ethical frameworks for the use of AI in managing natural ecosystems for carbon sequestration, extensive research is required. This entails determining standards for ethical AI research and application in ecological environments as well as evaluating possible effects on biodiversity, nearby communities, and land use.

- **Creating More Complex Integrated Ecological-AI Models:** Upcoming studies should concentrate on creating more complex integrated models that dynamically combine AI algorithms with ecological processes. For AI model architectures to more accurately predict carbon sequestration potential, ecosystem responses to interventions, and the long-term stability of stored carbon under different climate change scenarios, ecological principles and domain knowledge must be incorporated.
- **Investigating the Potential for Synergy Among Various NbS and AI Methods:** The synergistic potential of mixing different NbS with different AI approaches should be further explored. The advantages of combining AI-enhanced afforestation with AI-powered wildfire risk assessment or AI-optimized biochar production with AI-driven soil carbon monitoring are two examples.
- **Long-Term Monitoring and Adaptation Strategies:** To track the stability and permanence of carbon stored using NbS amid shifting environmental conditions, research is required to create AI-powered long-term monitoring strategies. Additionally, investigating AI-guided adaptive management techniques will be essential to guaranteeing the long-term viability of these carbon removal projects.
- **Optimizing for Trade-offs and Co-benefits:** Future studies should concentrate on creating AI-driven strategies that minimize potential trade-offs related to large-scale NbS deployment while simultaneously optimizing for co-benefits (such as biodiversity enhancement, improved water quality, and climate resilience) and maximizing carbon sequestration. Frameworks for multi-objective optimization that take social, economic, and ecological aspects into account are needed for this.

Realizing the full potential of combining AI and NbS to develop efficient, long-lasting, and scalable solutions for carbon dioxide capture, removal, and storage, and ultimately making a significant contribution to mitigating climate change, will require addressing these future research directions through interdisciplinary collaboration.

5. Result and Discussion

The synthesis of current research reveals a compelling synergy between Artificial Intelligence (AI) and Nature-Based Solutions (NbS) in advancing Carbon Dioxide Capture, Removal, and Storage (CCRS) technologies. AI's capacity for processing extensive environmental datasets, particularly from remote sensing and sensor networks, significantly enhances the monitoring and assessment of carbon stocks and fluxes in diverse ecosystems, while machine learning algorithms enable the detection of subtle changes indicative of sequestration. The management of NbS is also being improved through the use of AI-driven predictive models and optimization approaches. These include the understanding of ocean-based CDR, precision agriculture for soil carbon improvement, and the selection of species and sites for afforestation. One important result is that AI can completely transform the Monitoring, Reporting, and Verification (MRV) of carbon removal programs based on NbS. This would provide more precise, transparent, and scalable carbon accounting, which is crucial for market confidence. Even though there are still issues with data limitations, ethical concerns, and transparency in AI, the new applications in forestry, agriculture, and coastal ecosystems highlight how this convergence has the potential to revolutionize carbon removal at the regional and global levels. To maximize carbon sequestration and its co-benefits, more interdisciplinary research is required, with a focus on standardized methodologies, strong MRV frameworks, and the creation of integrated ecological-AI models.

6. Conclusion

The synergistic convergence of artificial intelligence (AI) and nature-based solutions (NbS) is thoroughly assessed in this thorough synthesis as a crucial tactic for improving the effectiveness and scalability of carbon dioxide capture, removal, and storage (CCRS) systems. Our research shows a paradigm shift in carbon management, with AI's advanced analytical powers providing game-changing improvements throughout the whole NbS-driven carbon sequestration lifespan. The incorporation of AI exhibits substantial added value from the early phases of optimized deployment, which include AI-driven site suitability assessments and species selection based on environmental parameters and predictive climate models, to the crucial stages of improved monitoring and assessment using cutting-edge remote sensing techniques and machine learning algorithms for accurate carbon stock and flux quantification. Additionally, this study emphasizes how important AI is to creating Monitoring, Reporting, and Verification (MRV) frameworks for NbS-based carbon removal initiatives that are more reliable, open, and economical. Building trust and drawing investment to nature-positive climate mitigation projects depend on carbon accounting's accuracy and scalability, which are made possible by AI's ability to process and interpret complex, multi-modal environmental datasets. Another significant benefit of this integrated approach is the possibility for AI to support adaptive management techniques that are based on predictive models that take into consideration the dynamic effects of climate change on ecosystem function and the permanence of carbon storage.

Nevertheless, the intrinsic difficulties and complexities connected to the convergence of AI and NbS are also critically addressed in this synthesis. Concerns regarding the interpretability and transparency of some AI algorithms, the necessity of maintaining data quality and reducing biases in ecological datasets, and the substantial energy consumption of AI infrastructure demand careful thought and focused research. For these integrated solutions to be deployed responsibly and ethically, it will be essential to address these issues by creating explainable AI approaches, standardized data standards, and sustainable AI practices. The establishment of standardized procedures and performance standards for AI-enhanced NbS, the development of integrated ecological-AI models that dynamically couple ecological processes with AI algorithms, and a thorough examination of the wider socio-ecological ramifications and ethical frameworks governing the use of AI in natural ecosystems for carbon sequestration must be the top priorities for future research directions. Important directions for future research include examining the synergistic potential of various NbS and AI approaches, optimizing for co-benefits other than carbon removal, and creating reliable long-term monitoring and adaptive management plans informed by AI insights. Achieving significant and scalable negative emissions is ultimately possible through the thoughtful and responsible fusion of artificial intelligence (AI) with the natural carbon sequestration capabilities of nature-based solutions. This is a crucial prerequisite for successfully reducing the growing threat of anthropogenic climate change and promoting a sustainable future.

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