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Negative emission technologies: a way forward?

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Negative Emission Technologies (NETs) can play a pivotal role in mitigating climate change by removing CO_2 from the atmosphere, complementing emission reduction efforts especially as 1.5 °C Paris Agreement targets are exceeded and historical emissions removals are required. This review systematically evaluates the current landscape, technical performance, and scalability of key NETs, including Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), afforestation, soil carbon sequestration and biochar, enhanced weathering, and ocean-based methods. Technological advancements required are analyzed to highlight and enhance the efficiency, scalability, resource requirements (land, water, and minerals), and economic viability of these solutions. The interplay between NETs and existing emissions reduction strategies is critically examined, emphasizing the need for synergies that maximize overall climate benefits while minimizing resource competition. Comparative analyses highlight differences in technological readiness, energy use, and environmental impacts, offering insights into the practical and theoretical limits of CO_2 sequestration for each approach. The review also explores energy balances, cost structures, and life-cycle assessments (LCA), identifying bottlenecks in deployment and potential areas for innovation to enhance efficiency and reduce costs. Additionally, we evaluate the current policy frameworks that support NET development, identifying key challenges in both governance and measurement/reporting/verification (MRV) that must be addressed to facilitate widespread deployment. The review underscores the necessity for robust international cooperation and financing mechanisms tailored to NETs, particularly for capacity building in developing regions. As we pursue a net-zero future, addressing the research gaps and promoting effective integration of NETs into comprehensive climate strategies will be crucial for mitigating the long-term impacts of anthropogenic CO_2 emissions.

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Sustainability spotlight

As global emissions continue to rise, limiting warming to 1.5 °C requires not only deep decarbonization but also large-scale carbon removal to remediate historical emissions. This review critically examines Negative Emission Technologies (NETs)—from afforestation and biochar to Direct Air Capture and ocean alkalinization—and their role in advancing sustainable climate solutions. By evaluating their scalability, resource needs, and integration with existing systems, this work identifies the opportunities and trade-offs essential to global deployment. Supporting the development of NETs directly advances several UN Sustainable Development Goals, particularly SDG 13 (Climate Action), SDG 7 (Affordable and Clean Energy), and SDG 15 (Life on Land), contributing to a balanced and resilient path to net-zero.

1. Introduction

Climate change poses an unprecedented challenge to global sustainability, with greenhouse gas emissions, particularly carbon dioxide (CO_2), driving the rise in global temperatures.[1,2] While emission reduction efforts have made significant strides, it is becoming increasingly clear that such measures alone may not be sufficient to limit global warming to 1.5 °C above pre-industrial levels.[3] This has led to growing interest in Negative Emissions Technologies (NETs), which actively remove CO_2 from the atmosphere and store it over various timescales.[4–7] CO_2 storage security improves over time through structural, residual, solubility, and mineral trapping, preventing leakage. Continuous monitoring ensures long-term stability. NETs, also referred to as Greenhouse Gas Removal (GGR) technologies, represent a fundamental shift in climate change mitigation. They focus not only on reducing current emissions but also on reversing the buildup of atmospheric CO_2 caused by historical emissions. These technologies offer a potential solution to addressing both ongoing emissions and the cumulative impacts of past emissions.

NETs encompass a broad range of approaches, from enhancing natural carbon sinks, such as reforestation[8–10] and

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soil carbon sequestration,[11–13] to advanced technological solutions like direct air capture (DAC).[14–16] These technologies are gaining prominence in climate policy discussions, particularly as part of integrated strategies to reach net-zero emissions.[1,17–19] Sectors that are difficult to decarbonize, including aviation and heavy industry, stand to benefit significantly from NETs, as these technologies can offset residual emissions that cannot be fully eliminated by conventional means. While conventional approaches emphasize permanent geological sequestration, increasing attention is being given to carbon capture, utilization, and storage (CCUS), where captured CO_2 is integrated into durable products or converted into value-added fuels. Utilization pathways include mineralization in construction materials, bio-based carbon storage, and the production of synthetic fuels (e-fuels) *via* hydrogenation or electrochemical processes. By combining sequestration with utilization, NETs can contribute to long-term carbon removal and the development of a circular carbon economy, enhancing scalability and economic viability. This integration also provides a sustainable pathway for producing low-carbon fuels, replacing fossil fuels, and advancing decarbonization efforts.

The inclusion of NETs in climate models, particularly in scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), has underscored their importance in meeting global climate goals. To achieve the Paris Agreement's target of limiting warming to 1.5 °C,[3,20] many models project the need for significant CO_2 removal—on the order of 6 gigatons per year by 2050-but most models only consider wide-scale deployment of a limited subset of NETs. Such global scales highlight the necessity of widespread NET deployment, as well as the associated technical, economic, and governance challenges. This comprehensive review aims to provide a thorough examination of the current status, future prospects, and implications of NETs for climate change mitigation. It explores the technical feasibility of various NET approaches, evaluates their potential impact on carbon reduction targets, and highlights the multifaceted challenges—ranging from energy and cost efficiency to policy integration—that must be addressed to enable successful large-scale implementation. By doing so, the review emphasizes the critical role of NETs in complementing emission reduction strategies, thereby offering a pathway to achieving long-term climate stability.

1.1 Climate change context and the need for negative emission technologies (NETs)

Global efforts to address climate change have increased awareness and prompted various initiatives; however, greenhouse gases (GHGs) continue to in the atmosphere. The Global Carbon Project reports that annual CO_2 emissions from fossil fuels and industry hit a record 36.8 billion tonnes in 2023, up 1.1% from 2022.[21] This rise follows a temporary decrease during the COVID-19 pandemic, indicating a return to pre-pandemic emission levels and highlighting insufficient progress towards a green transition. The energy sector, responsible for about two-thirds of global emissions, remains the largest contributor,[22,23] with industrial, agricultural, and land-use changes also playing significant roles. The key focus is on the anthropogenic CO_2 contributions that alter natural GHG exchanges, impacting Earth's climate balance and long-term carbon storage dynamics.

The carbon budget further emphasizes the need for urgent action. For a 1.5 °C target above pre-industrial levels, the remaining global carbon budget as of 2020 was approximately 400 gigatonnes of CO_2.[24] At current emission rates, this budget will be exhausted within a decade, stressing the immediate need for significant reductions in emissions and the rapid adoption of NETs.

Future climate scenarios suggest that current emission trends will exceed the Paris Agreement targets. Projections indicate a potential warming of approximately 2.7 °C by 2100, surpassing the 1.5 °C and 2 °C thresholds. The IPCC models various Shared Socioeconomic Pathways (SSPs) from rapid decarbonization to minimal action, revealing that meeting the Paris targets will require drastic emissions cuts and extensive deployment of NETs to address both existing CO_2 levels and residual emissions from challenging sectors. Fig. 1 shows that despite the IPCC's explicit warnings about the severe risks of surpassing 1.5 °C of warming, progress on setting more ambitious 2030 climate targets and engaging in sectoral initiatives has stagnated since COP26 in Glasgow. Without enhanced government action, global GHGs in 2030 will be twice the level permitted under the Paris Agreement's 1.5 °C limit. Current projections indicate that with the existing 2030 targets, the world is on a trajectory towards a 2.4 °C increase, and with current policies, this could rise to 2.7 °C.[25]

1.2 Role of negative emission technologies in IPCC reports and climate models

The inclusion of NETs in climate models has evolved as their potential role in addressing the emissions gap has become increasingly recognized. Initially, NETs were treated as speculative or long-term solutions,[26–38] but their prominence has grown as scenarios focusing on limiting warming to 1.5 °C demonstrate their necessity. In the IPCC's Fifth Assessment Report (AR5),[39] technologies such as Bioenergy with Carbon Capture and Storage (BECCS) featured heavily in long-term mitigation pathways. The subsequent Special Report on Global Warming of 1.5 °C,[3] released in 2018, expanded on the role of NETs, reinforcing the understanding that carbon removal will likely be required at a large scale by mid-century, even if the models used only resolve a limited set of NETs.

Integrated Assessment Models (IAMs)[4,14,40] used to explore future climate and policy scenarios incorporate NETs as a means to offset residual emissions and lower atmospheric CO_2 concentrations post-2050. NETs are often treated as a “backstop” technology in IAMs, providing a buffer that allows for flexibility in the timing of emissions reductions across sectors. However, their reliance on NETs has been critiqued for potentially downplaying the near-term urgency of emissions reductions (leading to moral hazards) and the technical challenges of large-scale deployment.

The challenges associated with scaling NETs—such as land-use requirements for BECCS,[2,41] energy demands for DAC,[42–44]

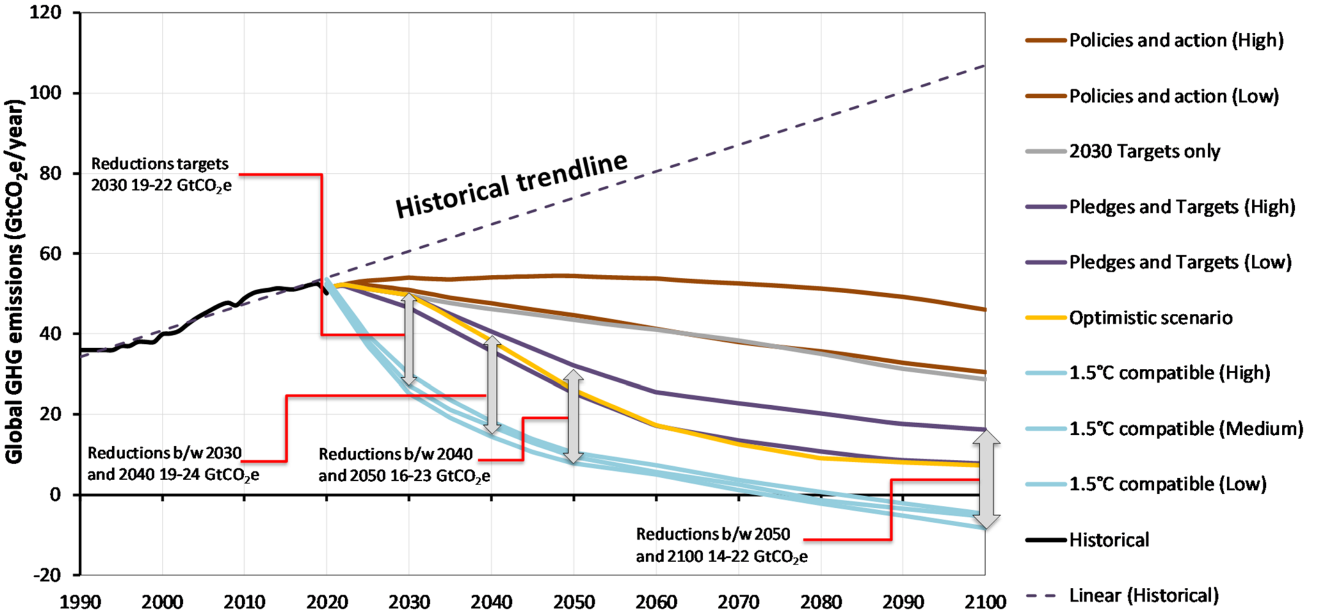

Fig. 1 Global greenhouse gas emissions pathways, comparing the Climate Action Tracker (CAT) estimates of policies and action, 2030 targets only, combined 2030 and long-term binding targets, and an optimistic pathway based on net zero targets from over 140 countries, against a pathway consistent with a 1.5 °C temperature limit (data from Climate Action Tracker[22]).

and environmental concerns with ocean-based NETs[45–47] have sparked debates about their feasibility and efficacy. While NETs may be necessary to achieve net-zero emissions, relying too heavily on future carbon removal without concurrently pursuing aggressive emissions reductions could lead to "mitigation deterrence," delaying essential action in the near term.

Considering the importance of the topic and scope and objectives of this comprehensive review study, Fig. 2 outlines the logical structure and thematic progression of the review. It begins with the context and motivation for NETs, followed by a comprehensive classification into biological, geochemical, and engineering-based approaches. Each NET is then assessed through a unified evaluation framework incorporating technological readiness, CO_2 removal potential, resource needs, environmental impacts, and economic feasibility. A comparative analysis is conducted based on these criteria, leading into a discussion on policy, governance, and monitoring, reporting, and verification (MRV). The review concludes with identified research gaps and recommendations, highlighting directions for future development and integration with global climate strategies.

2. Overview of negative emission technologies (NETs)

NETs encompass a broad range of methodologies designed to extract carbon dioxide (CO_2) from the atmosphere and securely sequester it over extended periods. Ultimately the goal is to reduce the radiate forcing of the atmosphere by the presence of excess greenhouse gases, and while CO_2 removal is the focus of this review as the dominant GHG, methane removal is starting to receive attention too.[48–50] Given the escalating urgency to mitigate climate change, NETs have garnered significant attention as potential adjuncts to traditional emissions reduction strategies. This section offers an in-depth analysis of the different categories of NETs, elucidates their fundamental mechanisms, and examines critical factors influencing their deployment and effectiveness. Bibliometric analysis can be developed to illustrate the current landscape of research in NETs, CO_2 capture, DAC, carbon dioxide removal, climate change mitigation, afforestation, and biochar. This method identifies historical and emerging developments by analyzing academic literature outputs, providing a comprehensive overview of key research areas. A systematic review of articles and book chapters published between 2014 and 2024 was conducted to evaluate and visualize research hotspots, trends, and frontiers in NETs globally.

Publications were sourced from the Web of Science (WoS) database, using "Science Citation Index Expanded" and "Science Citation Index" collections. Bibliometric mapping was performed using VOSviewer software, as depicted in Fig. 3. Search parameters included keywords such as NETs, CO_2 capture, DAC, carbon dioxide removal, climate change, afforestation, and biochar to ensure a comprehensive and valid data retrieval process. This approach enables a detailed exploration of the research landscape, identifying critical developments and emerging trends in the field. This figure visually represents the interconnections between key topics in carbon management, climate change mitigation, and sustainability. Different clusters highlight thematic groupings, such as biochar and soil sequestration (red), carbon capture and direct air capture (purple), bioenergy and emissions modeling (blue), and renewable energy and governance (green). The network

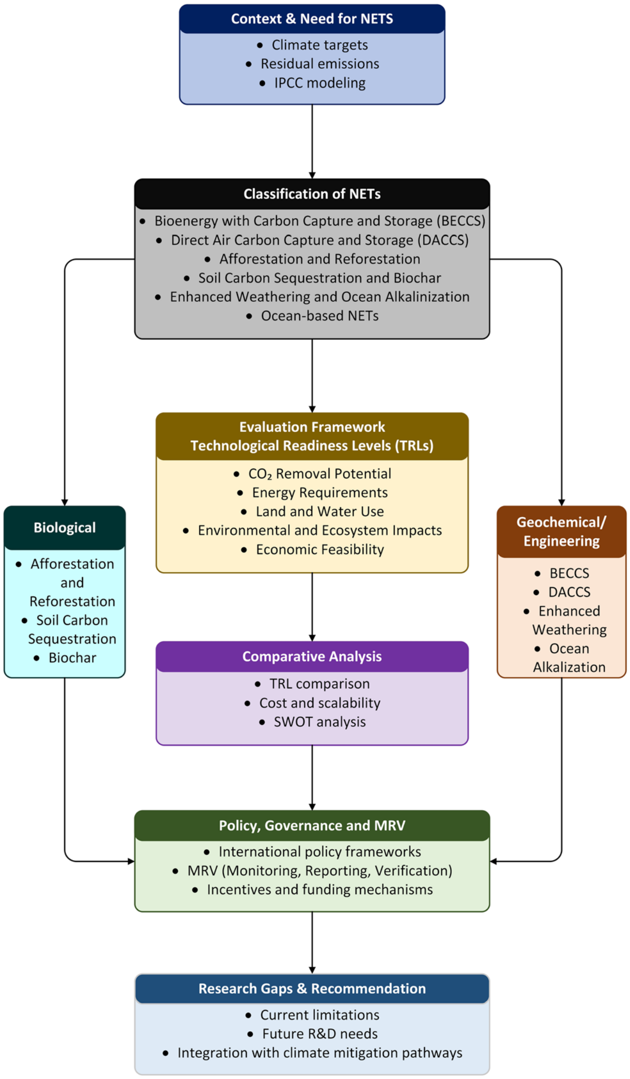

Fig. 2 Conceptual overview and flow structure of review approach.

structure reveals strong linkages between biomass, carbon sequestration, and climate change, emphasizing the integrated nature of negative emission technologies and policy considerations. Emerging connections between renewable energy and CO_2 removal suggest increasing research focus on sustainable decarbonization pathways.

2.1 Classification of NETs

2.1.1 Biological approaches. Biological NETs utilize natural processes to capture and sequester carbon dioxide (CO_2) through biological mechanisms. These approaches capitalize on the processes of photosynthesis and the inherent carbon storage potential of living carbon-based organisms and ecosystems. Prominent examples of biological NETs include:

• Afforestation involves establishing new forests on previously nonforested lands to sequester atmospheric CO_2 in biomass and soils. Reforestation refers to restoring deforested or degraded forest areas to enhance carbon storage in regenerated vegetation and soils.

• Soil carbon sequestration: techniques involve implementing practices like no-till farming, cover cropping, and organic matter addition to increase soil carbon content. The benefits include enhanced soil health and fertility, and potentially improved agricultural productivity.

• Biochar: production of biochar is achieved through the pyrolysis of biomass, which involves heating organic material in the absence of oxygen. Its application involves adding it to soils to enhance carbon sequestration and potentially improve soil fertility.

• Ocean fertilization: the process involves adding nutrients (*e.g.*, iron) to ocean waters to stimulate phytoplankton growth and enhance CO_2 uptake from the atmosphere, with at least some biomass eventually sinking to the ocean floor. However, this approach is controversial due to potential ecological risks, uncertainty about carbon sequestration permanence, and possible unintended environmental consequences.

2.1.2 Geochemical approaches. Geochemical NETs expedite natural geochemical weathering processes to increase atmospheric CO_2 removal. They generally employ minerals or mineral-based materials that chemically react with CO_2, forming stable carbonates. Key examples include:

• Enhanced weathering: the mechanism involves the application of crushed silicate minerals (*e.g.*, olivine, basalt) to soils or land surfaces to accelerate the natural chemical weathering process, which reacts with CO_2 to form stable carbonates. The objective is to increase the mineral surface area available for CO_2 reactions, thereby enhancing the overall CO_2 sequestration rate.

• Ocean alkalization: the mechanism involves adding alkaline substances (*e.g.*, lime, olivine) to ocean waters to increase the ocean's capacity to absorb and store CO_2. The added alkalinity enhances the ocean's ability to convert CO_2 into bicarbonates and carbonates. The objective is to boost the ocean's natural carbon sequestration processes, thereby mitigating atmospheric CO_2 levels.

2.1.3 Chemical engineering approaches. Chemical engineering NETs involve the use of engineered systems to directly capture CO_2 from the atmosphere or point sources. These technologies often require significant energy input but offer high control over the capture and storage process. Key examples include:

• Direct Air Capture (DAC): utilizes chemical/thermal/electrochemical processes to extract CO_2 directly from ambient air. DAC systems use either liquid solvents or solid sorbents to capture CO_2, which is then regenerated and compressed. This process demands substantial energy input for the regeneration and compression stages, impacting overall efficiency and cost.

• Bioenergy with Carbon Capture and Storage (BECCS): integrates bioenergy production with carbon capture and storage. Plants absorb atmospheric CO_2 during growth, and when this biomass is used for energy, the CO_2 emissions produced are captured and stored underground. This technique combines biomass energy with CO_2 sequestration, contributing to net-negative emissions.

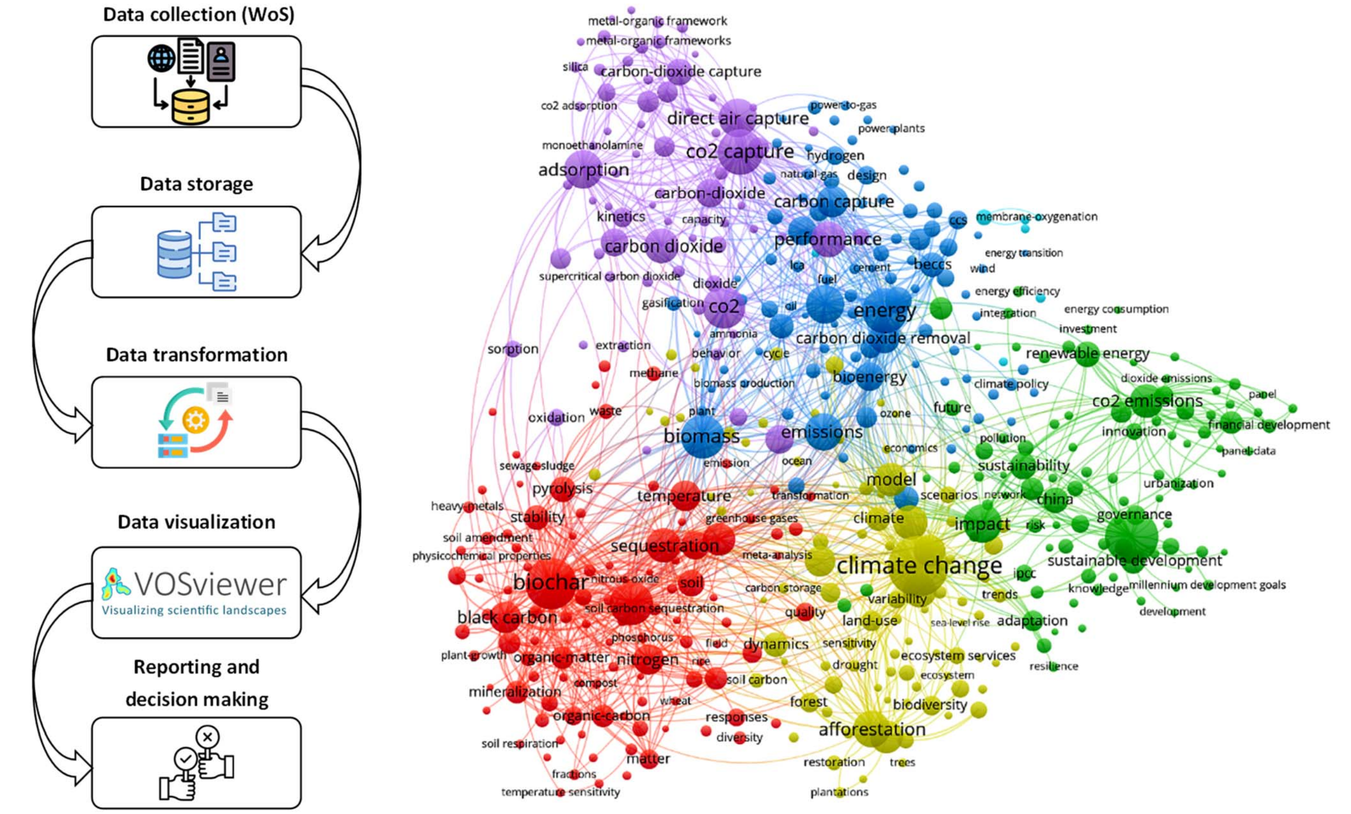

Fig. 3 Methodology and bibliometric map of co-occurrence network of keywords.

2.2 Key principles and mechanisms

2.2.1 Carbon cycle and NETs. Understanding the global carbon cycle is crucial for assessing the potential impact and effectiveness of NETs. The carbon cycle describes the movement of carbon between the atmosphere, biosphere, oceans, and geosphere. NETs aim to enhance the natural processes that remove CO_2 from the atmosphere or to create new pathways for carbon sequestration.

Biological NETs primarily interact with the fast carbon cycle, enhancing carbon uptake by plants and soils. These approaches can have relatively rapid impacts but may be less permanent. Geochemical and chemical engineering approaches often interact with the slow carbon cycle, potentially offering more stable long-term storage but with slower immediate impacts.

The effectiveness of NETs must be considered in the context of the entire carbon cycle, including potential feedback and saturation effects. For example, enhancing ocean CO_2 uptake could potentially reduce the ocean's future capacity to absorb atmospheric CO_2.

2.2.2 Permanence and storage considerations. The permanence of carbon storage is a critical consideration for all NETs. Different approaches offer varying degrees of storage stability:

• Biological storage (*e.g.*, in forests or soils) can be vulnerable to disturbances such as fires, pests, or land-use changes. The timescale of storage typically ranges from decades to centuries.

• Geological storage (*e.g.*, in depleted oil and gas reservoirs or saline aquifers) offers the potential for very long-term storage (thousands to millions of years) but requires careful site selection and monitoring to prevent leakage.

• Mineral carbonation (as in enhanced weathering) can provide extremely stable carbon storage on geological timescales, replicating but accelerating processes found in nature.

• Assessing and ensuring the permanence of carbon storage is crucial for the long-term effectiveness of NETs and their role in climate mitigation strategies.

2.2.3 Energy requirements and efficiency. The energy requirements of NETs vary widely and significantly impact their overall effectiveness and feasibility:

• Biological approaches generally have low direct energy requirements but may have indirect energy costs associated with land management and monitoring.

• Geochemical approaches, particularly enhanced weathering, can have significant energy requirements for mineral extraction, grinding, and distribution.

• Chemical engineering approaches, especially DAC, typically have high energy demands for capture material regeneration and CO_2 compression.

The energy efficiency of NETs is crucial for their net climate impact. If the energy used to power NETs comes from fossil fuel sources, it could potentially offset some or all of the climate benefits. Therefore, integration with low-carbon energy sources is essential for maximizing the effectiveness of NETs.

3. Major categories of NETs

NETs are categorized based on several dimensions:[1] technology category,[2] implementation options, and[3] storage medium as shown in Fig. 4. Among the six technology clusters considered Afforestation and Reforestation (AR), Soil Carbon Sequestration (SCS) and Biochar (BC), BECCS, and Ocean Fertilization (OF) – four utilize photosynthesis for CO_2 capture. In contrast, Direct Air Carbon Capture and Storage (DACCS), enhanced weathering, and ocean alkalization employ chemical processes to bind CO_2. Each technology can further be distanced based on the earth system (land or ocean-based) as Minx *et al.*[51] classified.

3.1 Bioenergy with carbon capture and storage (BECCS)

BECCS is a negative emission technology that has garnered significant attention in climate mitigation scenarios due to its potential for large-scale carbon dioxide removal. This approach combines the production of energy from biomass with the capture and long-term storage of the resulting CO_2 emissions. Fig. 5 displays the conceptual layout of BECCS along with sources, conversion technologies, carbon capture methods, and storage options for BECCS. In theory, BECCS offers the dual benefit of providing renewable energy while simultaneously removing CO_2 from the atmosphere, making it an attractive option in the pursuit of net-zero or negative emissions.

3.1.1 Technology description. BECCS technology integrates multiple processes that collectively enable the removal of CO_2 from the atmosphere through bioenergy use and carbon storage.

• Biomass production and types: energy crops are characterized by high energy content and rapid growth but require dedicated land, which may lead to potential competition with food production. Agricultural residues include crop by-products like corn stover and utilize existing land, though they can impact soil health if overharvested. Forestry residues come from logging waste, which helps reduce waste but requires careful management to protect ecosystems. Municipal solid waste contains organic components that can be used for energy, reducing waste, but it requires sorting and processing to ensure clean energy production.

• Conversion technologies: direct combustion involves burning biomass for heat and electricity; it is a simple method but potentially has lower efficiency.[53–55] Gasification converts biomass to syngas (CO and H_2), offering higher efficiency but requires advanced technology.[56–58] Pyrolysis decomposes biomass in the absence of oxygen, producing bio-oil, syngas, and biochar; it is less mature for large-scale use.[59–61] Anaerobic digestion converts organic matter to biogas (methane and CO_2); it is suitable for wet biomass and waste and typically operates on a smaller scale.[62–64]

• Carbon capture methods: post-combustion capture involves CO_2 removal from flue gases after combustion; it is retrofittable but energy-intensive.[65,66] Pre-combustion capture entails CO_2 separation during gasification before combustion; it is more efficient but requires complex design.[67,68] Oxy-fuel combustion burns biomass in pure oxygen, producing CO_2 and water vapor; it simplifies CO_2 separation but is energy-intensive due to the oxygen production required.[69,70]

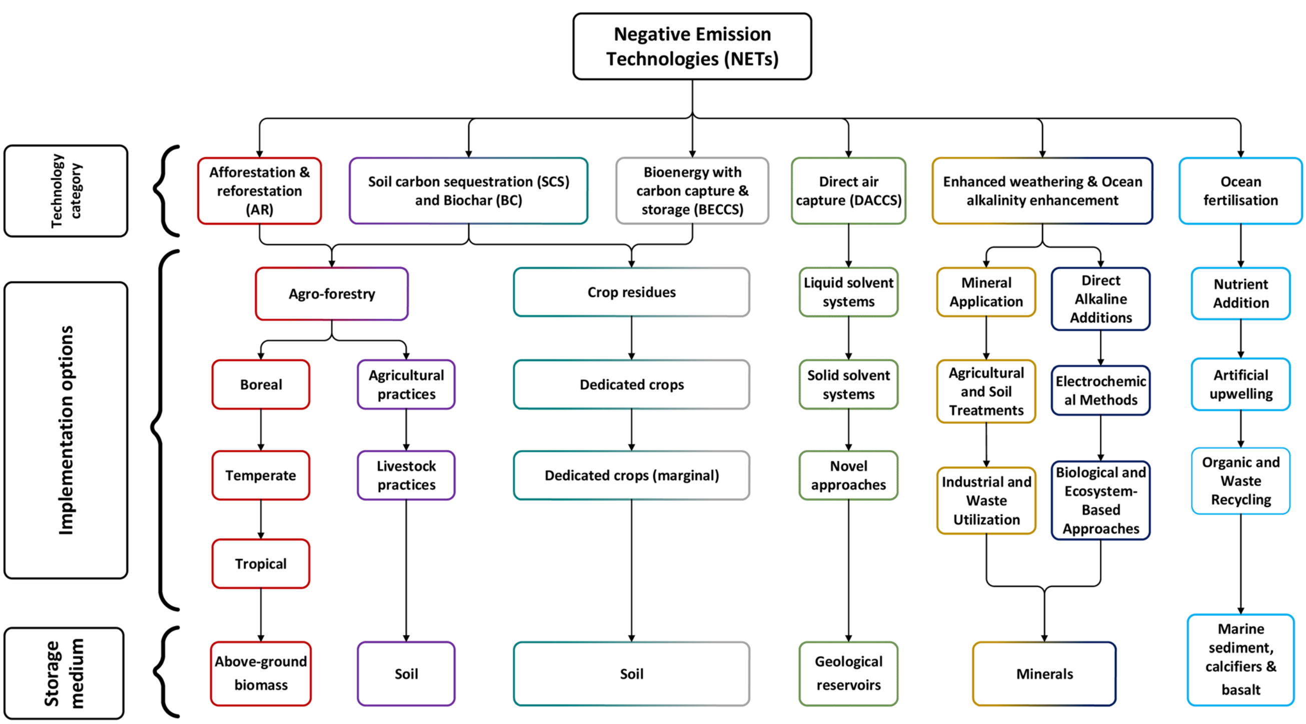

Fig. 4 A taxonomy of Negative Emission Technologies (NETs) categorizing technologies based on their approach to carbon capture and associated storage medium. This classification highlights the primary implementation options available for each type of NET (modified from ref. 52).

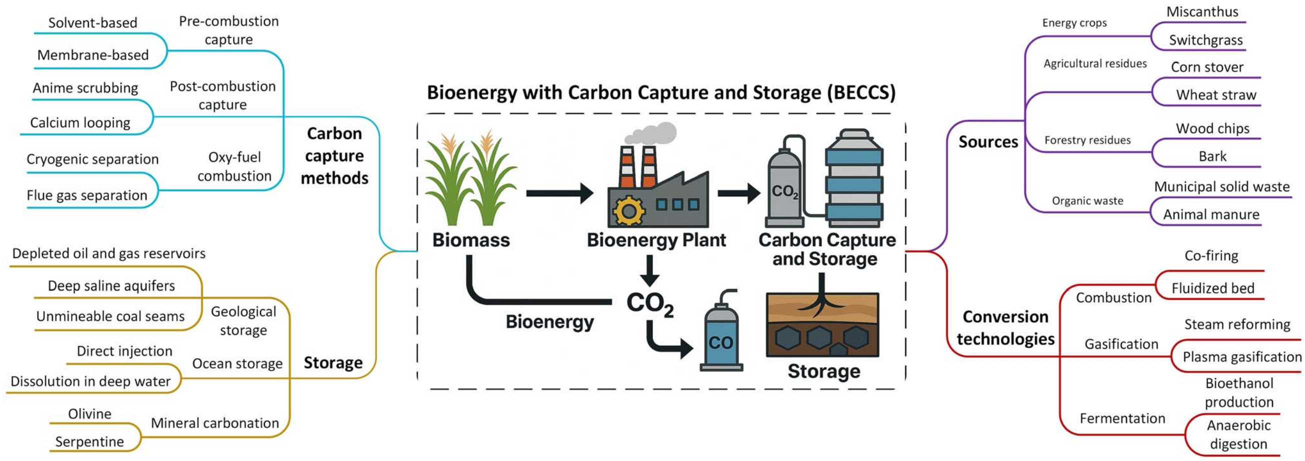

Fig. 5 Conceptual layout of bioenergy with carbon capture and storage (BECCS), illustrating sources, conversion technologies, carbon capture processes, and CO_2 transport and storage pathways.

• Storage options: geological storage involves the injection of CO_2 into depleted oil and gas reservoirs or deep saline aquifers; it is well-established but requires site monitoring.[71–73] Mineralization converts CO_2 to stable carbonates, offering permanent storage, but it is energy-intensive and less developed.[74,75] Ocean storage entails CO_2 injection into deep ocean waters; it is controversial due to ecological risks and concerns about long-term stability.[76–78]

3.1.2 Current status and projects. Operational and pilot projects:

• Drax North Yorkshire Power Station (UK): one of the largest BECCS projects, capturing up to 8 million tonnes of CO_2 annually from biomass combustion for electricity production.[79]

• Illinois Industrial Carbon Capture and Storage (USA): captures CO_2 from ethanol production and stores it underground, with an annual capacity of 1 million tonnes.[80]

• Stockholm Exergi (Sweden): a pilot BECCS project up to 800 000 tonnes of CO_2 annually from biomass-powered heat and electricity generation.[81]

• Huntly Power Station (New Zealand): BECCS pilot focused on biomass co-firing and carbon capture for potential large-scale deployment with 953 MW capacity.[82]

• Rotterdam Bio-CCS (Netherlands): a demonstration project at the port of Rotterdam aiming to capturing up to 5 million tonnes of CO_2 annually from waste-to-energy and biomass plants for offshore storage.[83]

3.1.3 Research and development initiatives.

• Biomass production and supply chain: focuses on sustainable feedstock supply and logistics for large-scale BECCS.

• Conversion and capture efficiency: enhances performance and reduces energy penalties through advanced materials and plant design innovations.

• Novel capture technologies: investigates integration with DAC to boost BECCS's negative emissions potential.

• Environmental impact assessments: conducts life cycle assessments and studies on land use and CO_2 storage behavior to ensure BECCS contributes positively to climate goals without adverse environmental effects. A potential comparison of the CO_2 capture capacity of planned BECCS and DACCS projects (2022–2030) is drawn and displayed in Fig. 6.

3.1.4 Potential and limitations. BECCS offers significant potential for large-scale carbon removal, but its deployment is constrained by a number of resource.

• Theoretical and practical CO_2 removal potential: theoretical estimates for global BECCS CO_2 removal range from 3 to 20 gigatonnes per year by 2050,[84] representing a substantial fraction of current global emissions. The practical potential is more constrained, with conservative estimates suggesting 0.5 to 5 gigatonnes per year by 2050, limited by biomass availability, land competition, and technology deployment challenges.

• Land use and biodiversity impacts: large-scale BECCS could require 0.1 to 0.4 hectares of land per tonne of CO_2 removed annually, potentially competing with food production and impacting global food security.[85,86] Biomass production may lead to biodiversity loss if natural habitats are converted to energy crop plantations; however, using marginal lands or agricultural residues might mitigate some ecological impacts.

• Water requirements: BECCS systems require significant water for biomass cultivation and conversion processes. Water use varies by biomass type and technology, with potential exacerbation of water scarcity in arid regions, impacting other water uses.[87,88]

• Energy balance and efficiency: the energy balance is affected by the energy penalty of CO_2 capture, which can reduce the net energy output of BECCS systems by 20–30%.[89,90] Efficiency improvements are needed across the entire BECCS supply chain to enhance negative emissions potential and economic viability.

• Cost estimates and economic viability: cost estimates for BECCS range from \$80–200/tCO_2 [90] removed, influenced by scale, biomass type, conversion technology, and storage methods. High costs compared to conventional emission reduction methods may become more competitive with increasing carbon prices and technological advancements. Supportive policies and incentives are crucial for economic viability.

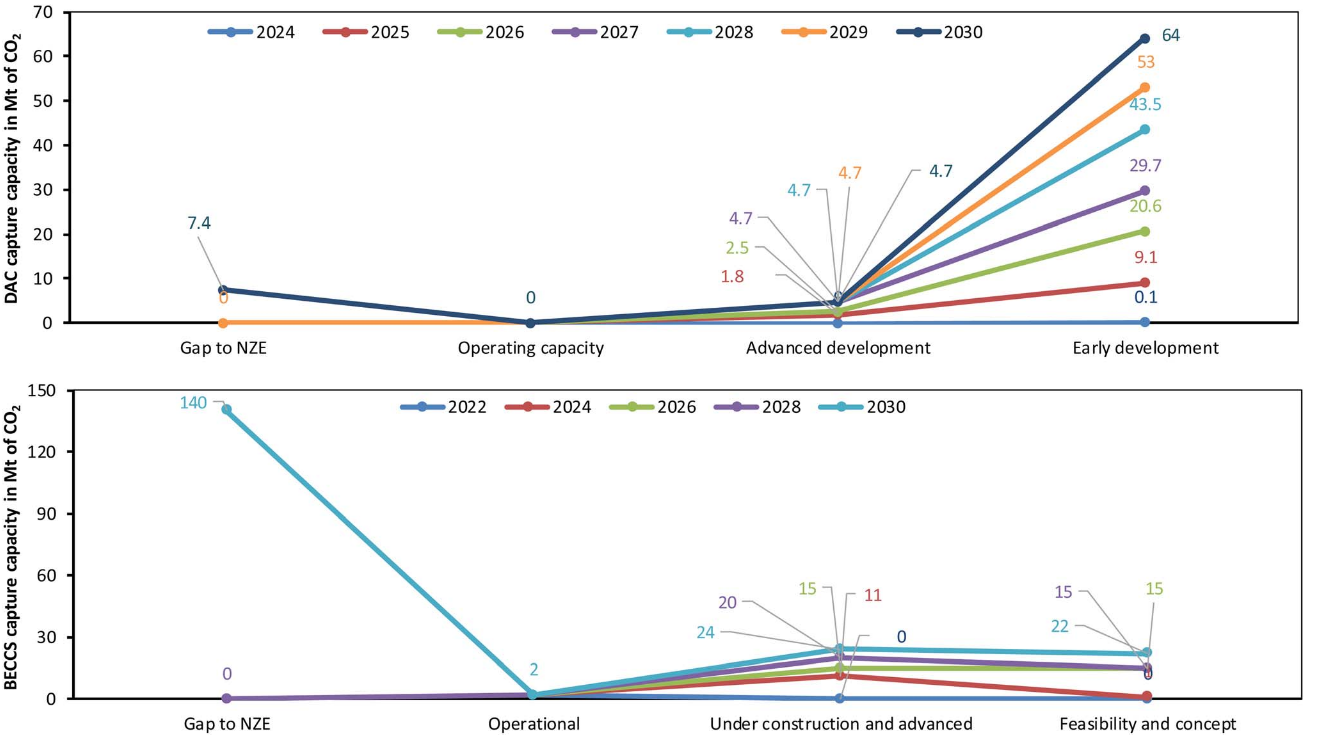

Fig. 6 CO_2 capture capacity comparison of planned BECCS and DACCS projects (2022–2030) (data from ref. 92).

3.2 Direct air carbon capture and storage (DACCS)

DACCS is an emerging negative emission technology that aims to remove carbon dioxide directly from the ambient air and store it permanently positioning itself as a key solution for achieving long-term carbon neutrality and offering a compelling business case driven by carbon credits, regulatory incentives, and growing demand for scalable carbon removal technologies. Fig. 7 shows the major conceptual layout of DAC along with DAC types, associated challenges and concerns, integration and applications, and storage options for DACCS. Unlike other carbon capture methods that focus on point sources of emissions, DACCS has the potential to address both current and historical CO_2 emissions, making it a powerful tool in the fight against climate change.

3.2.1 Technology description. An overview of DACCS technologies is provided below.

• Liquid solvent systems: hydroxide solutions (*e.g.*, potassium hydroxide) are used to absorb CO_2 from the air.[93,94] Air is contacted with the solution via large fans or air contactors, where CO_2 reacts with hydroxide to form carbonate ions. The solution is then processed to release CO_2 and regenerate the hydroxide. An example of this approach is Carbon Engineering, which uses potassium hydroxide in its air contactor design, involving chemical reactions to produce a pure CO_2 stream.[95]

• Solid sorbent systems: this approach employs materials, typically amine-based compounds on porous supports, to selectively adsorb CO_2 from the air.[96] CO_2 is captured as air flows over the sorbents; the sorbents are then heated or placed under vacuum to release the CO_2 and regenerate the materials. An example is Climeworks, which uses amine-based sorbents in modular filters, with captured CO_2 released by heating to around 100 °C.[97]

• Novel approaches: electrochemical systems utilize electricity to drive CO_2 capture and release, with electrodes absorbing CO_2 when voltage is applied and releasing it when the voltage is reversed. Cryogenic capture involves cooling air to freeze CO_2 as dry ice, producing a pure CO_2 stream but requiring high energy input. Membrane-based systems use selective membranes to permit CO_2 passage while blocking other gases; these systems are currently in the early stages of development.

3.2.2 Current status and projects. Globally leading commercial-scale DAC plants.

• Climeworks' Orca Plant (Iceland): world's largest DAC facility, with a capacity to capture 4000 tonnes of CO_2 per year for geological storage.[98]

• Carbon Engineering Facility (Merritt): planned facility in British Columbia in collaboration with Huron Clean Energy, The Upper Nicola Band, and Oxy Low Carbon Ventures, aiming to capture 0.25 million tonnes of CO_2 annually for fuels.[99]

• 1PointFive (Texas): planned facility in Texas in collaboration with Carbon Engineering, and Worley, aiming to capture 0.5 million tonnes of CO_2 annually for geological storage.[100]

3.2.3 Potential and limitations. The following outlines the key strengths and constraints associated with DACCS deployment.

• Theoretical and practical CO_2 removal potential: the theoretical potential for DACCS is up to 5–40 gigatonnes of CO_2 per year by 2050. The practical potential is estimated at 0.5 to 5

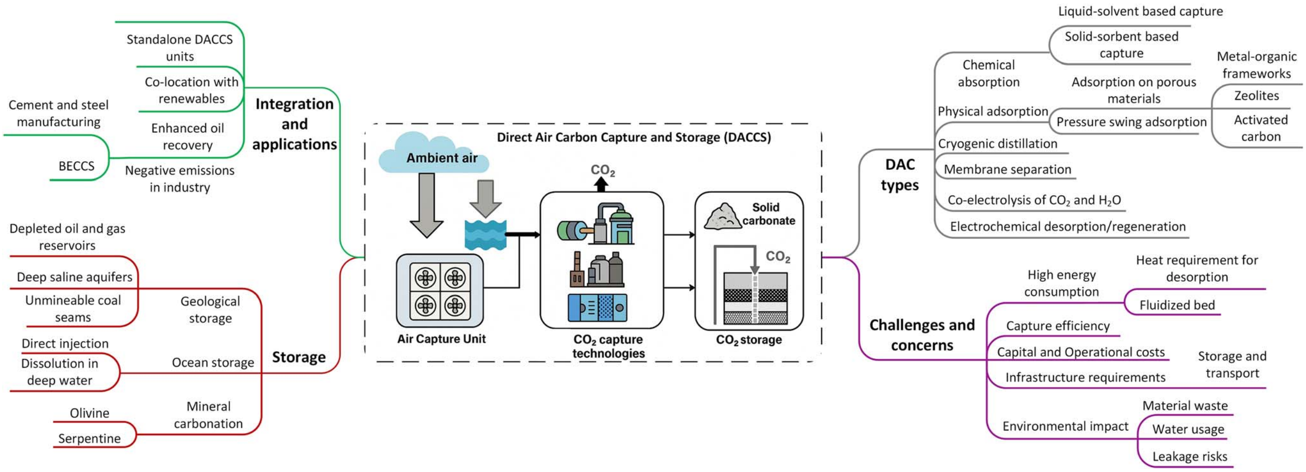

Fig. 7 Conceptual overview of direct air carbon capture and storage (DACCS) systems, including core technologies, storage options, DAC types, integration opportunities, and key challenges.

gigatonnes per year by 2050, limited by technological, economic, and policy constraints.

• Energy requirements and sources: DACCS is an energy-intensive process, requiring 1.5–2.5 MWh per tonne of CO_2 captured.[101] To ensure net-negative emissions, DACCS must rely on low-carbon energy sources, which may compete with other sectors for renewable energy. Carbon Engineering's design addresses this by integrating natural gas with carbon capture and renewable electricity for different stages of the process.

• Land and water use: DACCS has modest land use compared to other negative emission technologies (NETs), primarily associated with the generation of renewable energy. Water requirements vary by technology: liquid solvent systems may consume significant amounts of water, whereas solid sorbents typically have minimal water needs.

• Cost projections and economic feasibility: current costs for DACCS range from \$250 to \$600 per tonne of CO_2 removed. Potential future costs could drop to \$100–200 per tonne by 2030, with long-term projections suggesting prices may fall below \$100 per tonne. Economic viability is closely tied to carbon markets, policy support, and prevailing carbon prices.

• Scalability challenges: large-scale deployment of DACCS requires an extensive supply chain, including the production of materials like sorbents and air contactors. Expanding low-carbon energy generation is critical to meet the high energy demands of the process. Additionally, CO_2 transport and storage infrastructure must scale accordingly to match capture efforts. Strong and stable policy frameworks are essential to support deployment, while public acceptance and social support will be key factors for widespread adoption.

3.3 Afforestation and reforestation

Afforestation and reforestation are two closely related approaches to negative emissions that involve increasing forest cover to sequester carbon dioxide from the atmosphere. These nature-based solutions have gained significant attention in recent years as potentially cost-effective and environmentally friendly methods to mitigate climate change. Fig. 8 exhibits the conceptual layout along with methods, goals, benefits, differences and similarities of afforestation and reforestation. While both approaches aim to increase forest cover, they differ in their application and have distinct implications for land use, biodiversity, and carbon sequestration potential.

3.3.1 Technology description. An overview of the processes involved in afforestation and reforestation.

• Definitions and distinctions: afforestation involves establishing forests on land not forested for over 50 years, such as marginal agricultural lands or degraded areas.[9,102] Reforestation refers to restoring forests on land that was previously forested but later converted to other uses, through natural or assisted regeneration or active planting.[8,103] The key difference is that afforestation creates new forests, while reforestation restores existing ones—an important distinction that influences carbon accounting and biodiversity outcomes.

• Carbon sequestration mechanisms: forests sequester carbon through photosynthesis, storing it in biomass such as trunks, branches, roots, and in the soil. Carbon storage capacity depends on various factors including tree species, climate, soil type, and forest management practices. Over time, carbon accumulates in both above-ground biomass and soil organic matter.

• Forest management practices: effective forest management practices for carbon sequestration include selecting species adapted to local conditions with high carbon potential and employing planting techniques that ensure high survival rates and optimize growth. Thinning and pruning are used to improve forest health and enhance carbon storage, while fire management practices, such as controlled burns, help reduce wildfire risks. Pest and disease control is essential to prevent large-scale die-offs. Sustainable harvesting practices are implemented to maintain forest cover and carbon stocks even when timber is harvested. Additionally, carbon credits from conservation efforts can generate revenue by preserving existing forests and avoiding harvest, thereby incentivizing long-term carbon storage.

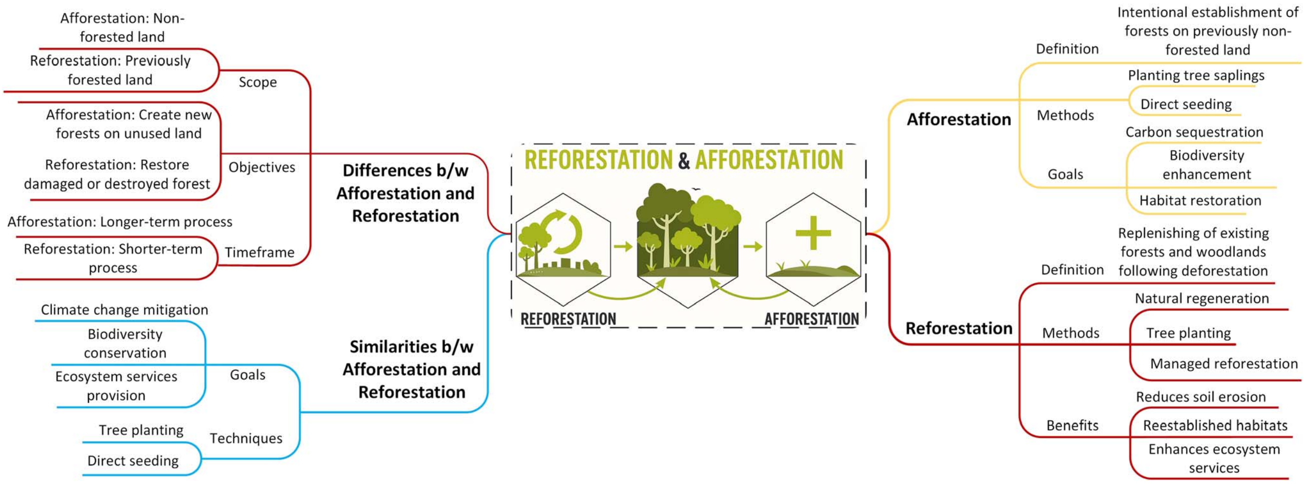

Fig. 8 Conceptual overview and comparison between afforestation and reforestation: key differences and similarities in terms of scope, objectives, timeframe, methods, goals, and benefits.

3.3.2 Current status and projects. A large number of reforestation projects are at various stages of implementation, with notable examples including:[104]

• Eden Reforestation Project, Madagascar: involves the planting of 23 792 493 trees, contributing significantly to regional reforestation efforts.

• Usambara Biodiversity Conservation Project, Tanzania: focuses on the planting of 4 672 522 trees to enhance biodiversity and ecosystem restoration.

• Eden Reforestation Projects, Nepal: encompasses the planting of 3 372 832 trees as part of broader reforestation and climate mitigation initiatives.

• CommuniTree Project, Nicaragua: aims to restore deforested areas with the planting of 1 957 352 trees, supporting local community and environmental benefits.

3.3.2.1 National and international programs. Many countries include afforestation and reforestation in their Nationally Determined Contributions (NDCs) under the Paris Agreement. REDD+ is a UN framework that provides financial incentives to reduce emissions from deforestation and forest degradation in developing countries. The Forest Carbon Partnership Facility, managed by the World Bank, supports efforts to reduce emissions from deforestation and degradation. The Green Climate Fund also plays a key role by backing forest-related climate mitigation and adaptation projects.

3.3.2.2 Monitoring and verification approaches. Remote sensing technologies, such as satellite imagery and LiDAR, are used to assess forest cover and estimate biomass. Ground-based inventories involve field measurements, including tree diameter and height, to calculate forest carbon stocks. Soil carbon sampling entails collecting soil samples to monitor changes in soil organic carbon levels. Additionally, eddy covariance flux towers provide real-time measurements of carbon flux between forests and the atmosphere.

3.3.3 Potential and limitations

3.3.3.1 Global sequestration potential. the IPCC estimates a technical potential of 0.5 to 10.1 $GtCO_2$ per year by 2050, depending on factors such as land availability, policy frameworks, and the effectiveness of implementation.[3,26]

3.3.4 Land availability and competition. Large-scale afforestation and reforestation efforts face limitations due to competing land use demands, such as agriculture, urbanization, and biodiversity conservation. Strategic land-use planning is essential to balance these demands and prevent negative impacts.

3.3.5 Biodiversity and ecosystem impacts. Positive effects on biodiversity depend on thoughtful planning; monoculture plantations can harm ecosystems. Afforestation on grasslands or wetlands may disrupt native ecosystems, highlighting the importance of using native species and promoting diverse forest structures.

3.3.6 Permanence and climate vulnerability. Forests are vulnerable to fires, pests, and diseases, all of which can reduce carbon sequestration or even turn forests into carbon emitters. Fire is of particular concern, as wildfires are becoming increasingly severe each year due to the impacts of climate change.

3.3.7 Socioeconomic implications. Projects can offer employment opportunities and ecosystem benefits but may also disrupt traditional land use and livelihoods. Involving local communities and ensuring equitable benefit-sharing are critical for the long-term success of these initiatives.

3.4 Soil carbon sequestration and biochar

Soil carbon sequestration and biochar application are two interrelated approaches to negative emissions that focus on enhancing the carbon storage capacity of soils. These methods have gained increasing attention as potential strategies for mitigating climate change while simultaneously improving soil health and agricultural productivity. Fig. 9 displays the conceptual layout of soil carbon sequestration along with carbon capture, storage, and land management practices associated with soil carbon sequestration. Soil carbon sequestration involves implementing agricultural practices that increase the

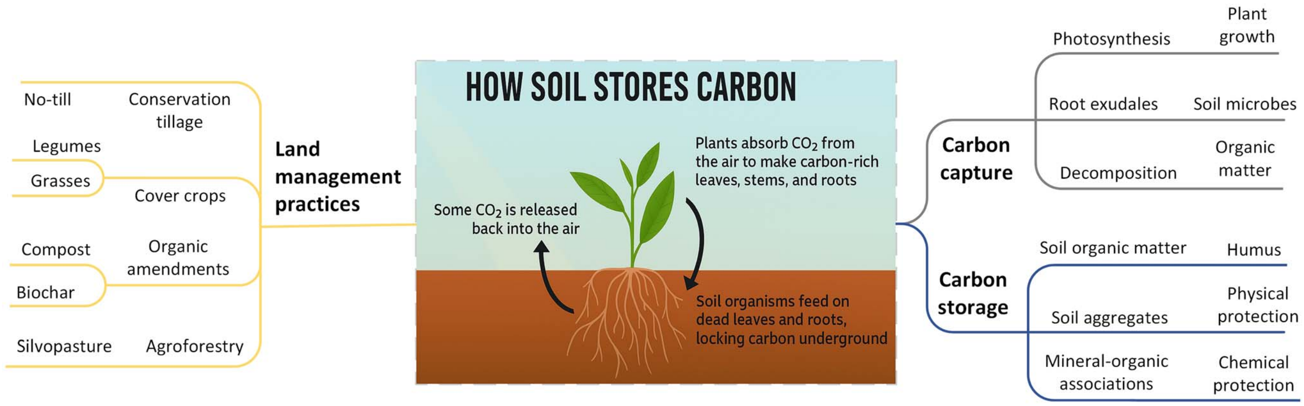

Fig. 9 Mechanisms of soil carbon storage through land management, carbon capture, and stabilization processes (conceptual layout modified from ref. 108).

amount of carbon inherently stored in soil organic matter, while biochar is a carbon-rich material produced from biomass that can be added to soils to enhance their carbon content and improve soil properties.

3.4.1 Processes, practices, and applications

3.4.1.1 Soil carbon dynamics. Carbon enters the soil through plant residues and root exudates, which are decomposed by microorganisms; some of this carbon is converted into stable soil organic carbon, while some is released as CO_2.[105–107] Whether soil acts as a net carbon sink or source depends on the balance between carbon inputs and losses. This balance is influenced by factors such as climate (temperature and precipitation), soil type, vegetation, and land management practices.

3.4.1.2 Agricultural practices for soil carbon enhancement. no-till or reduced tillage practices help preserve soil structure and reduce carbon loss. Cover cropping adds organic matter to the soil and prevents erosion, while crop rotation increases biomass and improves overall soil health. Agroforestry integrates trees into agricultural systems, boosting carbon input. Improved grazing management enhances both productivity and soil carbon levels. The use of organic amendments, such as compost or manure, increases soil organic matter. These practices also offer co-benefits, including improved soil fertility, better water retention, and greater resilience to climate extremes.

3.4.1.3 Biochar production and application. Biochar is produced through the pyrolysis of biomass in low-oxygen environments, a process that converts carbon into a stable form. Common feedstocks include agricultural residues, forestry waste, and purpose-grown crops, all of which influence the properties of the resulting biochar. When applied to soil—either incorporated into the topsoil or surface-applied—biochar improves water retention, nutrient availability, and microbial activity, while also contributing to long-term carbon sequestration.

3.4.2 Current status and projects

3.4.2.1 Soil carbon initiatives and policies. The “4 per 1000” Initiative aims to achieve a 0.4% annual increase in global soil organic carbon content.[109] The U.S. Department of Agriculture's Conservation Reserve Program offers incentives for practices that enhance soil health and carbon sequestration.[110] Australia's Emissions Reduction Fund includes soil carbon projects that can generate carbon credits.[111] Similarly, the European Union's Common Agricultural Policy emphasizes the importance of soil health and carbon sequestration.[112]

3.4.2.2 Biochar projects and commercial applications. In the United States, companies like Cool Planet and Pacific Biochar produce biochar for agricultural and environmental applications.[113] The European Biochar Industry Consortium actively promotes the use of biochar across Europe.[114] In developing countries, initiatives such as the Nepal Biochar Initiative explore the use of biochar for agriculture and cookstove applications.[115] Additionally, some carbon offset programs now include biochar-based carbon credits.[116,117]

3.4.2.3 Measurement and monitoring techniques. Direct soil sampling is the standard method for measuring soil carbon, though it is labor-intensive and costly for large-scale application. Spectroscopic techniques, such as near-infrared spectroscopy, enable rapid, in-field measurements. Remote sensing and modeling approaches combine satellite data, ground-based measurements, and machine learning to support large-scale monitoring. Additionally, eddy covariance flux towers are used to measure real-time carbon exchange between the land surface and the atmosphere.

3.4.3 Potential and limitations

3.4.3.1 Global sequestration potential. The IPCC estimates that soil carbon sequestration on croplands and grasslands has the potential to sequester 2.3–5.3 $GtCO_2$-eq. per year.[118] Studies suggest that the total global potential could reach up to 8–10 $GtCO_2$-eq. per year when all land types and management practices are considered.[119] The global sequestration potential of biochar is estimated at 0.5–2 $GtCO_2$-eq. per year by 2050, at a cost of $30–120 per ton of CO_2, depending on feedstock availability and application rates.[120]

3.4.3.2 Agricultural productivity co-benefits. Soil carbon sequestration practices can improve soil structure and water retention, resulting in increased crop yields and greater resilience to drought. Enhanced nutrient cycling from these practices reduces the need for fertilizers, benefiting both the environment and farming costs. Improvements in soil biodiversity also promote plant health and increase resistance to pests and diseases. Additionally, the application of biochar can enhance soil fertility, particularly in degraded soils, potentially leading to higher crop yields.

3.4.3.3 *Permanence and saturation issues.* Carbon stored in soil can be lost if land management practices change or due to climate variations, which affects the permanence of sequestration.[121] Additionally, soils can reach a saturation point beyond which further carbon sequestration becomes difficult to achieve.[122] The stability of biochar in soil can vary significantly, with persistence ranging from centuries to millennia depending on production conditions and environmental factors, necessitating careful analysis in each specific case.

3.4.3.4 *Scalability and adoption challenges.*[122–124] Scaling soil carbon sequestration and biochar application faces challenges related to the need for knowledge and technology transfer to farmers, particularly in developing countries. Initial costs and potential yield losses during the transition to new practices can deter adoption. Cultural and social barriers also pose challenges, as many farmers may be hesitant to shift away from traditional agricultural methods. Additionally, the development of biochar production and distribution infrastructure represents a significant hurdle to widespread implementation of these solutions.

3.4.3.5 *Cost-effectiveness and economic incentives.*[125–127] Soil carbon sequestration practices are often cost-effective or even profitable due to reduced input costs and improved crop yields. While the current cost of biochar remains high, it is expected to decrease as production scales and technology advances. Economic incentives, such as carbon pricing or payments for ecosystem services, can further enhance the financial viability of these practices for farmers. Additionally, recognizing co-benefits—such as improved water quality and reduced erosion—can increase the societal appeal of soil carbon sequestration and biochar applications.

3.5 Enhanced weathering and ocean alkalinity enhancement

Enhanced weathering and ocean alkalinity enhancement are two related negative emission technologies that aim to accelerate natural processes of CO_2 removal from the atmosphere. These approaches leverage the Earth's natural carbon cycle, particularly the weathering of rocks and the ocean's capacity to absorb CO_2, to mitigate climate change. Fig. 10 displays the conceptual layout along with carbon capture, chemical weathering, and mineral formation through enhanced weathering, and Fig. 11 presents

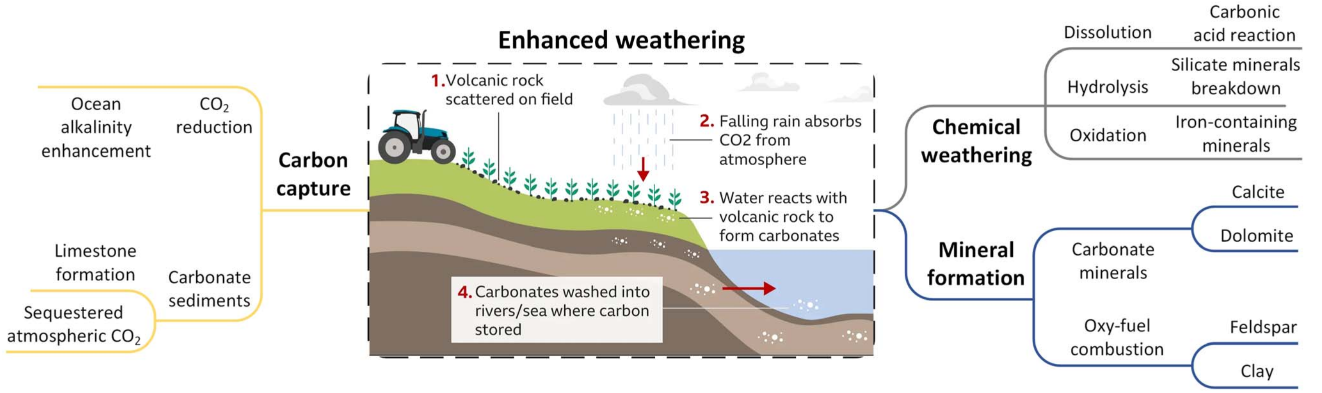

Fig. 10 Process of enhanced weathering for carbon capture and storage through chemical weathering and mineral formation (conceptual layout adapted from ref. 128).

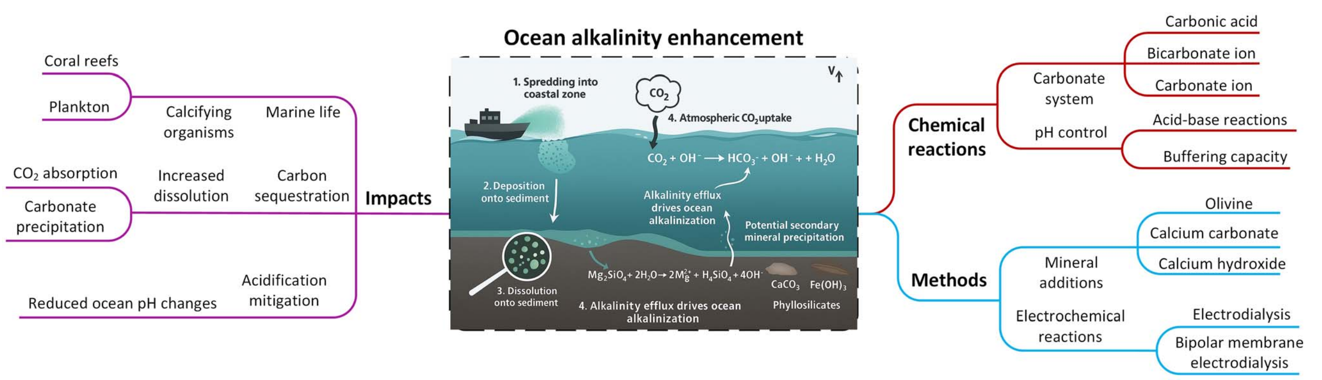

Fig. 11 Ocean alkalinity enhancement process: chemical reactions, methods, and environmental impacts (conceptual layout adapted from ref. 137).

the conceptual layout along with the chemical reactions, methods, and impact of ocean alkalinity enhancement. While these technologies show promise for large-scale carbon dioxide removal, they also face significant challenges in terms of implementation, environmental impacts, and governance.

3.5.1 Technology description

3.5.1.1 Terrestrial enhanced weathering.[129–132] Enhanced weathering involves accelerating the natural weathering process to capture and store atmospheric CO_2 by spreading finely ground silicate or carbonate rocks. In the presence of water, CO_2 reacts with these minerals to form stable bicarbonate ions, effectively removing CO_2 from the atmosphere. This approach can be applied to agricultural lands, forests, and urban areas, with commonly used minerals including olivine, basalt, and wollastonite. Mineral selection depends on factors such as reactivity, availability, and potential co-benefits, such as soil improvement for agricultural use.

3.5.1.2 Ocean alkalinity enhancement methods.[133–136] Ocean alkalinity enhancement aims to increase the ocean's CO_2 absorption capacity by adding alkaline substances to seawater. Techniques include the direct addition of alkaline minerals such as olivine or lime to coastal waters, electrochemical acceleration of weathering reactions, and enhanced weathering on beaches or coastal zones. These methods raise ocean pH and carbonate ion concentrations, improving the ocean's ability to absorb atmospheric CO_2 while also helping to mitigate ocean acidification.

3.5.1.3 Mineral resources and logistics. Both enhanced weathering and ocean alkalinity enhancement require large quantities of minerals. Potential sources include quarries and mines producing silicate rocks such as basalt and dunite, waste materials from mining like mine tailings and steel slag, and artificially produced alkaline materials. Large-scale implementation presents significant challenges due to the need for substantial mining operations, energy-intensive grinding processes, and complex transportation logistics to deliver the minerals to application sites.

3.5.2 Current status and research

3.5.2.1 Field trials and experiments. Several small-scale field trials have been conducted for both terrestrial and ocean-based enhanced weathering.[138,139] The Leverhulme Centre for Climate Change Mitigation has conducted trials on croplands in the UK and USA to evaluate CO_2 removal and associated co-benefits.[140] Project Vesta is conducting coastal experiments using olivine sand in the Caribbean, focusing on coastal enhanced weathering.[141] Additionally, the GEOMAR Helmholtz Centre for Ocean Research has carried out small-scale ocean alkalinity enhancement trials in the Southern Ocean to assess the impacts on marine ecosystems.[142]

3.5.2.2 Modeling studies. Global-scale modeling studies have been conducted to estimate the CO_2 removal potential of enhanced weathering and ocean alkalinity enhancement.[143] These models examine the impacts on ocean chemistry, marine ecosystems, and interactions with the global carbon cycle and climate system. They also assess the economic feasibility and energy requirements, identifying significant CO_2 removal potential while highlighting associated uncertainties and risks.[144–146]

3.5.2.3 Potential integration with other industries. Research is underway to explore synergies with other sectors, such as utilizing mining and steel production waste for enhanced weathering. Enhanced weathering is also being considered for integration with agricultural practices to improve soil health.[147] Ocean alkalinity enhancement could be combined with marine renewable energy projects or desalination plants to optimize deployment and reduce costs.[148,149]

3.5.3 Potential and limitations

3.5.3.1 Theoretical CO_2 removal capacity. Terrestrial enhanced weathering has a theoretical CO_2 removal range of 2–4 $GtCO_2$ per year, with some estimates suggesting potential removal of up to 95 $GtCO_2$ per year depending on the scale and types of minerals used.[150,151] Estimates for ocean alkalinity enhancement vary widely, ranging from 1 to 100 $GtCO_2$ per year, depending on the method and scale of deployment.[146,152] However, practical limitations such as resource availability and infrastructure significantly reduce the achievable removal rates.[153]

3.5.3.2 Energy requirements for mineral processing. Energy demands for mining and grinding minerals represent a major limitation for enhanced weathering, ranging from 1–3 GJ per tonne of CO_2 removed in optimal scenarios to over 10 GJ per tonne under less favorable conditions.[154] High energy use could offset the CO_2 removal benefits unless low-carbon energy sources are employed.[155]

3.5.3.3 Environmental impacts (terrestrial and marine). Terrestrial impacts of enhanced weathering include dust pollution from mineral spreading and alterations in soil pH, which can potentially affect local ecosystems. Ocean impacts may involve changes in ocean chemistry, disruptions to marine food webs, and the release of heavy metals from certain minerals. To minimize these environmental risks, careful mineral selection and appropriate application techniques are essential.

3.5.3.4 Scalability and cost projections. Large-scale deployment of enhanced weathering and ocean alkalinity enhancement would require billions of tonnes of minerals annually, along with significant land or ocean areas for application. Developing the necessary infrastructure for mining, processing, and transportation presents major challenges. Cost estimates range from \$50–200 per tonne of CO_2 in optimistic scenarios to over \$1000 per tonne, though technological advances could help reduce these costs over time.[156–159]

3.6 Other ocean-based NETs

Ocean-based NETs are a group of approaches that aim to enhance the ocean's natural capacity to absorb and store atmospheric carbon dioxide.[160] Fig. 12 displays the conceptual layout of ocean fertilization, ocean alkalinity enhancement and electrochemical seawater CO_2 capture along with blue carbon strategies, and deep ocean carbon injection techniques for ocean-based NETs. These methods seek to leverage the vast size

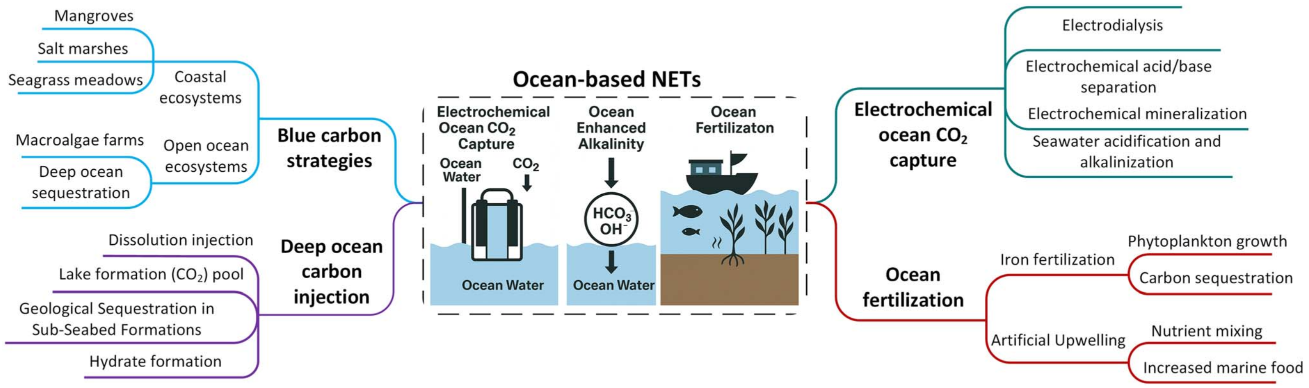

Fig. 12 Overview of ocean-based NETs, including blue carbon strategies, deep ocean carbon injection, electrochemical ocean CO_2 capture, ocean enhanced alkalinity, and ocean fertilization.

and biological productivity of the world's oceans to mitigate climate change. While the ocean already plays a crucial role in the global carbon cycle, absorbing about a quarter of anthropogenic CO_2 emissions, these technologies aim to amplify this effect. However, ocean-based NETs are among the most controversial climate intervention strategies due to their potential for large-scale ecological impacts and the challenges of governance in international waters.

3.6.1 Technology description

3.6.1.1 Ocean fertilization.[161–163] Ocean fertilization involves adding nutrients, such as iron, to nutrient-limited ocean regions to stimulate phytoplankton growth. Increased phytoplankton activity enhances CO_2 uptake through photosynthesis. A portion of the resulting organic carbon sinks to the deep ocean, effectively sequestering the CO_2 over long timescales.

3.6.1.2 Artificial upwelling.[164–166] Artificial upwelling uses mechanical systems, such as wave-powered pumps, to bring nutrient-rich deep waters to the surface. This approach mimics natural upwelling processes to stimulate phytoplankton growth and enhance the biological carbon pump. The goal is to increase oceanic CO_2 absorption in a manner similar to ocean fertilization.

3.6.1.3 Seaweed cultivation.[167,168] Large-scale seaweed farming, or macroalgae cultivation, is proposed as a method to capture CO_2 through photosynthesis. The harvested seaweed can be used for biofuels, food, or intentionally sunk into the deep ocean for long-term carbon storage.

3.6.1.4 Other emerging approaches. Marine biomass burial involves sinking terrestrial biomass into the deep ocean for long-term carbon storage.[169,170] Electrochemical CO_2 removal uses electricity to extract CO_2 from seawater, which indirectly draws down atmospheric CO_2 as surface waters re-equilibrate with the atmosphere.[171,172]

3.6.2 Current status and research

3.6.2.1 Past experiments and controversies. Ocean fertilization has undergone several field experiments since the 1990s, yielding mixed outcomes. The IRONEX experiments in the equatorial Pacific demonstrated enhanced phytoplankton growth but limited carbon sequestration.[173] The LOHAFEX experiment in 2009 faced strong opposition due to ecological concerns and governance challenges.[174,175] These experiments have been controversial, largely because of fears of unintended ecological consequences and uncertainties surrounding the long-term efficacy of carbon sequestration.

3.6.2.2 Ongoing research initiatives. Current efforts focus on small-scale experiments and advanced modeling studies. The Ocean-based Climate Solutions project at Woods Hole Oceanographic Institution is investigating various ocean-based carbon removal techniques.[176] The GEOMAR Helmholtz Centre is studying artificial upwelling and its potential ecological impacts.[177] Additionally, several companies and research groups are exploring large-scale seaweed cultivation for both carbon sequestration and biofuel production.[178]

3.6.2.3 Modeling and impact assessments. Modeling studies assess both the potential and risks associated with ocean-based negative emission technologies (NETs). Biogeochemical models estimate the CO_2 sequestration potential of various ocean-based approaches, while ecosystem models predict the ecological impacts and potential side effects of NET deployment. Integrated assessment models examine how these technologies fit within broader global climate mitigation strategies. These studies are essential for evaluating the viability and safety of large-scale deployment of ocean-based NETs.

3.6.3 Potential and limitations

3.6.3.1 Carbon sequestration potential. Ocean fertilization could sequester 1–3 $GtCO_2$ per year, with estimates varying based on region and nutrient availability.[179] Large-scale seaweed cultivation has a theoretical potential to sequester 2.5–13 $GtCO_2$ per year, depending on growth rates and the scale of deployment.[180] Artificial upwelling and other emerging ocean-based negative emission technologies present uncertain but potentially significant sequestration capacities.

3.6.3.2 Ecological impacts and risks. Alteration of nutrient cycles could disrupt marine ecosystems, affecting biodiversity and food webs. Ocean fertilization carries risks such as harmful algal blooms and oxygen depletion, particularly in nutrient-limited waters. Large-scale deployment of these techniques could also negatively impact fisheries and other marine ecosystem services. The potential for unforeseen ecological consequences underscores the importance of conducting thorough environmental assessments.

3.6.3.3 Monitoring and verification challenges. Tracking the fate of sequestered carbon in the dynamic ocean environment is challenging, and a full understanding along with quantitative monitoring remains lacking. Long-term monitoring is essential to verify the permanence of CO_2 storage. Additionally, distinguishing the impacts of ocean-based negative emission technologies (NETs) from natural variations in carbon uptake complicates verification efforts. Robust frameworks are needed to accurately incorporate ocean-based NETs into global carbon accounting systems.

3.6.3.4 Scalability and infrastructure requirements. Large-scale implementation of ocean-based interventions would require substantial infrastructure for deployment and management. Seaweed cultivation would necessitate vast ocean areas along with infrastructure for harvesting and processing. Artificial upwelling technologies would involve mechanical devices and energy inputs, raising concerns about scalability and efficiency. The development of robust logistical and operational frameworks is crucial to enable the effective scaling of these technologies.

3.6.3.5 International governance and ethical concerns. Ocean-based negative emission technologies (NETs) currently lack clear regulatory frameworks under international law, leading to significant governance challenges. Their deployment may conflict with existing marine protection laws and treaties, such as the London Convention, which must be carefully addressed. International cooperation is essential to manage the deployment, monitoring, and accountability of these technologies. Additionally, ethical concerns about manipulating marine ecosystems and the potential for unintended side effects will play a critical role in shaping public perception and policy decisions.

3.6.3.6 Cost and economic considerations. Cost estimates for nitrogen fertilization start at a lower bound of $20 per ton of CO_2 removed, while iron fertilization ranges from $10 to $450 per ton, though uncertainties remain high.[181] Seaweed cultivation costs are variable, with estimates ranging from $100 to $480 per ton of CO_2.[182,183] Artificial upwelling and other emerging approaches are less mature, with limited data available on their cost-effectiveness. Economic incentives, such as carbon credits or government subsidies, could play a critical role in making ocean-based negative emission technologies financially viable.

4. Comparative analysis of NETs

NETs have emerged as potential tools to address climate change by removing carbon dioxide from the atmosphere. However, these technologies vary widely in their approaches, readiness levels, costs, scalability, environmental impacts, and social implications. A detailed comparison of NETs is displayed in Table 1. This comparative analysis aims to provide a comprehensive overview of the major NET categories, evaluating them across several key dimensions to inform policy decisions and research priorities.

4.1 Technological readiness levels

4.1.1 Assessment criteria and methodology. Technological readiness levels (TRLs) are assessed using a standardized scale from 1 to 9, where 1 represents basic principles observed and 9 indicates a fully operational technology. The assessment considers factors such as:

- Proof of concept
- Laboratory testing
- Pilot-scale demonstrations
- Full-scale prototypes
- Commercial deployment

4.1.2 Comparison across NET categories. A general comparison of TRLs across major NET categories:

- Afforestation/reforestation: TRL 9 (fully mature and deployed).
- Soil carbon sequestration: TRL 7–8 (demonstrated at scale, some commercial deployment).
- BECCS: TRL 6–7 (large-scale pilot demonstrations).
- DACCS: TRL 6–7 (pilot plants operational).
- Enhanced weathering: TRL 4–5 (technology demonstrated in relevant environment).
- Ocean fertilization: TRL 3–4 (technology validated in lab).

4.1.3 Technological bottlenecks and research priorities. Key bottlenecks and research priorities vary by technology:

- BECCS: improving capture efficiency, reducing energy penalties.
- DACCS: developing more efficient sorbents, reducing energy requirements.
- Enhanced weathering: optimizing mineral processing and application methods.
- Ocean-based NETs: addressing ecological uncertainties, improving monitoring.

4.2 Costs and economic feasibility

4.2.1 Current cost estimates. The costs of implementing Negative Emission Technologies (NETs) vary significantly across different categories due to the wide range of technological maturity, infrastructure requirements, scalability challenges, and energy consumption. An overview of the current cost estimates for major NET categories is displayed in Fig. 13(a) with the achievable potential shown in Fig. 13(b) and economic feasibility considerations are described in this section.

4.2.1.1 Afforestation and reforestation.

- Cost estimates: $5–50 per tonne of CO_2 removed.
- Economic feasibility: afforestation and reforestation is one of the most cost-effective NETs due to the low technology and infrastructure requirements. However, these methods require vast amounts of land and long-term maintenance to ensure carbon storage, which can limit scalability.

4.2.1.2 Soil carbon sequestration.

- Cost estimates: $0–100 per tonne of CO_2 removed.
- Economic feasibility: soil carbon sequestration involves relatively low upfront costs and benefits from existing agricultural practices. It can be economically feasible for small-scale and local projects, particularly in regions where it can align with regenerative agriculture.

Table 1 Detailed comparative analysis of NETs (data from ref. 1, 52, 91, 184 and 185)[a]

Aspect	BECCS	DACCS	Afforestation/reforestation	Soil carbon sequestration/Biochar	Enhanced weathering/ocean alkalinization	Ocean-based NETs
Type	Biological/engineering	Engineering	Biological	Biological/chemical	Chemical/geological	Biological/chemical
Maturity	More developed, some facilities operating	Emerging, pilot projects	Well-established	Established, ongoing research	Early research stage	Early research stage
CO_2removal potential	**0-22 $GtCO_2$per year**	**Varies, potentially large**	**Limited by land availability**	**Moderate**	**Potentially large**	**Potentially large**
Scalability	**Moderate**	**High**	**Moderate**	**High**	**High**	**High**
Current implementation	~1.5 $MtCO_2$ per year (as of 2019)	Small-scale, ~1 $MtCO_2$ per year planned	Ongoing globally	Limited commercial use	Experimental	Experimental
Cost estimates	**\$100–200 per tCO_2**	**\$95–600 per tCO_2**	**\$5–50 per tCO_2**	**\$0–100 per tCO_2**	**\$50–200 per tCO_2**	**\$50–120 per tCO_2**
Main challenges	Biomass availability, CO_2 transport infrastructure	High energy requirements, costs	Land use competition, permanence	Measurement, permanence	Scale, environmental impacts	Ecological impacts, governance
Land use impact	High	Low	High	Moderate	Moderate to high	Low
Water use	High	Moderate	Moderate	Low to moderate	Varies	Low
Energy requirements	**Moderate**	**High**	**Low**	**Low**	**Moderate to high**	**Low to moderate**
Resource availability	Limited by land and biomass	Unlimited (air)	Limited by land	Limited by land	Large mineral resources required	Vast ocean resources
Permanence of storage	**High (geological storage)**	**High (geological storage)**	**Medium (vulnerable to disturbances)**	**Medium (soil dynamics)**	**High (mineral carbonation)**	**Uncertain**
Co-benefits	Energy production	Potential for CO_2 utilization	Biodiversity, ecosystem services	Soil health, agricultural productivity	Potential soil improvement	Potential marine ecosystem benefits
Main risks	Competition with food production	High costs, energy use	Monoculture plantations, land conflicts	Reversibility of carbon storage	Mineral extraction impacts	Marine ecosystem disruption
Readiness for scale-up	**Medium**	**Low to medium**	**High**	**Medium**	**Low**	**Low**
Governance challenges	Moderate	Moderate	Low	Low to moderate	High (especially for ocean alkalinization)	Very high

[a] This table provides a general comparison of NETs. It's important to note that many of these technologies are still in development, and their characteristics may change as research progresses.

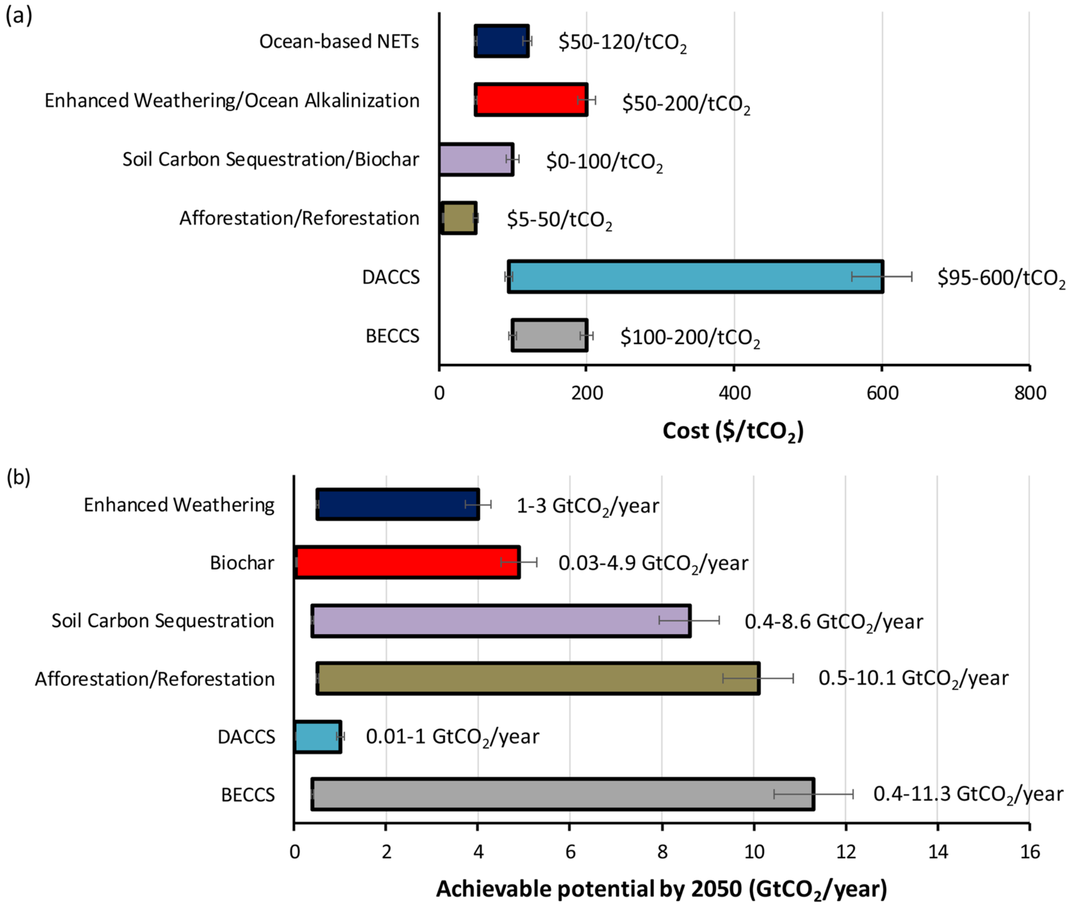

Fig. 13 Negative emission technologies and their associated (a) costs, and (b) achievable potential by 2050 (data from ref. 1 and 185).

4.2.1.3 Biochar.

• Cost estimates: \$30–100 per tonne of CO_2 removed.

• Economic feasibility: biochar production is relatively affordable, especially in regions with excess biomass waste. It has the dual benefits of carbon sequestration and soil fertility improvement, which can make it economically attractive in agricultural settings.

4.2.1.4 BECCS.

• Cost estimates: \$100–200 per tonne of CO_2 removed.

• Economic feasibility: BECCS has a high potential for large-scale carbon removal, but the high costs stem from biomass production, transportation, and the CCS infrastructure needed for capturing and storing CO_2.

4.2.1.5 DACCS.

• Cost estimates: \$95–600 per tonne of CO_2 removed.

• Economic feasibility: DAC is among the most technologically advanced but also the most energy-intensive methods, making it costly. The high energy demands, combined with the need for specialized infrastructure, make it economically challenging at present scales.

4.2.1.6 Ocean-based NETs.

• Cost estimates: \$50–120 per tonne of CO_2 removed.

• Economic feasibility: ocean-based NETs have highly uncertain costs due to a lack of large-scale deployment and concerns over ecological impacts. Fertilization methods are generally less costly but face significant regulatory and environmental hurdles.

4.2.1.7 Enhanced weathering.

• Cost estimates: \$50–200 per tonne of CO_2 removed.

• Economic feasibility: enhanced weathering involves spreading minerals like olivine to react with atmospheric CO_2, a process that can capture large amounts of CO_2. However, costs include mining, transportation, and dispersal of large volumes of material.

4.2.2 Cost uncertainty across NETs. The cost of deploying negative emission technologies (NETs) varies widely, with significant uncertainty arising from technological maturity, energy requirement, carbon pricing and economic barriers, regional factors, and scale of implementation.

• Technological maturity: emerging technologies like DAC and enhanced weathering are still in the early stages of development, leading to high uncertainty in cost projections. Cost estimates for these NETs are largely based on pilot projects or theoretical models, which may not reflect the actual costs at large scales.

• Energy requirements: NETs like DAC and BECCS rely heavily on energy inputs, and their costs are closely tied to energy prices. Access to low-cost renewable energy can dramatically lower these costs, but variability in energy prices introduces uncertainty.

• Projected cost reductions and learning curves: most NETs are expected to see cost reductions as technologies mature and scale up. For example: DACCS costs are projected to potentially fall below \$100 per tCO_2 by 2050 and BECCS costs could decrease by 30–40% with technological improvements.

• Carbon pricing and incentives: it can enhance the economic viability of NETs by creating market value for carbon removal and reducing investment barriers. These mechanisms help scale deployment by closing the cost gap between NETs and conventional mitigation strategies.

• Regional variability: the cost-effectiveness of NETs can vary significantly by location. For example, DAC deployed in regions with abundant geothermal energy might be far cheaper than in areas relying on fossil fuels.

• Economic barriers and incentives: key economic barriers include high upfront costs, uncertain revenue streams, and lack of carbon pricing. Potential incentives include carbon pricing mechanisms. Tax credits (*e.g.*, 45Q in the US for carbon capture), public procurement of negative emissions, and integration with carbon offset markets.

• Resource availability: BECCS and soil carbon sequestration depend on biomass and land availability, respectively. Competition with food production, biodiversity conservation, or other land uses can drive up costs and limit scalability.

• Policy and carbon pricing: the future of carbon markets and regulatory frameworks will strongly influence NET costs. Policies that increase the price of carbon or offer incentives for carbon removal could make expensive NETs more feasible, while weak regulatory support could stifle their adoption.

4.2.3 Scalability and potential for CO_2 removal

4.2.3.1 Theoretical vs. achievable potentials. Theoretical potentials for CO_2 removal are vast (Fig. 11(b)), but the achievable potentials are much lower due to various constraints and uncertainties, particularly as they rely on scaled-up projections out to 2050. Afforestation and reforestation are estimated to remove 0.5–10.1 $GtCO_2$ per year by 2050. Soil carbon sequestration could achieve 0.4–8.6 $GtCO_2$ per year, while biochar has a potential of 0.03–4.9 $GtCO_2$ per year. BECCS may contribute 0.4–11.3 $GtCO_2$ per year, DACCS is estimated at 0.01–0.98 $GtCO_2$ per year, and enhanced weathering could remove 1–3 $GtCO_2$ per year by 2050.

4.2.3.2 Resource requirements (land, water, energy, materials). Resource requirements vary significantly across negative emission technology (NET) categories. Afforestation and reforestation demand large land areas, while BECCS involves substantial needs for land, water, and energy. DACCS is characterized by high energy requirements but only moderate land use. Enhanced weathering requires large quantities of mineral resources and energy for processing. Ocean-based NETs use minimal land but have the potential to cause large-scale impacts on marine environments.

4.2.3.3 Timeframes for deployment and impact. Deployment timeframes range from immediate (afforestation) to decades (large-scale DACCS or BECCS). Impact timeframes also vary, with some approaches (*e.g.*, enhanced weathering) potentially having very long-term effects.

4.2.3.4 Interactions and competition between NETs. NETs may compete for resources (land, water, energy) and funding. Some approaches may be complementary (*e.g.*, biochar and soil carbon sequestration), while others may conflict (*e.g.*, large-scale BECCS and afforestation competing for land).

4.2.4 Strengths, weaknesses, opportunities, threats (SWOT) analysis. Even though the field of Negative Emission Technologies (NETs) is rapidly evolving, with ongoing research that may shift the current understanding, a SWOT analysis offers a valuable snapshot of the current landscape. It highlights key factors shaping the development and deployment of NETs by examining their strengths, weaknesses, opportunities, and threats. This approach helps identify the potential advantages and challenges associated with these technologies, while also revealing areas for growth and innovation. The assessment, presented in Table 2, reflects the current state of knowledge but should be viewed as a dynamic framework that will evolve as NETs mature and new insights emerge.

5. Policy and governance

The development and deployment of NETs present unique challenges and opportunities in the realm of policy and governance. They are in many cases unique as they involve waste disposal, as opposed to creation of a value-added product. As these technologies gain prominence in climate change mitigation strategies, there is an increasing need for robust policy frameworks and governance structures to guide their implementation, ensure their effectiveness, and manage potential risks. This section explores the current policy landscape for NETs, the challenges in governance and regulation, and the prospects for international cooperation and frameworks.

5.1 Current policy landscape for NETs

5.1.1 National policies and incentives. Many countries have begun incorporating negative emission technologies (NETs) into their climate policies to support carbon capture and storage efforts. The 45Q tax credit in the U.S.[186] incentivizes carbon capture, utilization, and storage (CCUS) as well as direct air capture (DAC), and was expanded under the Inflation Reduction Act to increase credit value and broaden project eligibility. Other countries, such as the UK[187] and Norway,[188] have implemented policies that promote the development and scaling of CCUS and engineered NETs. Meanwhile, China's Grain for Green Program[189,190] focuses on afforestation to increase forest cover and enhance carbon sequestration.

5.1.2 International agreements and frameworks. The Paris Agreement indirectly acknowledges the role of negative emission technologies (NETs) in balancing emissions and removals to meet global temperature targets by mid-century. The UNFCCC and IPCC are increasingly recognizing the importance of NETs, with recent reports emphasizing their necessity in achieving long-term climate goals. IPCC reports[24,26–38] have specifically highlighted the critical role of deploying NETs to meet stringent emission reduction targets, underscoring their growing prominence in international climate discussions.

Table 2 A detailed SWOT (strengths, weaknesses, opportunities, threats) analysis of NETs[a]

Technology	Strengths	Weaknesses	Opportunities	Threats
BECCS	• Provides energy while removing CO_2	• Requires large amounts of biomass	• Integration with existing bioenergy industries	• Sustainability concerns for large-scale biomass production
	• Relatively mature technology	• Potential competition with food production	• Potential for negative emissions power plants	• Public acceptance issues
	• Can be low-cost in some applications (*e.g.* bioethanol)	• Needs CO_2 transport infrastructure		
DACCS	• Can be implemented anywhere	• Currently high costs ($95–600/t$CO_2$)	• Potential for cost reductions with scale and innovation	• High energy requirements could limit the scale
	• Doesn't compete directly with land use	• Energy-intensive process	• Integration with CO_2 utilization markets	• May divert focus from emissions reduction
Afforestation/reforestation	• Well-established and understood	• Limited by land availability	• Integration with sustainable development goals	• Potential for monoculture plantations
	• Multiple co-benefits (biodiversity, soil health)	• Vulnerable to climate change impacts	• Carbon offset markets	• Reversibility due to wildfires or land-use changes
Soil carbon sequestration/Biochar	• Can improve soil health and agricultural productivity	• Difficult to measure and verify	• Integration with sustainable agriculture practices	• Changes in land management could release stored carbon
	• Relatively low-cost ($0–100 per t$CO_2$)	• Potential for reversal	• Biochar market development	• Limited long-term storage potential
Enhanced weathering/ocean alkalinization	• Large potential for CO_2 removal	• Requires large-scale mineral extraction and processing	• Integration with mining industries	• Public concern over large-scale environmental modification
	• Could help address ocean acidification	• Environmental impacts not fully understood	• Potential for improving soil quality	• International governance challenges
Ocean-based NETs	• Vast potential due to ocean size	• Ecological impacts uncertain	• Integration with marine industries (*e.g.*, seaweed farming)	• International legal and governance issues
	• Could enhance marine productivity	• Challenging to monitor and verify	• Potential for enhancing fisheries	• Potential for unintended ecosystem impacts

[a] The effectiveness and impacts of these technologies can vary greatly depending on specific implementation methods and local conditions.

5.1.3 Carbon markets and NET integration. Voluntary carbon markets are beginning to integrate negative emission technology (NET) projects, particularly nature-based solutions such as afforestation and soil carbon sequestration. Engineered NETs, like direct air capture (DAC), have seen limited integration so far but are gradually attracting more interest. Compliance markets, such as the EU Emissions Trading System, are actively debating how to incorporate NETs while maintaining the priority of direct emission reductions. A key governance challenge is ensuring that the use of NET credits does not undermine efforts to reduce emissions at the source.

5.2 Challenges in governance and regulation

5.2.1 Measurement, reporting, and verification (MRV). Developing robust measurement, reporting, and verification (MRV) systems is crucial for accurately quantifying CO_2 removal and ensuring the permanence of long-term storage. Precise measurement is particularly challenging for approaches such as soil carbon sequestration and ocean-based NETs due to the complexity of carbon fluxes. Standardized MRV methodologies are essential for integrating NETs into carbon markets and policy frameworks. Significant investment is also required in monitoring technologies and the development of universally accepted protocols.

5.2.2 Liability and long-term responsibility. The long-term nature of CO_2 storage presents challenges regarding liability and responsibility for potential leakage over centuries. In the case of geological CO_2 storage, there are concerns about who will monitor and manage the storage sites in the long term, and who would be held liable in the event of leakage. Similar concerns apply to biological carbon storage, such as in forests, where disturbances like fires could release stored carbon, raising important questions about the permanence of storage and associated liability.

5.2.3 Cross-border and international issues. Some negative emission technologies (NETs) have cross-border implications—for example, large-scale afforestation could impact neighboring countries' water resources. Ocean-based NETs, particularly those operating in international waters, present complex governance challenges and legal uncertainties. Addressing these cross-border impacts will require international cooperation and the development of new governance frameworks.

5.3 International cooperation and frameworks

5.3.1 Technology transfer and capacity building. Successful global deployment of negative emission technologies (NETs) requires significant technology transfer and capacity building, particularly in developing countries. This transfer includes not only the physical technologies but also the associated knowledge and skills necessary for effective implementation and management. Existing international frameworks for technology transfer, such as the UNFCCC's Technology Mechanism, could support this effort, though they may need to be expanded or adapted to address the specific challenges associated with NETs.

5.3.2 Financing mechanisms. Deploying negative emission technologies (NETs) on a global scale requires substantial financial investment, yet current funding mechanisms, such as the Green Climate Fund, are not specifically designed to support NETs. There is a clear need for financing mechanisms tailored to the unique characteristics of NET projects, which often involve long-term commitments and challenges in quantifying benefits. Innovative financing approaches, including advanced market commitments and results-based finance for carbon removal, are being explored but have not yet been widely adopted.

5.3.3 Global governance proposals. Negative emission technologies (NETs) have large-scale global impacts, leading to growing calls for comprehensive governance frameworks. Proposed approaches include expanding the roles of existing institutions, such as the UNFCCC, or establishing new specialized bodies to oversee the development, deployment, and regulation of NETs at the international level.

6. Future research and development needs

As NETs continue to evolve and gain prominence in climate change mitigation strategies, it is crucial to identify and address key areas for future research and development. This section explores the technological advancements required, the challenges associated with scaling up and deployment, and the need for integration with existing emissions reduction strategies. By focusing on these areas, we can enhance the effectiveness, efficiency, and feasibility of NETs in contributing to global climate goals. Fig. 14 displays United Nations (UN) Sustainable Development Goals (SDGs) associated with different NETs. Each technology has the potential to contribute to multiple SDGs due to their environmental, economic, and social implications.

6.1 Technological advancements required

6.1.1 Materials science and engineering. Advancements in materials science and engineering are critical for improving the performance and reducing the costs of many NETs. For DAC systems, research is needed to develop more efficient and durable sorbents that can capture CO_2 at lower energy costs. This includes exploring novel materials such as metal–organic frameworks (MOFs) and amine-functionalized porous materials.

For enhanced weathering, research should focus on identifying and developing minerals with optimal CO_2 absorption properties and minimal environmental impacts. This may involve studying the reactivity of different mineral types and developing methods to enhance their weathering rates.

In the field of ocean alkalinization, there is a need to develop materials that can safely and effectively increase ocean alkalinity without causing adverse environmental effects. This could include research into the production and behavior of various alkaline substances in marine environments.

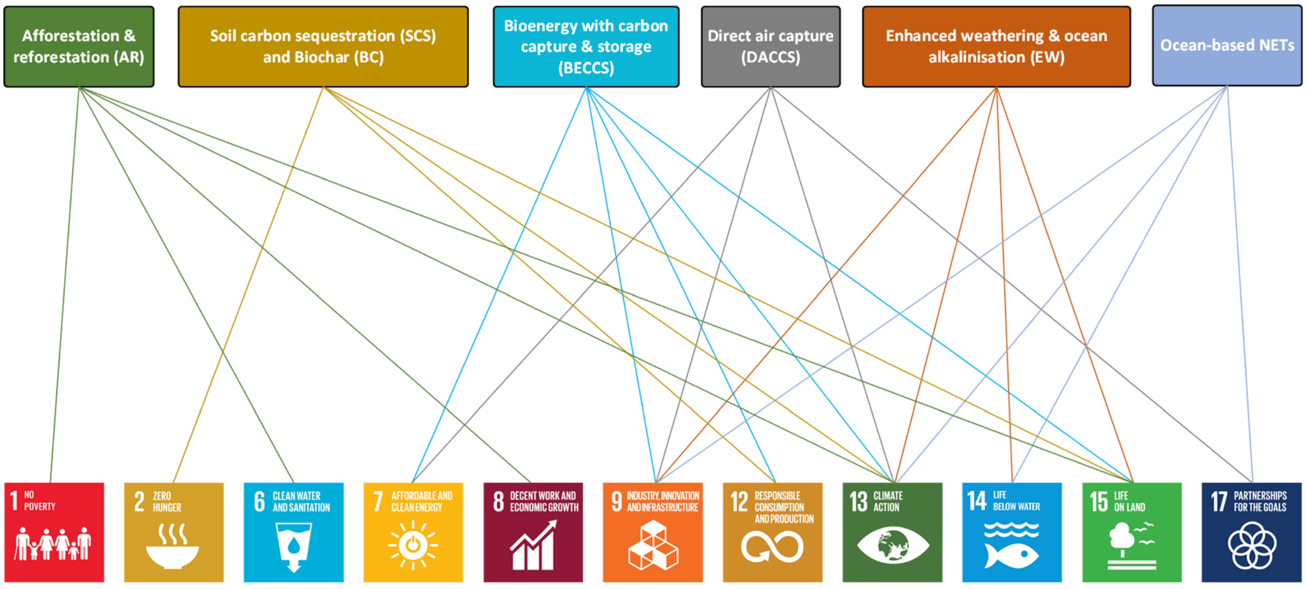

Fig. 14 UN sustainable development goals (SDGs) associated with NETs.

6.2 Process optimization and efficiency improvements

Improving the overall efficiency of NET processes is crucial for their large-scale implementation. For BECCS, research should focus on optimizing biomass production, conversion, and carbon capture processes to maximize CO_2 removal while minimizing energy and resource inputs.

For DAC systems, process optimization could involve improving heat integration, developing more efficient regeneration cycles for sorbents, and exploring novel system designs that reduce energy consumption.

In soil carbon sequestration, research is needed to optimize agricultural practices that enhance carbon storage while maintaining or improving crop yields. This could include studies on crop rotation strategies, tillage practices, and the use of biochar and other soil amendments.

6.3 Monitoring and verification technologies

Developing accurate and cost-effective monitoring and verification technologies is essential for assessing the performance of negative emission technologies (NETs) and ensuring their credibility within carbon markets and policy frameworks. Research in this area should focus on advanced remote sensing technologies for monitoring forest growth and soil carbon changes, in situ sensors for real-time monitoring of CO_2 fluxes in various ecosystems, improved methodologies for quantifying carbon storage in geological formations, and the development of standardized protocols for measuring and reporting carbon removal across different NET approaches.

6.4 Scaling up and deployment challenges

6.4.1 Infrastructure requirements. Scaling up negative emission technologies (NETs) to levels necessary for significant climate impact will require substantial infrastructure development. Research is needed to assess and optimize the infrastructure requirements for various NET approaches, including CO_2 transport and storage systems for BECCS and DAC, mineral extraction, processing, and distribution systems for enhanced weathering, and large-scale nursery and planting operations for afforestation and reforestation projects. Additionally, studies should explore opportunities to integrate NET infrastructure with existing industrial and energy systems to enhance efficiency and reduce costs.

6.4.2 Supply chain and logistical considerations. As negative emission technologies (NETs) scale up, managing complex supply chains and logistics will become increasingly important. Research should focus on optimizing biomass supply chains for BECCS, taking into account factors such as transportation, storage, and seasonal availability. Efforts are also needed to develop efficient systems for the production, transport, and application of minerals used in enhanced weathering. Additionally, assessing and mitigating potential bottlenecks in the supply of critical materials and equipment for DAC and other engineered NETs will be crucial for ensuring reliable and scalable deployment.

6.4.3 Workforce development and training. The widespread deployment of negative emission technologies (NETs) will require a skilled workforce across multiple disciplines. Research and development efforts should focus on identifying existing skills gaps and developing targeted training programs for NET-related jobs. This includes creating educational curricula at vocational, undergraduate, and graduate levels to prepare a future workforce capable of supporting NET deployment. Additionally, studies should examine the potential for job creation and economic development associated with NETs, particularly in regions undergoing transitions away from fossil fuel industries.

6.5 Integration with emission reduction strategies

6.5.1 Synergies and trade-offs with mitigation efforts. Research is needed to better understand how negative emission technologies (NETs) can complement and interact with emissions reduction strategies. This includes assessing potential competition for resources such as land, water, and energy between NETs and other mitigation approaches, as well as identifying synergies where NETs can enhance or support emissions reduction efforts. Additionally, studies should explore the optimal balance between emissions reductions and negative emissions across different climate scenarios to inform integrated and effective climate strategies.

6.5.2 Sector-specific integration (energy, agriculture, industry). Each economic sector presents unique opportunities and challenges for integrating negative emission technologies (NETs). In the energy sector, research should explore how BECCS and DAC can be integrated with renewable energy systems and grid management. In agriculture, efforts should focus on developing farming practices that combine food production with enhanced soil carbon sequestration. In industry, there are opportunities to integrate NETs with existing processes, such as utilizing captured CO_2 in manufacturing or pairing DAC systems with waste heat from industrial facilities.

6.5.3 System-level modeling and optimization. To fully understand the potential role of negative emission technologies (NETs) in climate change mitigation, comprehensive system-level modeling is essential. This research should focus on developing integrated assessment models that accurately capture the potential and limitations of various NET approaches. It should also aim to optimize the deployment of NETs across different regions and sectors to maximize CO_2 removal while minimizing costs and negative environmental or social impacts. Additionally, studies should examine the long-term implications of large-scale NET deployment on the global carbon cycle and the broader climate system.

7. Conclusion

The comparative analysis presented highlights several key insights into the advancement of NETs essential for meeting global climate objectives and facilitating a transition toward a sustainable, net-zero future. NETs comprise a diverse array of approaches and technologies, each with distinct characteristics, potentials, and limitations. These technologies vary significantly in terms of their maturity, with some like afforestation being well-established, while others, such as ocean-based approaches, are still in early research stages. Despite these differences, NETs collectively have the potential to remove significant amounts of CO_2, making them important tools for achieving climate goals. However, challenges related to cost, scalability, environmental, and social impacts must be addressed. Moreover, current policy frameworks and governance structures need to evolve to effectively manage large-scale NET deployment.

Looking ahead, NETs will likely complement emissions reduction efforts, playing a critical role in addressing residual emissions. A portfolio approach will be necessary, integrating multiple NETs to achieve meaningful carbon removal at global scales. As climate urgency increases, NETs are expected to gain prominence, with ongoing research and technological advancements improving their efficiency and reducing costs. However, integrating NETs into existing climate strategies will remain a challenge.

Policymakers should create comprehensive frameworks, establish economic incentives, and ensure robust monitoring systems. Researchers should focus on improving the efficiency of NETs, conducting life cycle assessments, and studying the social and ethical impacts. MRV requirements are also evolving with regulations and markets increasingly valuing durability of carbon storage removal in the face of climate change impacts and atmospheric carbon cycle timescales. Ethical considerations, including intergenerational equity, global justice, and moral hazards, must also be addressed.

Finally, the successful deployment of NETs will require interdisciplinary collaboration, international cooperation, and public engagement. Public-private partnerships and educational programs will be essential in fostering innovation and acceptance. Overall, NETs hold significant promise in mitigating climate change, but they must be carefully developed and deployed alongside strong emissions reductions and thoughtful policy frameworks.

Advancing NETs requires a multi-faceted approach focused on improving efficiency, reducing costs, and addressing scalability challenges. Technological advancements, such as optimizing DACCS processes with renewable energy integration and hybridizing NETs (*e.g.* BECCS with enhanced weathering) are critical to enhancing performance. Comprehensive lifecycle assessments should evaluate environmental impacts, including resource use and ecosystem effects, to mitigate unintended consequences. Addressing cost barriers through process optimization, economies of scale, and policy incentives, such as carbon credits or subsidies, will be essential to promote widespread adoption.

Moreover, robust governance frameworks are necessary to ensure effective monitoring, reporting, and verification of NET deployment. Social and ethical considerations, such as land-use conflicts, global equity, and public acceptance, must be integrated into decision-making processes. Interdisciplinary collaboration across academia, industry, and government is vital to drive innovation and establish international cooperation for capacity building in developing regions. Finally, designing regional and global portfolios that combine multiple NETs with emission reduction strategies can maximize climate benefits while addressing diverse socio-economic and environmental contexts.

Data availability

Data will be provided on request.

Conflicts of interest

There are no conflicts to declare.

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