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Review

Application of carbon biological sequestration technology in CCUS: Potential and optimization strategies for inorganic carbon absorption by plant root and CO_2 carriers by biogas slurry

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HIGHLIGHTS

- Exploring carbon bio-sequestration in CCUS systems to optimize plant root inorganic carbon uptake.
- Biogas slurry serves as an agricultural CO_2 carrier, offering both carbon fixation and soil enhancement.
- Research highlights plant root inorganic carbon uptake's role in climate resilience under drought and heat.
- Low-energy, high-value CCUS pathways provide theoretical and practical guidance for global carbon neutrality.

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ABSTRACT

Atmospheric CO_2 concentrations have surged to historically high levels, driving extreme weather events, biodiversity loss, and threats to food security. Carbon Capture, Utilization, and Storage (CCUS) is recognized as a critical pathway to mitigate these impacts, yet conventional physicochemical methods incur high energy demands and operational costs. Biological carbon sequestration—harnessing autotrophic organisms to convert inorganic CO_2 into organic biomass—offers a low-energy, clean alternative, but its large-scale deployment is hindered by limited fixation efficiency and technological maturity. This review synthesizes advances in CCUS with a focus on plant-based inorganic carbon uptake and novel CO_2 carriers for agricultural applications. We dissect the molecular and physiological mechanisms underpinning HCO_3^- absorption by plant roots and evaluate biogas slurry—a nutrient-rich byproduct of anaerobic digestion—as a dual-function carrier and fertilizer. Strategies to enhance slurry CO_2 loading, including pH elevation via biomass ash and biochar amendments, are discussed alongside their impacts on crop growth, soil health, and carbon retention. Lifecycle assessments demonstrate that biogas slurry–based sequestration reduces energy requirements by up to 65% and greenhouse-gas intensity by 67% compared to monoethanolamine capture. We outline tailored deployment scenarios across tropical, temperate, arid, and cold agroecosystems and propose research priorities—multisite field trials, optimization of carrier composites, comprehensive LCAs, and interdisciplinary collaboration—to drive the transition toward low-energy, high-value carbon biological sequestration in global agriculture.

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1. Introduction

Amid ongoing advancements in human civilization, industrialization, and intensified production activities, atmospheric carbon dioxide (CO_2) levels have shown a consistent upward trend. By January 2025, CO_2 concentration reached 424.57 ppm—the highest in recorded history—representing a 50.5% increase compared to pre-industrial levels (Fig. 1, Lan et al., 2025; Consortium et al., 2023). This escalating CO_2 concentration has triggered a series of significant environmental challenges, including frequent extreme weather events, accelerated glacial melting, progressive sea-level rise, and substantial biodiversity loss (Richardson et al., 2024). These impacts have significantly disrupted human activities, forest ecosystem stability, social cohesion, and agricultural productivity (Zhou et al., 2023). Recent studies indicate that elevated atmospheric CO_2 concentrations alter crop nutritional profiles. For example, rice exhibits declines in protein content and essential micronutrients such as iron and zinc. This phenomenon—termed the "nutrient dilution effect"—poses direct and indirect risks to global public health via transmission through the food chain (Song et al., 2024). Current projections indicate that reductions in these critical nutrients could directly affect the health of approximately 10%–20% of the global population by the end of this century (Zhu et al., 2018).

To mitigate the rising atmospheric CO_2 concentrations and associated adverse effects, global efforts to reduce emissions have intensified. A major milestone occurred on December 12, 2015, with the signing of the Paris Climate Agreement, under which participating nations pledged to limit the increase in global average temperature to well below 2 °C and pursue efforts to cap it at 1.5 °C (Gong et al., 2024). As the world's largest emitter of CO_2, China remains heavily dependent on coal, resulting in consistently high emissions. It is estimated from Climate Action Tracker that by 2030, China's CO_2 emissions might reach 13.8–14.6 Gt (CAT, 2024. 09. 17). Therefore, China's environmental policies hold a pivotal position in global climate change initiatives, playing a crucial role in addressing climate change. Confronting the severe situation of increasing atmospheric CO_2 levels and China's grave CO_2 emissions scenario, on September 22, 2020, President Xi Jinping formally proposed China's "dual carbon" strategic goals. These mandate that China peak its carbon emissions overall by 2030 and achieve carbon neutrality overall by 2060 (Liu et al., 2022).

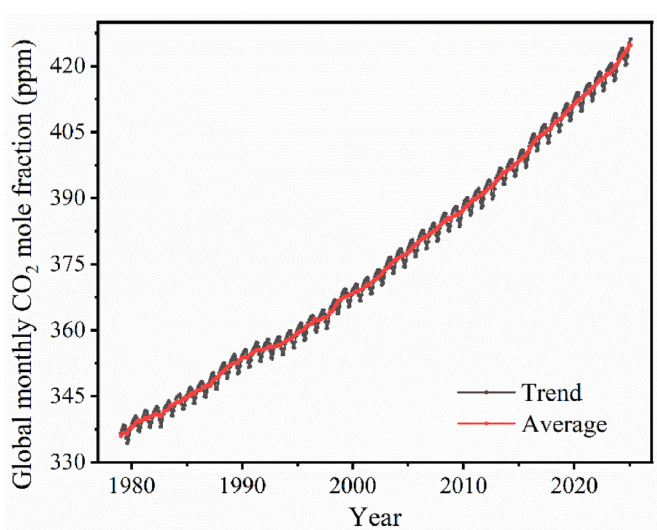

Fig. 1. The trend of changes in CO_2 concentration (ppm) in the atmosphere. The red line symbols represent the monthly global CO_2 concentration value based on marine surface sites, and the black line symbols obtained after correction for the average seasonal cycle represent the trend of long-term changes. The data reveals a significant increase in CO_2 concentration since the Industrial Revolution, highlighting the urgency of carbon reduction actions (Data source: Lan et al., 2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Against the backdrop of global climate change and the pursuit of sustainable development, Carbon Capture, Utilization, and Storage (CCUS) technology has emerged. This concept, based on Carbon Capture and Storage (CCS) technology, was first proposed innovatively by China by incorporating the CO_2 utilization segment in alignment with its specific circumstances (Sun et al., 2025). The CCUS framework addresses three key technical pathways for CO_2 mitigation: capture, utilization, and storage (Fig. 2). Capture technologies focus on extracting CO_2 during pre-, mid-, and post-combustion stages in industrial processes, aiming to reduce emissions at the source. Utilization methods convert captured CO_2 into valuable products or energy via chemical, biological (e.g., carbon fixation), or geological pathways. Storage technologies, including deep-sea and geological sequestration, aim to permanently isolate CO_2 underground or underwater (Lin et al., 2024).

CCUS technology is considered one of the key technologies for achieving near-zero CO_2 emissions during rapid industrial development. Currently, CCUS technologies in the practical application stage face numerous challenges, including high operating costs, the need for further maturity of key technologies, delays in supporting infrastructure construction, and insufficient policy support (Liu et al., 2023a). Despite this, countries around the world and international organizations are actively investing resources to promote the development of CCUS technology (Wesche et al., 2023). Among the various branches of CCUS technology (Table 1), carbon biological sequestration technology has gradually gained prominence due to its unique advantages. Carbon biological sequestration is a critical technology in the CO_2 utilization phase of CCUS, featuring low energy consumption and cleanliness without pollution. It utilizes biological or biotechnological means to convert inorganic CO_2 into organic compounds, serving as an essential driver of the global carbon cycle. Autotrophic organisms on Earth possess a substantial capability to fix CO_2, theoretically reaching 380 Gt/year (Gong et al., 2018), highlighting the immense potential of carbon biological sequestration for large-scale CO_2 reduction and utilization.

A significant subset of this technology involves higher plants, which absorb atmospheric CO_2 via photosynthesis and store it in their biomass. This process not only lowers atmospheric CO_2 levels but also enriches ecosystems with organic material (Piao et al., 2009). However, its sequestration efficiency remains suboptimal under stress conditions such as drought and elevated temperatures, which impair photosynthetic carbon fixation (Hu et al., 2023). To address these limitations, researchers are investigating strategies to enhance inorganic carbon uptake and fixation through plant root systems (Jones et al., 2009). This plant-based carbon biological sequestration technology not only contributes to CO_2 emissions reduction but also enhances ecosystem carbon sinks, offering a sustainable solution to climate change mitigation.

Here, we review the state of CCUS technologies with an emphasis on carbon biological sequestration and its agricultural deployment. We first summarize current CCUS strengths and gaps. Next, we dissect the molecular and physiological mechanisms of plant root HCO_3^- absorption. We then evaluate carrier strategies—especially biogas slurry, biomass ash and biochar amendments—for converting and delivering industrial CO_2 into soil. Finally, we outline climate-tailored deployment scenarios and propose research priorities to advance low-energy, high-value agricultural carbon sinks.

2. Advances and challenges in carbon biological sequestration

2.1. Potential and challenges of carbon biological sequestration technology in CCUS

Against the backdrop of rising CO_2 emissions and the urgent need for low-energy mitigation strategies, carbon biological sequestration has emerged as a promising component within the CCUS framework. By

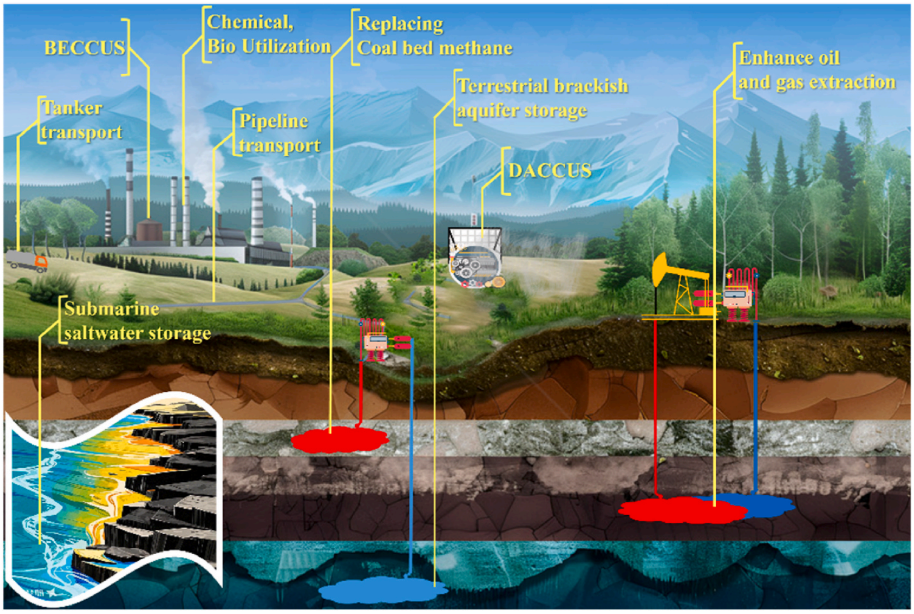

Fig. 2. Schematic of CCUS technology categories. Caption: Illustration of three CCUS pillars—capture (pre-, mid-, post-combustion separation), utilization (chemical, biological, geological pathways), and storage (deep geological, subsea)—with key technical principles highlighted.

Table 1
Commonly used CCUS technologies.

Technology	Technical Principle	Key Features	References
Physical Adsorption	Separation of CO_2 using porous materials or chemical adsorbents without chemical reactions in the process.	Simple process, low energy consumption, operable at normal temperature, but with low capacity and selectivity of adsorbents and high costs.	Siegelman et al. (2021)
Chemical Absorption	CO_2 separation and enrichment using absorbents such as alkanolamines.	Currently the most common CO_2 capture method with high capture efficiency and selectivity; however, high energy consumption for absorbent regeneration and corrosive properties.	Chen et al. (2024)
Membrane Separation	CO_2 separation using materials like porous inorganic membranes, target membranes, or polymer membranes through diffusion, dissolution, reaction, or molecular sieving.	Can't achieve high separation, require multiple stages or recycling; high system energy consumption and membrane material costs.	Wang et al. (2021)
Geological Utilization and Storage	Injection or sequestration of captured CO_2 into geological formations through engineering techniques for permanent storage.	Strict geological requirements with certain risks of leakage.	Lin et al. (2024)
Chemical Synthesis and Conversion	Transforming CO_2 into high-value chemicals or fuels through thermal, electro-, or photochemical catalysis.	Mature technology, but high cost of reactants, with low product profitability and conversion rates.	Okoye-Chine et al. (2022)
Carbon biological sequestration	Conversion of CO_2 into organic matter using biological/ biotechnological methods.	Inherent natural capability, no additional energy consumption, high carbon sequestration potential, but immature artificial technology.	(Fu and Xu, 2023; Wang et al., 2023b)

leveraging autotrophic organisms to convert inorganic CO_2 into organic compounds, this approach offers clean, sustainable fixation without the high energy penalties of conventional chemical processes (Wang et al., 2024). As an emerging CCUS component, although current human mastery of carbon biological sequestration technology remains immature, given that Earth's ecosystems are the primary channels for the global carbon cycle, influencing carbon stock in all aspects of the biosphere, this technology has shown immense potential for carbon dioxide fixation and reduction by leveraging the vastness and complexity of Earth's ecosystems (Fu and Xu, 2023). Research indicates that Earth's autotrophic organisms are capable of fixing up to 380 Gt of carbon dioxide annually (Gong et al., 2018), underscoring that biological carbon fixation may be among the most promising and suitable large-scale carbon reduction and utilization technologies.

However, the accelerated urbanization process in China over the past 50 years has led to a sevenfold expansion in urban areas across 75 major cities (Wang et al., 2023a). This rapid urban sprawl has disrupted natural vegetation coverage, causing a loss of ecosystem carbon stocks. To mitigate the adverse impacts of urbanization and other human activities on ecosystem carbon stocks, it is critical to enhance the carbon biological sequestration capacities of various ecosystems.

Current research on carbon biological sequestration spans the global biosphere and ecosystems, involving components like higher plants, animals, microorganisms, algae, soil, and their roles in carbon reduction (He et al., 2024; Liang et al., 2025; Nolan et al., 2021; Stukel et al., 2023). Over the past 80 years, scientists have identified six natural carbon dioxide fixation pathways associated with carbon biological sequestration (Table 2). With the rapid advancements in genomics, metagenomics, and microbiome technologies, new enzymes and pathways for carbon dioxide fixation are expected to be discovered in the future. However, carbon biological sequestration currently faces challenges such as low overall efficiency, limited genetic modification capabilities, and the inability of natural ecosystems alone to meet global carbon reduction demands (Gong et al., 2018). Researchers are striving to build more efficient systems or methods to enhance carbon biological sequestration efficiency.

Common terrestrial ecosystems, such as farmland, grasslands, forests, shrubs, lakes, and bamboo forests, play key roles in reducing

Table 2
Six Natural Carbon biological sequestration Pathways.

Pathway	Energy Source	Found In	Discovery Year	References
Calvin Cycle	Light energy	Higher plants	1948	Akinyede et al. (2020)
Reductive Tricarboxylic Acid Cycle	Light energy and sulfur	Some photosynthetic purple and green sulfur bacteria	1966	Evans et al. (1966)
Anaerobic Acetyl-CoA Pathway	Hydrogen	Anaerobic microorganisms	1972	Schulman et al. (1972)
3-Hydroxypropionate Cycle	Light energy	Thermophilic photosynthetic green bacteria	1993	Strauss and Fuchs (1993)
Dicarboxylate/4-Hydroxybutyrate Cycle	Hydrogen and sulfur	Archaea	2007	Berg et al. (2007)
3-Hydroxypropionate/4-Hydroxybutyrate Cycle	Hydrogen and sulfur	Archaea	2008	Huber et al. (2008)

atmospheric carbon dioxide concentrations due to their carbon sink capacities (Table 3) (Gurmesa et al., 2022). Higher plants within these ecosystems are the most common natural carbon fixation agents, with forest and shrub ecosystems exhibiting strong carbon dioxide conversion abilities in the vegetation layer, while farmland ecosystems demonstrate substantial potential in soil carbon sink accumulation (Table 3). This is mainly attributed to frequent human management measures in farmland, such as crop rotation and organic fertilizer application, which enhance soil organic carbon input. Enhancing the carbon fixation capabilities of higher plants will significantly boost terrestrial carbon sinks and focus primarily on enhancing photosynthetic capacity and maintaining rhizosphere carbon balance, which involves research areas like plant photosynthetic efficiency and rhizosphere carbon cycling (Winkler et al., 2019). Current studies heavily emphasize improving plant photosynthetic efficiency, while limited attention is given to rhizosphere carbon cycling (including rhizosphere carbon deposition and absorption). The contributions of plants to soil carbon cycling and the underlying mechanisms remain unclear. Agricultural ecosystems have high controllability, and through optimized management (such as rational fertilization and conservation tillage), their soil carbon sequestration capacity can be further enhanced (Table 3). Simultaneously, studies suggest that rhizosphere carbon cycling is crucial for soil carbon sink balance and accumulation (Liu et al., 2023b; Zhao et al., 2022), necessitating further research on promoting rhizosphere carbon cycling to enhance soil carbon sink capabilities.

2.2. Absorption and fixation of inorganic carbon by plant roots: a potential strategy to combat climate change

Against the backdrop of global ecological and environmental changes, the role of plant roots in the carbon cycle has received increasing attention. By releasing photosynthetically synthesized organic compounds into the soil, plant roots not only enhance soil organic carbon pools but also provide essential nutrients and energy for soil microorganisms (Jones et al., 2009). However, rhizosphere carbon deposition mainly depends on the photosynthetic carbon fixation of plants, which may become a limiting factor under certain environmental conditions. Studies have shown that CO_2 can be a limiting factor for photosynthesis in organisms with carbon concentrating mechanisms, which actively enriching CO within cells through a series of biochemical processes, such as cyanobacteria, algae, and aquatic macrophytes, as well as in terrestrial higher plants (Cummins, 2021). Extreme weather conditions such as drought and high temperatures, brought about by rising CO_2 concentrations, increase stomatal resistance in plant leaves, limiting the availability of CO_2 to Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) in terrestrial plants (Ancín et al., 2024). To enable plants to more effectively absorb and fix CO_2 under different environmental conditions, especially maintaining stable CO_2 assimilation rates under drought and heat stress, it is necessary to explore methods to transport CO_2 into plants through alternative pathways to alleviate the adverse effects of increased stomatal resistance on photosynthetic carbon fixation. Additionally, in CCUS technologies, the CO_2 to be processed is often in a gaseous state at relatively high concentrations. To avoid limitations in application scenarios and timing when using it as a fertilizer for plants, alternative approaches to transporting CO_2 into plants are also needed.

Table 3
Carbon sinks in ecosystems containing higher plants (Tg, Million Tons).

Ecosystem	Vegetation Layer (Tg-C/year)	Soil Layer (Tg-C/year)
Forest	75 ± 35	4 ± 4
Grassland	7 ± 3	6 ± 1
Farmland	13 ± 1	26 ± 11
Shrubland	22 ± 10	39 ± 9
Lakes	20 ± 1	–
Bamboo Forest	1 ± 1	–

Note: The data in the table are averages calculated based on the results of the literature, "±" represents standard error (Data Source: Gurmesa et al., 2022; Keenan and Williams, 2018; Piao et al., 2009).

The absorption and fixation of inorganic carbon from the soil by plants is considered a promising method of rhizosphere carbon absorption, particularly in addressing rising atmospheric CO_2 concentrations (Liang et al., 2020). Enhancing the absorption of inorganic carbon from the rhizosphere environment by plant roots can not only address the impacts of extreme weather on plants' photosynthetic carbon fixation capacity, maintaining stable carbon fixation rates, but also facilitate the utilization of high-concentration CO_2 that needs processing in CCUS technologies (Liang et al., 2025). Some studies provide indirect support for the uptake of HCO_3^- by plant roots (Table 4). For instance, in calcareous soils, HCO_3^- can passively enter plant roots and then be transported over long distances to leaves via xylem vessels. In the leaves, it is transformed by carbonic anhydrase into CO_2, which can then be assimilated by photosynthesis along with atmospheric CO_2 (Rao and Wu, 2022). Early research using ^{11}C or ^{14}C isotopes as HCO_3^- markers also provided evidence for HCO_3^- uptake by plant roots and its transport to branches (Poschenrieder et al., 2018). Liang et al. found that lettuce can intermittently utilize HCO_3^- from its growing environment under drought conditions to alleviate drought stress and fix the absorbed HCO_3^- through epidermal photosynthesis in stems and leaves (Liang et al., 2020). Additionally, biological activities can introduce atmospheric CO_2 into the soil through CO_2 hydration reactions, forming soil inorganic carbon pools. CO_2 dissolves in water to form carbonic acid, which then dissociates into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) (Huang et al., 2024). Therefore, it is worth considering converting atmospheric CO_2 into HCO_3^- through a medium or carrier, which can then be introduced into the soil to promote artificial absorption of inorganic carbon in the rhizosphere by plants.

Agricultural ecosystems are the only terrestrial ecosystems on Earth where carbon pools can be significantly influenced by human intervention and have a strong capacity for enhancing soil carbon sinks (Table 3) (Liang et al., 2022). Introducing CO_2 in the form of HCO_3^- into agricultural ecosystems and utilizing crops with short growth cycles and large planting areas to fix HCO_3^- in the soil could become a large-scale carbon reduction technology with high potential for CO_2 utilization. However, soils with high concentrations of carbonates/bicarbonates may limit the performance and yield of calcifying crops, especially in crops with low iron efficiency, such as certain varieties of citrus, peaches, pears, or soybeans suffering from chlorosis (Kinzel, 1983; Poschenrieder et al., 2018). The high pH of soils caused by high concentrations of carbonates/bicarbonates can reduce plants' uptake of

Table 4
Advances in the utilization of inorganic carbon (including HCO_3^-, soluble inorganic carbon, etc.) in plants and soils in the last decade.

Reference	Highlights
Gamarra Reinoso et al. (2024)	Plants absorb inorganic carbon (e.g., HCO_3^-) through their roots, converting it into organic carbon forms (e.g., sucrose) and transporting it to aboveground parts. This process is regulated by various transport proteins and metabolic pathways.
Poschenrieder et al. (2018)	The transport and utilization of bicarbonate in plants is a complex process involving multiple transport proteins and metabolic pathways. Root absorption and utilization of inorganic carbon can enhance photosynthesis and plant growth.
Terés et al. (2019)	Organic acids secreted by plant roots can increase the availability of inorganic carbon in the soil, promoting plant absorption.
Vinyard and Govindjee (2024)	Plant adaptation to high concentrations of inorganic carbon in the soil involves multiple physiological and molecular mechanisms, elucidating responses under such conditions.
Dąbrowska-Bronk et al. (2016)	The absorption and utilization of inorganic carbon by plant roots are influenced by various factors, including soil pH, inorganic carbon concentration, and plant genotypes.
Li et al. (2024)	Inorganic carbon absorbed by plant roots can be fixed and converted into organic carbon, thereby affecting the plant's carbon-nitrogen balance and growth.
Nel and Cramer (2019)	Plant root absorption and utilization of inorganic carbon interact with soil microbial communities, significantly influencing plant growth and ecosystem carbon cycling.
Gamarra Reinoso et al. (2024)	Root absorption and utilization of inorganic carbon are regulated by various transport proteins, including nitrate and sulfate transporters.
Han et al. (2022)	Root absorption and utilization of inorganic carbon enhance plant stress tolerance, such as drought and salinity resistance.
Xia and Wu (2022)	Karst-adapted plants are better suited to environments with high bicarbonate and nitrate concentrations, with photosynthesis and growth promoted by their interaction.
Liang et al. (2023a)	Physiological stress from HCO_3^- on tomatoes initially arises from soil pH changes. As HCO_3^- concentration increases, overlapping soil EC and high pH begin to induce irreversible physiological stress on tomatoes.
Rao and Wu (2022)	The contribution of soil dissolved inorganic carbon (DIC) to total leaf photosynthesis varies among species and changes with altitude, helping plants adapt to drought and alkaline conditions in karst habitats.
Hang and Wu (2016)	Soil inorganic carbon (e.g., bicarbonate) significantly impacts plant photosynthesis and growth. Species-specific differences in utilization affect growth and metabolic processes.
Rao and Wu (2017)	Roots can absorb and utilize bicarbonate in the soil to meet carbon demands under water stress, helping maintain photosynthesis and growth in arid environments.
Wang et al. (2017)	In simulated karst soils, three bioenergy plants utilized new carbon sources (e.g., soil inorganic carbon) through carbonic anhydrase, increasing biomass production.

essential nutrients, particularly iron, zinc, and phosphorus, while high concentrations of HCO_3^- in calcareous soils suppress root growth in sensitive plant species (Lee and Woolhouse, 1969). Compared to monocotyledonous plants like barley and oats, dicotyledonous plants such as peas, legumes, or sunflowers experience more pronounced root growth inhibition in soils containing high concentrations of CO_2 and/or HCO_3^- (Xia and Wu, 2022). Given the multiple effects of HCO_3^- on plant metabolism, introducing HCO_3^- into agricultural ecosystems' cultivated soils requires mitigating the physiological toxicity of HCO_3^- to crops. Liang et al. explored the causes of physiological toxicity caused by HCO_3^- on crops through HCO_3^- supplementation experiments and found that, aside from concentration stress, the alkaline environment caused by high concentrations of HCO_3^- is a primary reason for physiological toxicity in crops (Liang et al., 2023a). As HCO_3^- concentrations continue to increase, the overlap of increased soil electrical conductivity (EC) with high soil pH begins to cause irreversible physiological stress to tomatoes (Liang et al., 2023a). Therefore, when introducing HCO_3^- into cultivated soils, it is necessary to find a suitable CO_2 carrier that meets plants' growth needs. This carrier should possess the unique characteristics such as CO_2 absorption capacity, low cost and availability, low plant physiological toxicity, and maintenance of rhizosphere buffering capacity to ensure the enhancement of carbon fixation without the negative impact plant growth and soil ecology.

2.3. The potential and improvement strategies of biogas slurry as a carrier for agricultural CO_2 application

There are numerous substances capable of absorbing CO_2, but when selecting a carrier for CO_2 transport in agriculture, priority should be given to its affordability and accessibility. Based on this principle, a series of renewable CO_2 absorbents derived from agricultural waste can be considered for transporting CO_2 into cultivated soil. These absorbents mainly include alkanolamines, soybean-based amino acids, biogas slurry, and biomass ash (Karimi et al., 2022). Among them, alkanolamines and soybean-based amino acids have gained attention due to their excellent CO_2 absorption properties and abundant sources; however, studies have found that their high physiological toxicity to plants limits their application value in agriculture (Eide-Haugmo et al., 2012; Gusnawan et al., 2018; Liang et al., 2018b; Vaidya and Kenig, 2007).

2.3.1. The potential of biogas slurry as a carrier for agricultural CO_2 application

Biogas slurry, a byproduct of anaerobic fermentation of biomass and agricultural waste in biogas digesters, has a certain alkalinity due to its substantial content of free ammonia. This implies that biogas slurry has a CO_2 absorption capacity (He et al., 2017a). Moreover, because of the anaerobic fermentation process, the nutrient content of biogas slurry is generally higher than that of other organic fertilizers produced through composting or retting. The recovery rates of nitrogen, phosphorus, and potassium in biogas slurry exceed 90%, with a significant portion already converted into a form directly absorbable by plants (Liang et al., 2023b). Despite the variations in nutrient content caused by different fermentation feedstocks, the nutritional diversity of biogas slurry is remarkable. In addition to essential macro-elements, trace elements, and beneficial elements required for crop growth, it also contains humic acid and organic matter, including small molecule organic acids conducive to crop absorption. Growth-promoting substances such as butyric acid, indoleacetic acid, and gibberellins in organic acids further enhance crop growth and development (Li et al., 2016). Some of the organic matter in biogas slurry improves crop nutrient utilization efficiency; its humic acid promotes the formation and stability of soil aggregate structures, strengthens soil buffering capacity and fertility retention, and significantly enhances soil conditions (Terhoeven-Urselmans et al., 2009). Hence, biogas slurry is considered a high-quality slow-release organic fertilizer.

Additionally, studies demonstrate the notable effects of CO_2-enriched biogas slurry in various crop applications. It should be particularly noted that these effects are induced by the HCO_3^- carried in the biogas slurry, rather than the slurry itself. For example, in the rice cultivation, using CO_2-enriched biogas slurry significantly improved rice growth performance and biomass while enhancing soil carbon sink function and increasing the efficiency of nitrogen, phosphorus, and potassium nutrient uptake by rice (Liang et al., 2023c). In tomato cultivation, applying biogas slurry enriched with CO_2 not only enhanced tomatoes' CO_2 fixation capacity but also improved soil carbon sink function, optimized soil pH, and nutrient balance, creating a more conducive growth environment for plants (Liang et al., 2025). In hydroponic lettuce experiments, biogas slurry effectively absorbed CO_2 while significantly improving lettuce's nitrogen, phosphorus, and potassium nutrient uptake efficiency, growth performance, and quality

(Liang et al., 2023b). Furthermore, introducing CO_2 into biogas slurry in the form of HCO_3^- can greatly enhance plants' CO_2 fixation capacity, alleviate drought stress, and improve photosynthetic efficiency and water use efficiency (Liang et al., 2020).

Long-term field studies consistently demonstrate that repeated biogas slurry applications not only build soil organic carbon (SOC) pools but also foster resilient microbial communities and sustain nutrient cycling. In a 12-year paddy-field trial, Chen et al. (2024) showed that biogas slurry markedly increased fungal necromass contributions to SOC—enhancing aggregation, water-holding capacity and N-P-K retention—without exacerbating salt accumulation or pH stress. Similarly, a 27-year upland experiment by Ye et al. (2019) revealed that continuous slurry amendments elevated total SOC and microbial biomass, stabilized aggregate structure and maintained high microbial diversity, even as the relative share of microbial necromass shifted. A global meta-analysis of cropland soils (Zhou et al., 2023) further corroborated these findings, linking long-term organic amendments—including biogas by-products—to enhanced microbial necromass formation, improved nutrient-use efficiencies and greater soil resilience under changing climatic conditions. Collectively, these multi-decadal investigations underscore that biogas slurry–based carbon biological sequestration not only sequesters CO_2 efficiently but also safeguards and enhances soil health through durable improvements in microbial community structure, organic matter stability and nutrient cycling.

Evidently, biogas slurry possesses significant CO_2 absorption capacity and rich nutritional content, making it a potential carrier for agricultural CO_2 application. It can absorb and convert CO_2 from industrial CO_2-rich gases into HCO_3^-, then introduce it into the soil's inorganic carbon pool. After being absorbed by crops, CO_2 is fixed within their biomass (Fig. 3). Applying biogas slurry carrying CO_2 to crop cultivation not only facilitates effective CO_2 fixation by plants/microorganisms but also enhances crop growth performance and quality while improving soil conditions. As shown in Fig. 3, tomatoes absorb 43.8% of the HCO_3^- introduced into the soil for their normal metabolic processes. The 0.5 ‰ of HCO_3^- introduced into the soil is utilized by microorganisms to synthesize structural substances—phospholipid fatty acids. Additionally, 38.9% of the HCO_3^- absorbed by microorganisms or tomatoes is converted into organic matter and subsequently returns to the cultivated soil in the form of residues or secretions, contributing to the formation of soil organic carbon. Furthermore, 5.5% of the HCO_3^- is transformed into an insoluble inorganic carbon form, remaining in the soil. A maximum of 11.7% of the HCO_3^- is released back into the atmosphere. However, the CO_2 enrichment capacity of biogas slurry is relatively low, limiting its potential application in agricultural carbon sink enhancement (Liang et al., 2024). The main principle of biogas slurry's CO_2 absorption involves the transformation of ammonium nitrogen into free ammonia, which then reacts with CO_2 to form HCO_3^- or carbamate (He et al., 2019b). However, the initial pH of biogas slurry is relatively low, ranging between 7.2 and 8.5, resulting in limited free ammonia content and, consequently, restricted CO_2 loading capacity (He et al., 2017a). To enable biogas slurry to carry more CO_2, its CO_2 loading capacity needs to be further strengthened and improved.

2.3.2. Enhancing CO_2 absorption performance of biogas slurry and its applications

Based on the CO_2 absorption characteristics and the properties of biogas slurry, enhancing its CO_2 absorption performance can be approached through the following three strategies:

I. Adding Chemical Absorbents: Chemical absorbents with strong CO_2 absorption capabilities, such as alkanolamines or amino acid salts, can be directly added to biogas slurry to improve its performance. However, even trace amounts of these absorbents can cause physiological toxicity to crops (Liang et al., 2018b), significantly increasing the slurry's toxicity to plants.
II. Pressure Desorption of CO_2: Reducing the pressure on absorbed CO_2 within the slurry can slightly improve its absorption performance while maintaining low toxicity for plants. However, this method has limited overall effectiveness and requires high energy consumption (Liang et al., 2018a, 2023b).
III. Increasing pH Levels: Raising the pH of biogas slurry increases its free ammonia content, thereby enhancing its CO_2 absorption capacity. Due to the slurry's complex composition and strong acid-base buffering properties, overcoming its buffering capacity to raise the pH requires substantial alkaline solutions (He et al., 2017b, 2019a).

Although each method has pros and cons, these strategies provide insights into low-toxicity modifications for enhancing CO_2 absorption in biogas slurry. Currently, the most feasible method involves using additives to raise the pH of the slurry (He et al., 2019a). Additives should be cost-effective, readily available, and maintain the slurry's original low physiological toxicity to plants.

2.3.2.1. Biomass ash as an additive to enhance CO_2 absorption and Agro-utilization. Biomass ash, a byproduct of high-temperature combustion of agricultural residues like crop straw and wood, is projected to reach a global production of 476 million tons annually by 2050 (Feng et al., 2021). Biomass ash primarily consists of alkali metal oxides such as K_2O, CaO, and SiO_2 and contains essential macro- and micro-elements

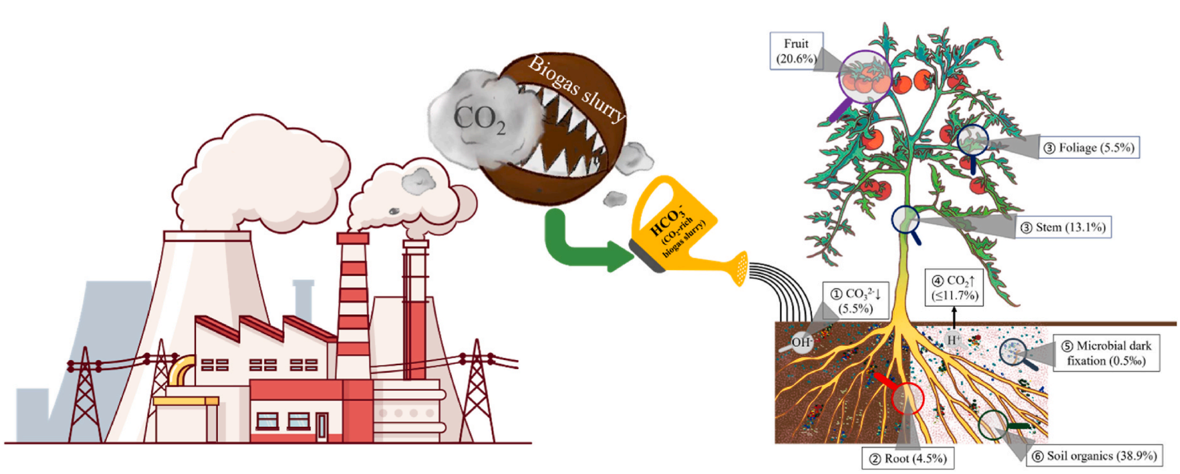

Fig. 3. Framework diagram of once-through CO_2 chemical absorption and agricultural utilization via biogas slurry. From industrial CO_2 capture and HCO_3^- formation, through soil application and root/microbial uptake, to biomass fixation and residual soil carbon storage (Data source: Liang et al., 2025).

required by plants, including phosphorus and magnesium (Liang et al., 2022). Studies on its use in forestry and agriculture have highlighted their superior properties, including high water absorption, porosity, and nutrient richness, which can promote crop growth, reduce diseases, and improve soil conditions (Abioye et al., 2024; Feng et al., 2021). Biomass ash enhances microbial activity in crop root layers, facilitating humification processes and creating an optimal environment for plant growth (Lopez et al., 2018). Recycling biomass ash into soil allows for mineral nutrient reuse, prevents soil acidification, increases crop yields, and reduces solid waste accumulation (Scheepers and du Toit, 2016).

However, its alkaline oxides yield a highly alkaline solution upon contact with water, potentially disrupting the pH balance of neutral soils and damaging surface vegetation (He et al., 2019a). Despite these challenges, its alkalinity also gives biomass ash potential for CO_2 absorption and sequestration. Studies indicate that biomass ash solutions can have pH levels above 13 (Pengthamkeerati et al., 2008), suggesting that adding biomass ash to biogas slurry could raise the slurry's pH and enhance CO_2 absorption capacity. Furthermore, biomass ash could serve as a promising CO_2 carrier, transferring CO_2 in the form of HCO_3^- to plants for fixation. However, measures must be taken to minimize the physiological toxicity caused by its strong alkalinity to crops and avoid pH stress that might hinder the uptake of soil inorganic carbon by plants (Liang et al., 2022).

Research shows that combining biogas slurry and biomass ash significantly improves CO_2 absorption capacity. Experiments revealed that this mixture not only effectively fixes CO_2 but also functions as a high-quality fertilizer, promoting tomato growth and reducing environmental pollution (Liang et al., 2024). This synergy presents a novel approach to valorizing agricultural waste. Studies further explored the carbon fixation potential of this mixture in crop-soil ecosystems, demonstrating that it enhances crop carbon fixation capacity while improving soil physical and chemical properties. By adjusting the composition ratios of the mixture, its CO_2 absorption and fixation performance can be further optimized.

2.3.2.2. Other potential methods. In addition to the strategies described above, other renewable materials remain underexplored for enhancing CO_2 absorption in biogas slurry. Among these, biochar—produced by pyrolyzing agricultural residues—has emerged as a particularly promising additive due to its unique physicochemical properties. Co-application of biochar with biogas slurry leverages the physicochemical properties of both materials to markedly enhance CO_2 absorption and retention. The hierarchical porous network and high specific surface area of biochar introduce a multitude of active adsorption sites, while its surface oxygen-containing functional groups (e.g., carboxyl and hydroxyl moieties) stabilize pH fluctuations in the slurry, maintaining an optimal alkaline environment (pH 8–9) for ammonia-driven conversion of gaseous CO_2 into bicarbonate. This mechanistic synergy not only accelerates mass transfer—by creating micro-zones where dissolved CO_2 diffuses rapidly into biochar micropores—but also impedes desorption, resulting in over a 55% improvement in CO_2 adsorption capacity and a 30% increase in adsorption kinetics compared to untreated slurry (Duan et al., 2024; Guo et al., 2022). To fully capitalize on these advantages, future research must refine biochar production parameters (feedstock type, pyrolysis temperature, particle size), identify optimal biochar-to-slurry ratios, and validate multi-year field performance across diverse soil types and climatic regions to ensure sustained CO_2 mitigation, soil resilience, and crop productivity.

2.3.3. Life cycle assessment and energy savings of biogas slurry-based carbon biological sequestration

We use life cycle assessment (LCA) and energy-comparison studies quantify the environmental advantages of biogas slurry–based carbon biological sequestration versus conventional chemical CCUS routes (Table 5):

Table 5
Summary Table of Comparative Metrics for two CO_2 capture pathways. All data in the table are sourced from authoritative life cycle assessment (LCA) or industrial demonstration reports published between 2020 and 2024. MEA-Based Capture: Represents the conventional monoethanolamine (MEA) chemical absorption process, indicative of the current mainstream post-combustion capture technology; Biogas Slurry-CBS: Denotes a novel process utilizing biogas slurry integrated with Carbon Biological Sequestration (CBS).

Technical Pathway	Energy demand (GJ/t CO_2)	GHG emissions (t CO_2-eq/t CO_2 fixed)	Water/ chemical input (relative units [a])	Reference
MEA-Based Capture	2.4–3.0	0.18–0.22	1.0	IEAGHG 2024; GCCSI 2024; Capocelli and De Falco (2022); Zhang et al. (2017)
Biogas Slurry-CBS	0.6–0.9	~0.1	0.3	Varling et al. (2023); Bauer et al. (2021); IEA Bioenergy (2022); Liang et al. (2023b); Liang et al. (2025)

[a] Relative units: Values are expressed relative to a baseline of 1.0, representing the "water/chemical consumption of the -Based Capture ". This indicator is not converted to absolute mass units and serves solely for comparative purposes.

Monoethanolamine (MEA) scrubbing, the industry benchmark for chemical CO_2 capture, typically requires 2.4–3.0 GJ per t CO_2 for solvent regeneration and compression (IEAGHG, 2024; GCCSI, 2024). In contrast, biogas slurry–based carbon biological sequestration processes consume only 0.6–0.9 GJ/t CO_2, primarily for low-grade mixing and mild pH adjustment, achieving up to 72% energy savings (Varling et al., 2023; Bauer et al., 2021).

A LCA found that MEA systems emit 0.18–0.22 t CO_2-eq/t CO_2 captured, driven by thermal regeneration and solvent manufacture (GCCSI, 2024; Capocelli and De Falco, 2022). Biogas slurry–carbon biological sequestration, by leveraging on-farm digestate without additional high-temperature inputs, reduces net GHG emissions to 0.10 t CO_2-eq/t CO_2 fixed—a 50% decrease in lifecycle greenhouse-gas intensity (Bauer et al., 2021; IEA Bioenergy, 2022).

Chemical CCUS often demands fresh water for solvent cooling and makes heavy use of ammonia inhibitors (Zhang et al., 2017). Carbon biological sequestration with biogas slurry operates at ambient temperature, requires no external freshwater for cooling, and repurposes residual nitrogen in the digestate, thus cutting ancillary water and chemical demands by over 70% in field trials (Liang et al., 2023b, 2025).

These quantifications demonstrate that integrating biogas slurry–based carbon biological sequestration not only leverages existing agricultural waste streams but also delivers substantial energy and emissions savings compared to benchmark chemical CCUS methods, reinforcing its classification as a low-energy, cleaner production technology.

3. Summary and outlook

3.1. Summary of key findings

As one of the main strategies for addressing CO_2 emission reduction pressures and global climate change, CCUS (Carbon Capture, Utilization, and Storage) technology will face significant market opportunities and practical challenges in the future. To address the issues and difficulties encountered by current mainstream CCUS technologies, it is essential to continuously innovate China's CCUS technologies, gain mastery of more core CCUS technologies, and enhance China's competitiveness in the emerging CCUS technology market. Developing or finding new CCUS pathways that are energy-efficient and produce high-value-added products is particularly necessary.

The absorption of inorganic carbon by rhizospheres in higher plants undoubtedly represents a forward-looking and promising CCUS technology. However, the CO_2 handled in CCUS processes is typically in a high-concentration gaseous form. When using this CO_2 as a fertilizer for plants, it is highly limited by weather conditions and application timing, and can only be applied in greenhouse environments. This significantly restricts the flexibility and widespread application of plant utilization of CO_2. Therefore, it is necessary to find suitable carriers that can convert CO_2 into other plant-useable forms, such as HCO_3^-. Introducing CO_2 in the form of HCO_3^- into the soil's inorganic carbon pool and transferring it to plants aligns well with the "4 per mille" goal proposed by the Paris Agreement during the UN Framework Convention on Climate Change (Minasny et al., 2017).

3.2. Global deployment scenarios

Global implementation of biogas slurry–based carbon biological sequestration must be carefully tailored to distinct climatic regimes and farming systems to unlock its full carbon-sink potential. In tropical regions, persistently high temperatures and humidity accelerate heterotrophic microbial turnover of soil organic matter, demanding optimization of slurry formulations—through pH buffering agents, nutrient balancing and adsorption enhancers such as biochar—as well as the selection or engineering of crop varieties with enhanced root-localized carbon concentrating mechanisms to offset rapid mineralization. Temperate zones, by contrast, combine moderate thermal regimes and extended growing seasons that inherently favor organic carbon accrual; here, large-scale integration of slurry-enriched bicarbonate into both paddy and dryland rotations can secure sequestration rates of 0.5–1.0 t C/(ha·year) under current enrichment protocols. In cold and subarctic agroecosystems, low soil temperatures suppress microbial activity and necromass formation, positioning controlled-environment agriculture—greenhouses or high tunnels—with slurry-derived bicarbonate fertigation and cold-tolerant cultivars as the primary avenues for carbon biological sequestration application. Arid and semi-arid drylands similarly stand to gain by timing slurry applications to coincide with peak root growth phases, thereby coupling moisture retention with inorganic carbon delivery, though this requires precision irrigation to minimize volatilization losses. Finally, deployment must reflect farm-scale realities: smallholders can adopt simplified digestate collection and manual enrichment methods, while commercial operations may invest in on-farm digesters, automated slurry enrichment systems and precision delivery technologies to maximize capture efficiency and economies of scale. By aligning carbon biological sequestration protocols with local climate constraints, soil properties, crop physiology and socioeconomic conditions, biogas slurry–driven carbon sequestration can be effectively scaled across diverse agroecosystems worldwide.

3.3. Future perspectives

As global priorities shift toward green and circular economies, carbon biological sequestration will gain ever broader acceptance as a cornerstone technology for climate mitigation in agriculture. In particular, the development of truly "green" CO_2 transport carriers—materials that combine high absorption capacity with agronomic safety and low energy demand—will command growing research and investment. While biogas slurry, biomass ash and biochar each show promise, future efforts must refine production parameters (e.g., pyrolysis temperatures, feedstock selection), optimize amendment ratios and engineer multi-functional composites that maintain soil pH and nutrient balance while maximizing bicarbonate loading and retention.

Moreover, translating carbon biological sequestration from the lab and greenhouse into the field will hinge on rigorous, landscape-scale validation and socioeconomic integration. Long-term, multi-site trials should quantify not only carbon sequestration rates but also co-benefits such as improved water-use efficiency, enhanced crop resilience and reduced fertilizer requirements. Comprehensive life-cycle assessments (LCAs) will be essential to benchmark energy inputs, greenhouse-gas footprints and economic viability against established CCUS methods. Finally, fostering interdisciplinary collaborations—uniting soil scientists, agronomists, process engineers and policy experts—will accelerate the design of farm-ready, low-carbon products and enable the policy frameworks needed to scale carbon biological sequestration technologies across diverse cropping systems and climatic zones.

CRediT authorship contribution statement

Feihong Liang: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shuiping Yan:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Zhan Shi:** Writing – review & editing. **Te Tu:** Writing – review & editing. **Andrea Pezzuolo:** Writing – review & editing. **Qi Feng:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

Abioye, K.J., Harun, N.Y., Sufian, S., Yusuf, M., Jagaba, A.H., Ekeoma, B.C., Kamyab, H., Sikiru, S., Waqas, S., Ibrahim, H., 2024. A review of biomass ash related problems: mechanism, solution, and outlook. J. Energy Inst. 112, 101490.

Akinyede, R., Taubert, M., Schrumpf, M., Trumbore, S., Kusel, K., 2020. Rates of dark CO_2 fixation are driven by microbial biomass in a temperate forest soil. Soil Biol. Biochem. 150.

Ancín, M., Gámez, A.L., Jauregui, I., Galmes, J., Sharwood, R.E., Erice, G., Ainsworth, E. A., Tissue, D.T., Sanz-Sáez, A., Aranjuelo, I., 2024. Does the response of rubisco and photosynthesis to elevated [CO_2] change with unfavourable environmental conditions? J. Exp. Bot. 75 (22), 7351–7364.

Bauer, L., Ranglová, K., Masojídek, J., Drosg, B., Meixner, K., 2021. Digestate as sustainable nutrient source for microalgae—challenges and prospects. Appl. Sci. 11 (3), 1056.

Berg, I.A., Kockelkorn, D., Buckel, W., Fuchs, G., 2007. A 3-Hydroxypropionate/4-Hydroxybutyrate autotrophic carbon dioxide assimilation pathway in archaea. Science 318 (5857), 1782–1786.

CAT, 2024. 09. 17. China. https://climateactiontracker.org/countries/china/.

Capocelli, M., De Falco, M., 2022. Generalized penalties and standard efficiencies of carbon capture and storage processes. Int. J. Energy Res. 46 (4), 4808–4824.

Chen, W., Chen, M., Jiang, B., Lei, T., Zhang, F., Zhang, Z., 2024. The improvement of ionic liquids on CO_2 capture with biphasic absorbents. Chem. Eng. J. 493, 152720.

Chen, Z., Ma, J., Ma, J., Ye, J., Yu, Q., Zou, P., Sun, W., Lin, H., Wang, F., Zhao, X., Wang, Q., 2024. Long-term biogas slurry application increases microbial necromass

but not plant lignin contribution to soil organic carbon in paddy soils as regulated by fungal community. Waste Manag. 175, 254–264.
Consortium, C.C.P.I.P., Hönisch, B., Royer, D.L., Breecker, D.O., Polissar, P.J., Bowen, G. J., Henehan, M.J., Cui, Y., Steinthorsdottir, M., McElwain, J.C., 2023. Toward a Cenozoic history of atmospheric CO_2. Science 382 (6675), eadi5177. https://doi.org/10.1126/science.adi5177.
Cummins, P.L., 2021. The coevolution of RuBisCO, photorespiration, and carbon concentrating mechanisms in higher plants. Front. Plant Sci. 12, 662425.
Dąbrowska-Bronk, J., Komar, D.N., Rusaczonek, A., Kozłowska-Makulska, A., Szechyńska-Hebda, M., Karpiński, S., 2016. β-carbonic anhydrases and carbonic ions uptake positively influence Arabidopsis photosynthesis, oxidative stress tolerance and growth in light dependent manner. J. Plant Physiol. 203, 44–54.
Duan, Y., Liu, Y., Liu, H., Shi, Z., Shen, X., Sun, X., Zhao, S., Yan, S., Liang, F., 2024. CO_2 absorption performance of biogas slurry enhanced by biochar as a potential solvent in once-through CO_2 chemical absorption process. Carbon Capture Sci. Technol. 13, 100317.
Eide-Haugmo, I., Brakstad, O.G., Hoff, K.A., da Silva, E.F., Svendsen, H.F., 2012. Marine biodegradability and ecotoxicity of solvents for CO_2-capture of natural gas. Int. J. Greenh. Gas Control 9, 184–192.
Evans, M.C., Buchanan, B.B., Arnon, D.I., 1966. A new ferredoxin-dependent carbon reduction cycle in a photosynthetic bacterium. Proc. Natl. Acad. Sci. 55 (4), 928–934.
Feng, L., Liang, F., Xu, L., Ji, L., He, Q., Yan, S., 2021. Simultaneous biogas upgrading, CO_2 sequestration, and biogas slurry decrement using biomass ash. Waste Manag. 133, 1–9.
Fu, C., Xu, M., 2023. Achieving carbon neutrality through ecological carbon sinks: a systems perspective. Green Carbon 1 (1), 43–46.
Gamarra Reinoso, L., Majláth, I., Dernovics, M., Fábián, A., Jose, J., Jampoh, E.A., Hamow, K.Á., Soós, V., Sági, L., Éva, C., 2024. Root-based inorganic carbon uptake increases the growth of Arabidopsis thaliana and changes transporter expression and nitrogen and sulfur metabolism. Front. Plant Sci. 15, 1448432.
GCCSI, 2024. Global status of CCS 2024. https://www.globalccsinstitute.com/resources/global-status-report/.
Gong, C., Tian, H., Liao, H., Pan, N., Pan, S., Ito, A., Jain, A.K., Kou-Giesbrecht, S., Joos, F., Sun, Q., 2024. Global net climate effects of anthropogenic reactive nitrogen. Nature 632 (8025), 557–563.
Gong, F., Zhu, H., Zhang, Y., Li, Y., 2018. Biological carbon fixation: from natural to synthetic. J. CO2 Util. 28, 221–227.
Guo, S., Li, Y., Wang, Y., Wang, L., Sun, Y., Liu, L., 2022. Recent advances in biochar-based adsorbents for CO_2 capture. Carbon Capture Sci. Technol. 4, 100059.
Gurmesa, G.A., Wang, A., Li, S., Peng, S., de Vries, W., Gundersen, P., Ciais, P., Phillips, O.L., Hobbie, E.A., Zhu, W., 2022. Retention of deposited ammonium and nitrate and its impact on the global forest carbon sink. Nat. Commun. 13 (1), 880.
Gusnawan, P.J., Zha, S., Zou, L., Zhang, G., Yu, J., 2018. Soybean and moringa based green biosolvents for low-concentration CO2 capture via a hollow fiber membrane contactor. Chem. Eng. J. 335, 631–637.
Han, X., Jing, Y., Xu, C., Gao, L., Li, M., Liu, Y., Qi, H., 2022. Root-zone CO_2 concentration affects partitioning and assimilation of carbon in oriental melon seedlings. Int. J. Mol. Sci. 23 (18), 10694.
Hang, H., Wu, Y., 2016. Quantification of photosynthetic inorganic carbon utilisation via a bidirectional stable carbon isotope tracer. Acta Geochimica 35, 130–137.
He, Q., Shi, M., Liang, F., Xu, L., Ji, L., Yan, S., 2019a. Renewable absorbents for CO_2 capture: from biomass to nature. Greenhouse Gases: Sci. Technol. 9 (4), 637–651.
He, Q., Xi, J., Shi, M., Feng, L., Yan, S., Deng, L., 2019b. Developing a vacuum-assisted gas-permeable membrane process for rapid ammonia recovery and CO_2 capture from biogas slurry. ACS Sustain. Chem. Eng. 8 (1), 154–162.
He, Q., Xi, J., Wang, W., Meng, L., Yan, S., Zhang, Y., 2017a. CO_2 absorption using biogas slurry: recovery of absorption performance through CO_2 vacuum regeneration. Int. J. Greenh. Gas Control 58, 103–113.
He, Q., Yu, G., Tu, T., Yan, S., Zhang, Y., Zhao, S., 2017b. Closing CO_2 loop in biogas production: recycling ammonia as fertilizer. Environ. Sci. Technol. 51 (15), 8841–8850.
He, Z., Wang, J., Li, Y., 2024. Recent advances in microalgae-driven carbon capture, utilization, and storage: strain engineering through adaptive laboratory evolution and microbiome optimization. Green Carbon 3 (1), 74–99.
Hu, J., Zhao, X., Gu, L., Liu, P., Zhao, B., Zhang, J., Ren, B., 2023. The effects of high temperature, drought, and their combined stresses on the photosynthesis and senescence of summer maize. Agric. Water Manag. 289, 108525.
Huang, Y., Song, X., Wang, Y.-P., Canadell, J.G., Luo, Y., Ciais, P., Chen, A., Hong, S., Wang, Y., Tao, F., 2024. Size, distribution, and vulnerability of the global soil inorganic carbon. Science 384 (6692), 233–239.
Huber, H., Gallenberger, M., Jahn, U., Eylert, E., Berg, I.A., Kockelkorn, D., Eisenreich, W., Fuchs, G., 2008. A dicarboxylate/4-hydroxybutyrate autotrophic carbon assimilation cycle in the hyperthermophilic Archaeum Ignicoccus hospitalis. Proc. Natl. Acad. Sci. 105 (22), 7851–7856.
IEA Bioenergy, 2022. Task 37 the role of biogas and biomethane in pathway to net zero. https://task37.ieabioenergy.com/technical-reports/the-role-of-biogas/.
IEAGHG, 2024. 7th Post Combustion Capture Conference Summary. https://publications.ieaghg.org/technicalreports/2024-TR01%207th%20Post-Combustion%20Capture%20Conference%20Summary.pdf.
Jones, D.L., Nguyen, C., Finlay, R.D., 2009. Carbon Flow in the Rhizosphere: Carbon Trading at the soil–root Interface. Springer.
Karimi, M., Shirzad, M., Silva, J.A., Rodrigues, A.E., 2022. Biomass/biochar carbon materials for CO_2 capture and sequestration by cyclic adsorption processes: a review and prospects for future directions. J. CO2 Util. 57, 101890.
Keenan, T.F., Williams, C.A., 2018. The terrestrial carbon sink. Annu. Rev. Environ. Resour. 43 (1), 219–243.
Kinzel, H., 1983. Influence of limestone, silicates and soil pH on vegetation. In: Physiological Plant Ecology III. Springer, pp. 201–244.
Lan, X., Tans, P., Thoning, K.W., 2025. Trends in globally-averaged CO_2 determined from NOAA global monitoring laboratory measurements. https://doi.org/10.15138/9N0H-ZH07.
Lee, J., Woolhouse, H., 1969. A comparative study of bicarbonate inhibition of root growth in calcicole and calcifuge grasses. New Phytol. 68 (1), 1–11.
Li, A., Lv, D., Zhang, Y., Zhang, D., Zong, Y., Shi, X., Li, P., Hao, X., 2024. Elevated CO_2 concentration enhances drought resistance of soybean by regulating cell structure, cuticular wax synthesis, photosynthesis, and oxidative stress response. Plant Physiol. Biochem. 206, 108266.
Li, X., Guo, J., Pang, C., Dong, R., 2016. Anaerobic digestion and storage influence availability of plant hormones in livestock slurry. ACS Sustain. Chem. Eng. 4 (3), 719–727.
Liang, F., Cui, Q., Tu, T., Yu, G., Wang, W., Yan, S., 2018a. Benign treatment of biogas slurry and improvement in lettuce quality using hydroponics. J. Agro-Environ. Sci. 37 (4), 788–795.
Liang, F., Feng, L., Liu, N., He, Q., Ji, L., De Vrieze, J., Yan, S., 2022. An improved carbon fixation management strategy into the crop–soil ecosystem by using biomass ash as the medium. Environ. Technol. Innov. 28, 102839.
Liang, F., Shi, Z., Wei, S., Wu, L., Yan, S., 2023a. What is the appropriate content of HCO_3^- irrigated into tomato cultivation soil for enhancing its carbon fixation? Environ. Technol. Innov. 32, 102839.
Liang, F., Shi, Z., Wei, S., Yan, S., 2023b. Biogas slurry purification-lettuce growth nexus: nutrients absorption and pollutants removal. Sci. Total Environ. 890, 164383.
Liang, F., Tu, T., Yu, G., Wang, W., He, Q., Yan, S., Ran, Y., 2018b. Ecological treatment of MEA aqueous solution using a hydroponic method. Int. J. Energy a Clean Environ. (IJECE) 19 (3–4).
Liang, F., Wei, S., Ji, L., Yan, S., 2025. A potential CO_2 carrier to improve the utilization of HCO_3^- by plant-soil ecosystem for carbon sink enhancement. J. Adv. Res. 73, 43–52.
Liang, F., Wei, S., Wu, L., Yan, S., 2023c. Improving the value of CO_2 and biogas slurry in agricultural applications: a rice cultivation case. Environ. Exp. Bot. 208, 105233.
Liang, F., Wei, S., Xue, L., Yan, S., 2024. Adopting green absorbent for CO_2 capture and agricultural utilization: biogas slurry and biomass ash case. Green Carbon 2 (2), 252–261.
Liang, F., Yang, W., Xu, L., Ji, L., He, Q., Wu, L., Ran, Y., Yan, S., 2020. Closing extra CO_2 into plants for simultaneous CO_2 fixation, drought stress alleviation and nutrient absorption enhancement. J. CO2 Util. 42, 101319.
Lin, Z., Kuang, Y., Li, W., Zheng, Y., 2024. Research status and prospects of CO_2 geological sequestration technology from onshore to offshore: a review. Earth Sci. Rev., 104928
Liu, E., Lu, X., Wang, D., 2023a. A systematic review of carbon capture, utilization and storage: status, progress and challenges. Energies 16 (6), 2865.
Liu, R., Yao, Y., Li, Q., Cai, Z., Wei, D., Wang, X., Zhang, S., 2023b. Rhizosphere soil microbes benefit carbon and nitrogen sinks under long-term afforestation on the Tibetan Plateau. Catena 220, 106705.
Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, J., Qi, Y., Liang, X., 2022. Challenges and opportunities for carbon neutrality in China. Nat. Rev. Earth Environ. 3 (2), 141–155.
Lopez, R., Diaz, M.J., Gonzalez-Perez, J.A., 2018. Extra CO_2 sequestration following reutilization of biomass ash. Sci. Total Environ. 625, 1013–1020.
Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86.
Nel, J.A., Cramer, M.D., 2019. Soil microbial anaplerotic CO_2 fixation in temperate soils. Geoderma 335, 170–178.
Nolan, C.J., Field, C.B., Mach, K.J., 2021. Constraints and enablers for increasing carbon storage in the terrestrial biosphere. Nat. Rev. Earth Environ. 2 (6), 436–446.
Okoye-Chine, C.G., Otun, K., Shiba, N., Rashama, C., Ugwu, S.N., Onyeaka, H., Okeke, C. T., 2022. Conversion of carbon dioxide into fuels—A review. J. CO2 Util. 62, 102099.
Pengthamkeerati, P., Satapanajaru, T., Singchan, O., 2008. Sorption of reactive dye from aqueous solution on biomass fly ash. J. Hazard Mater. 153 (3), 1149–1156.
Piao, S., Fang, J., Ciais, P., Peylin, P., Huang, Y., Sitch, S., Wang, T., 2009. The carbon balance of terrestrial ecosystems in China. Nature 458 (7241), 1009–1013.
Poschenrieder, C., Fernández, J.A., Rubio, L., Pérez, L., Terés, J., Barceló, J., 2018. Transport and use of bicarbonate in plants: current knowledge and challenges ahead. Int. J. Mol. Sci. 19 (5), 1352.
Rao, S., Wu, Y., 2017. Root-derived bicarbonate assimilation in response to variable water deficit in Camptotheca acuminate seedlings. Photosynth. Res. 134 (1), 59–70.
Rao, S., Wu, Y., 2022. Species-specific and altitude-induced variation in karst Plants' use of soil dissolved inorganic carbon. Agronomy 12 (10), 2489.
Richardson, C., Davis, K., Ruiz-González, C., Guimond, J.A., Michael, H., Paldor, A., Moosdorf, N., Paytan, A., 2024. The impacts of climate change on coastal groundwater. Nat. Rev. Earth Environ. 5 (2), 100–119.
Scheepers, G.P., du Toit, B., 2016. Potential use of wood ash in South African forestry: a review. South. For. a J. For. Sci. 78 (4), 255–266.
Schulman, M., Parker, D., Ljungdahl, L.G., Wood, H.G., 1972. Total synthesis of acetate from CO_2 V. Determination by mass analysis of the different types of acetate formed from $^{13}CO_2$ by Heterotrophic Bacteria. bournal of Bacteriology 109 (2), 633–644.
Siegelman, R.L., Kim, E.J., Long, J.R., 2021. Porous materials for carbon dioxide separations. Nat. Mater. 20 (8), 1060–1072.

Song, L., Tao, Y., van Groenigen, K.J., Chang, S.X., Peñuelas, J., Zhang, J., You, L., Cai, C., Wang, S., Jiang, Y., 2024. Rising atmospheric carbon dioxide concentrations increase gaps of rice yields between low-and middle-to-high-income countries. Nat. Food 5 (9), 754–763.
Strauss, G., Fuchs, G., 1993. Enzymes of a novel autotrophic CO_2 fixation pathway in the phototrophic bacterium Chloroflexus aurantiacus, the 3-hydroxypropionate cycle. Eur. J. Biochem. 215 (3), 633–643.
Stukel, M.R., Irving, J.P., Kelly, T.B., Ohman, M.D., Fender, C.K., Yingling, N., 2023. Carbon sequestration by multiple biological pump pathways in a coastal upwelling biome. Nat. Commun. 14 (1), 2024.
Sun, M., Pang, K., Shao, S., Liu, D., 2025. Application, challenges, and prospects of CCUS technology in steel industry. J. Sustain. Metall. 1–18.
Terés, J., Busoms, S., Perez Martín, L., Luís-Villarroya, A., Flis, P., Álvarez-Fernández, A., Tolrà, R., Salt, D.E., Poschenrieder, C., 2019. Soil carbonate drives local adaptation in Arabidopsis thaliana. Plant Cell Environ. 42 (8), 2384–2398.
Terhoeven-Urselmans, T., Scheller, E., Raubuch, M., Ludwig, B., Joergensen, R.G., 2009. CO_2 evolution and N mineralization after biogas slurry application in the field and its yield effects on spring barley. Appl. Soil Ecol. 42 (3), 297–302.
Vaidya, P.D., Kenig, E.Y., 2007. Absorption of CO_2 into aqueous blends of alkanolamines prepared from renewable resources. Chem. Eng. Sci. 62 (24), 7344–7350.
Varling, A.S., Christensen, T.H., Bisinella, V., 2023. Life cycle assessment of alternative biogas utilisations, including carbon capture and storage or utilisation. Waste Manag. 157, 168–179.
Vinyard, D.J., Govindjee, G., 2024. Bicarbonate is a key regulator but not a substrate for O_2 evolution in Photosystem II. Photosynth. Res. 162 (1), 93–99.
Wang, H., Wang, M., Liang, X., Yuan, J., Yang, H., Wang, S., Ren, Y., Wu, H., Pan, F., Jiang, Z., 2021. Organic molecular sieve membranes for chemical separations. Chem. Soc. Rev. 50 (9), 5468–5516.
Wang, M., Wang, Y., Liu, J., Yu, H., Liu, P., Yang, Y., Sun, D., Kang, H., Wang, Y., Tang, J., 2024. Integration of advanced biotechnology for green carbon. Green Carbon.
Wang, N., Du, Y., Liang, F., Yi, J., Qian, J., Tu, W., Huang, S., Luo, P., 2023a. Protected areas effectively resisted 33.8% of urban development pressures in China during 2000–2018. Appl. Geogr. 159, 103079.
Wang, Q., Zhang, J., Dai, Q., Cui, M., Yang, H., Cao, P., Zhao, L., 2023b. When green carbon plants meet synthetic biology. Mod. Agric. 1–14.
Wang, R., Wu, Y., Xing, D., Hang, H., Xie, X., Yang, X., Zhang, K., Rao, S., 2017. Biomass production of three biofuel energy plants' use of a new carbon resource by carbonic anhydrase in simulated karst soils: mechanism and capacity. Energies 10 (9), 1370.
Wesche, J., Germán, S., Gonçalves, L., Jödicke, I., López-Asensio, S., Prades, A., Preuß, S., Algado, C.O., Dütschke, E., 2023. CCUS or no CCUS? Societal support for policy frameworks and stakeholder perceptions in France, Spain, and Poland. Greenhouse Gases: Sci. Technol. 13 (1), 48–66.
Winkler, A.J., Myneni, R.B., Alexandrov, G.A., Brovkin, V., 2019. Earth system models underestimate carbon fixation by plants in the high latitudes. Nat. Commun. 10 (1), 1–8.
Xia, A., Wu, Y., 2022. Joint interactions of carbon and nitrogen metabolism dominated by bicarbonate and nitrogen in Orychophragmus violaceus and Brassica napus under simulated karst habitats. BMC Plant Biol. 22 (1), 264.
Ye, G., Lin, Y., Kuzyakov, Y., Liu, D., Luo, J., Lindsey, S., Fan, J., Ding, W., 2019. Manure over crop residues increases soil organic matter but decreases microbial necromass relative contribution in upland ultisols: results of a 27-year field experiment. Soil Biol. Biochem. 134, 15–24.
Zhang, W., Jin, X., Tu, W., Ma, Q., Mao, M., Cui, C., 2017. Development of MEA-based CO_2 phase change absorbent. Appl. Energy 195, 316–323.
Zhao, X., Tian, P., Sun, Z., Liu, S., Wang, Q., Zeng, Z., 2022. Rhizosphere effects on soil organic carbon processes in terrestrial ecosystems: a meta-analysis. Geoderma 412, 115739.
Zhou, S., Yu, B., Zhang, Y., 2023. Global concurrent climate extremes exacerbated by anthropogenic climate change. Sci. Adv. 9 (10), eabo1638.
Zhu, C.W., Kobayashi, K., Loladze, I., Zhu, J.G., Jiang, Q., Xu, X., Liu, G., Seneweera, S., Ebi, K.L., Drewnowski, A., Fukagawa, N.K., Ziska, L.H., 2018. Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Sci. Adv. 4 (5), eaaq1012.
Zhou, R., Liu, Y., Dungait, J.A.J., Kumar, A., Wang, J., Tiemann, L.K., Zhang, F., Kuzyakov, Y., Tian, J., 2023. Microbial necromass in cropland soils: a global meta-analysis of management effects. Glob. Change Biol. 29, 1998–2014.