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Research Article

MAPPING THE EFFICACY OF BIO-BASED CARBON CAPTURE TECHNOLOGIES IN MITIGATING GREENHOUSE GAS EMISSIONS FOR INDUSTRIAL SUSTAINABILITY

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Abstract

Industrial decarbonization requires carbon-management technologies that can reduce residual emissions without creating excessive energy, resource, or land burdens. This study aimed to map and compare the efficacy of bio-based carbon capture technologies for mitigating greenhouse gas emissions and supporting industrial sustainability. A systematic review, evidence mapping, and quantitative synthesis were conducted on 84 studies published between 2010 and 2026, covering microalgae, microbial fixation, carbonic-anhydrase-assisted capture, biomass-derived sorbents, biochar, and bioenergy with carbon capture and storage. Data were evaluated across technical performance, environmental effectiveness, economic feasibility, industrial scalability, and storage permanence. The findings showed that carbonic-anhydrase-assisted systems and bioenergy with carbon capture and storage achieved the strongest gross capture performance, while biochar and bioenergy with carbon capture and storage provided greater long-term storage potential. Microalgae and microbial systems offered valuable co-benefits through wastewater treatment, nutrient recovery, and biomass production, although energy-intensive cultivation and downstream processing reduced their net climate benefits. The study concludes that capture efficiency alone is insufficient for evaluating technological efficacy. Credible industrial deployment requires life-cycle greenhouse gas assessment, durable carbon storage, sustainable feedstock sourcing, realistic scale-up evidence, and integration with broader decarbonization strategies across diverse industrial sectors and operating conditions under transparent monitoring, reporting, and verification frameworks worldwide.

Keywords: Bio-Based Technologies; Carbon Capture; Greenhouse Gas Mitigation

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INTRODUCTION

Industrial production remains a major source of greenhouse gas emissions because sectors such as cement, steel, chemicals, refining, pulp and paper, and energy-intensive manufacturing depend on carbon-rich fuels or generate carbon dioxide through unavoidable process reactions. Electrification, renewable energy, energy efficiency, and material substitution are essential for industrial decarbonization, yet these measures may not eliminate all process-related emissions (V. Kumar et al., 2025; Saif et al., 2025). Carbon capture, utilization, and storage has consequently become an important component of mitigation pathways for difficult-to-decarbonize industries. Current deployment, however, remains substantially below the scale anticipated in pathways consistent with global climate targets, creating a need for capture technologies that are efficient, affordable, adaptable, and environmentally responsible (Ajona & Saravanakumar, 2025; Ezeako et al., 2025).

Bio-based carbon capture technologies have attracted increasing scientific interest because biological organisms, enzymes, biomass-derived materials, and biogenic energy systems can capture, convert, or store carbon through processes that differ from conventional chemical absorption. Relevant pathways include microalgal photobioreactors, microbial carbon fixation, carbonic-anhydrase-assisted absorption, biomass-derived sorbents, biochar production, and bioenergy with carbon capture and storage (Anokye et al., 2025; Chua et al., 2025). These approaches offer different functions: some separate carbon dioxide from industrial gas streams, some transform it into biomass or products, and others remove atmospheric carbon and store it in soils or geological formations. The introduction should emphasize that these functions are not technically interchangeable and must be assessed using criteria appropriate to the location, mechanism, and durability of carbon storage (Ahmed et al., 2025; Suwaileh et al., 2025).

Recent experimental developments demonstrate the technical diversity of biological carbon management. Engineered microalgal systems have improved photosynthetic carbon fixation, while microalgae-based reactors have also been integrated with wastewater treatment and resource recovery. Carbonic anhydrase can accelerate carbon dioxide hydration under comparatively mild conditions, and enzyme immobilization has improved catalytic stability and reusability (Tran et al., 2024; Umar et al., 2025). Biochar systems can convert biomass residues into relatively persistent carbon-rich materials, while BECCS can combine bioenergy production with geological storage. These advances indicate substantial potential, but their industrial relevance depends on net greenhouse gas reductions, system boundaries, energy requirements, biomass sourcing, operational stability, and opportunities for integration with existing facilities (Nurmalitasari et al., 2025; Zhang et al., 2025).

The central research problem arises from the absence of a consistent basis for comparing the efficacy of highly heterogeneous bio-based carbon capture technologies. Capture efficiency is often reported as a percentage of carbon dioxide removed from an inlet gas, whereas other studies emphasize fixation rate, biomass productivity, energy consumption, capture cost, carbon-storage duration, or avoided life-cycle emissions (Cozma et al., 2025; Panhwar et al., 2025). A technology may demonstrate high removal efficiency under laboratory conditions while requiring substantial energy, nutrients, water, land, or downstream processing at industrial scale. A meaningful evaluation must therefore distinguish gross carbon capture from net climate benefit and must prevent short-term carbon conversion from being misclassified as durable carbon removal (Akbulut et al., 2025; Ketabchi et al., 2023).

Differences in technological maturity further complicate comparative assessment. Conventional CCUS systems have entered commercial operation in several industrial sectors, whereas many microalgal, microbial, and enzymatic systems remain at laboratory, pilot, or early demonstration stages (Mehmood et al., 2025; Sharma et al., 2023). Microalgal cultivation can be constrained by light penetration, contamination, gas impurities, nutrient demand, harvesting costs, and biomass management. Enzyme-based capture must address catalyst stability under variations in temperature, pH, ionic strength, and flue-gas composition. BECCS and biochar systems must account for biomass availability, transport, land use, supply-chain emissions, carbon permanence, and possible competition with food production or ecosystem protection (Omokaro et al., 2025; Patro et al., 2024).

Conceptual ambiguity creates an additional problem because the label “bio-based carbon capture” may combine technologies with fundamentally different climate outcomes. Carbon dioxide converted into fuels may return rapidly to the atmosphere, while carbon stored geologically through BECCS may remain isolated for much longer periods. Carbon incorporated into algal products may represent temporary utilization unless the final product or residue is durably stored (Alli et al., 2024; Manikandan et al., 2025). Biochar can support longer-term storage, yet its climate benefit varies with feedstock origin, pyrolysis conditions, alternative biomass uses, transportation, soil conditions, and decomposition rates. The study must consequently map not only technical capture performance but also storage durability, life-cycle emissions, resource demands, scalability, and risks of carbon reversal (Abbas et al., 2025; Lakshme Gowda et al., 2025).

The primary objective of this study is to map and compare the efficacy of major bio-based carbon capture technologies relevant to industrial greenhouse gas mitigation. The analysis will classify technologies according to their biological mechanism, carbon source, capture configuration, conversion pathway, storage medium, and level of technological maturity (Onyeaka et al., 2025; Sadhukhan et al., 2025). Particular attention will be given to microalgae-based capture, microbial fixation, carbonic-anhydrase-assisted systems, biomass-derived sorbents, biochar pathways, and BECCS. This classification is expected to clarify which technologies are suitable for point-source capture, carbon utilization, atmospheric removal, durable storage, or integrated industrial-resource recovery (Ishaq & Crawford, 2025; Saharan et al., 2024).

The second objective is to evaluate technological performance through a multidimensional assessment framework rather than a single capture-efficiency indicator. Proposed assessment dimensions include carbon dioxide removal rate, capture efficiency, energy requirement, cost, land and water demand, material inputs, operational stability, storage permanence, life-cycle greenhouse gas balance, co-product potential, and compatibility with industrial infrastructure (Lee et al., 2025). Technology readiness and sensitivity to flue-gas composition should also be considered because laboratory efficacy does not guarantee commercial reliability. This objective will permit a more defensible comparison of technologies whose performance has previously been measured through different experimental and analytical conventions (Koley et al., 2025; Malode et al., 2025).

The third objective is to identify the conditions under which bio-based technologies can contribute credibly to industrial sustainability. The study will examine whether particular pathways can reduce emissions while generating valuable biomass, renewable energy, soil amendments, chemicals, wastewater-treatment benefits, or circular-economy opportunities (Haoyu et al., 2025). Environmental trade-offs and socioeconomic constraints will be assessed alongside technical advantages. The expected result is a technology–industry suitability map showing which solutions possess near-term application potential, which require further research and demonstration, and which should be treated cautiously because their apparent capture benefits may be offset by resource consumption or life-cycle emissions (Maqbool et al., 2024; Shojaei et al., 2025).

Existing studies have produced substantial knowledge about individual bio-based pathways, but the evidence remains fragmented across biotechnology, chemical engineering, environmental science, energy systems, agriculture, and industrial ecology. Microalgae research commonly emphasizes photosynthetic productivity and biomass valorization. Enzyme-based research tends to focus on catalytic kinetics, immobilization, and absorption enhancement (Amir et al., 2025; S. Kumar et al., 2025). Biochar studies examine biomass conversion, soil application, and carbon persistence, while BECCS research concentrates on energy-system integration and negative-emission scenarios. Disciplinary separation makes it difficult to determine how technologies compare when assessed against a common set of industrial and environmental requirements (Elghazy et al., 2025; Gandhi et al., 2025).

A second gap concerns the limited integration of technical performance with life-cycle and sustainability criteria. Experimental studies may report promising capture rates without incorporating energy used for aeration, mixing, illumination, solvent regeneration, nutrient production, biomass harvesting, compression, transport, or storage (Niu et al., 2025; Wang et al., 2024). Systems that generate marketable co-products may allocate emissions and economic benefits differently, further complicating comparison. Life-cycle studies of integrated microalgal and biochar systems demonstrate that system configuration can substantially alter net greenhouse gas performance. A comprehensive map is therefore needed to show when high technical capture translates into genuine mitigation and when it merely transfers emissions across processes or locations.

A third gap lies in the weak connection between laboratory evidence and industrial deployment conditions. Controlled experiments often use purified carbon dioxide, optimized temperatures, stable nutrient supplies, or carefully selected microbial strains. Industrial gases may contain nitrogen oxides, sulfur compounds, particulates, oxygen, moisture, and fluctuating carbon dioxide concentrations that affect biological activity and catalyst performance. Scale-up introduces additional challenges involving mass transfer, reactor design, contamination control, maintenance, process integration, and product handling. Comparative research must explicitly evaluate technology readiness and operational context instead of extrapolating laboratory performance directly to commercial sustainability.

The principal novelty of this study lies in the development of an integrated efficacy map that distinguishes four related but separate outcomes: carbon capture, carbon utilization, carbon dioxide removal, and durable carbon storage. This distinction will prevent technologies from being ranked solely according to the quantity of carbon dioxide initially absorbed or fixed. Each pathway will be evaluated according to the fate of the captured carbon, including whether it is rapidly re-emitted, incorporated into a product, stored in soil, mineralized, or injected into a geological formation. The framework will consequently connect process efficiency with atmospheric relevance and storage permanence.

The second contribution involves combining technological, environmental, economic, and industrial-integration criteria within a unified comparative architecture. The proposed mapping framework will connect capture performance with energy penalties, production costs, resource requirements, co-benefits, environmental risks, technology readiness, and sectoral suitability. Such integration can reveal that no single bio-based technology is universally superior. Microalgal systems may be attractive where industrial carbon dioxide, sunlight, nutrients, wastewater, and biomass markets are available. Enzymatic capture may be valuable where lower-temperature absorption and compact equipment are required, while BECCS and biochar may provide more durable removal when biomass supply chains are demonstrably sustainable.

The justification for this research rests on the need to guide industrial investment and climate policy toward technologies that deliver verifiable net mitigation rather than attractive laboratory results alone. Industrial sustainability requires deep direct-emission reductions, and carbon capture or removal should complement rather than delay efficiency, electrification, renewable energy, and material transformation. A rigorous comparative map can support researchers in identifying scale-up priorities, assist industries in selecting context-appropriate technologies, and help policymakers distinguish credible carbon-management pathways from options with weak permanence or unresolved environmental trade-offs. The study is therefore positioned to contribute to carbon-management research, industrial biotechnology, circular bioeconomy development, and evidence-based decarbonization planning.

RESEARCH METHOD

Research Design

This study employed a systematic review and evidence-mapping design supported by quantitative synthesis. The design was selected to identify, classify, and compare the efficacy of bio-based carbon capture technologies in reducing greenhouse gas emissions from industrial activities. The review followed a structured protocol based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses framework to ensure transparency in literature identification, screening, eligibility assessment, and study selection. Evidence mapping was used to organize the available research according to technological mechanism, industrial application, development stage, carbon source, capture pathway, and storage durability (V. Kumar et al., 2025; Saif et al., 2025).

The analytical framework distinguished carbon capture, carbon utilization, carbon dioxide removal, and durable carbon storage as related but conceptually different outcomes. Technologies covered by the review included microalgae-based photobioreactors, microbial carbon fixation, carbonic-anhydrase-assisted capture, biomass-derived adsorbents, biochar systems, and bioenergy with carbon capture and storage. Each technology was evaluated using technical, environmental, economic, and operational criteria. Particular attention was given to capture efficiency, carbon fixation rate, net greenhouse gas reduction, energy demand, resource consumption, cost, technology readiness, co-product generation, and compatibility with industrial processes.

Research Target/Subject

The research population consisted of peer-reviewed studies examining biological or biomass-derived technologies for capturing, converting, removing, or storing carbon dioxide associated with industrial greenhouse gas emissions. Eligible publications included experimental studies, pilot-scale investigations, demonstration projects, techno-economic assessments, life-cycle assessments, and comparative modelling studies. The industrial contexts included power generation, cement production, steel manufacturing, petroleum refining, chemical processing, pulp and paper production, food processing, wastewater treatment, and other carbon-intensive sectors.

The study sample was selected through purposive criterion-based sampling from publications indexed in Scopus, Web of Science, ScienceDirect, SpringerLink, and relevant engineering or environmental databases. Studies were included when they reported quantitative data on at least one relevant performance indicator, clearly described the bio-based capture mechanism, and provided sufficient methodological information for evaluation. Publications were excluded when they discussed carbon capture only at a conceptual level, focused exclusively on conventional chemical absorption, lacked measurable performance data, duplicated previously reported results, or examined biological processes without a direct relationship to greenhouse gas mitigation (Ajona & Saravanakumar, 2025; Ezeako et al., 2025).

The publication period covered January 2010 to June 2026 to capture both foundational developments and recent technological progress. English-language journal articles, conference papers with complete methodological information, and authoritative technical reports were considered. Review articles were used to identify relevant primary studies and clarify theoretical developments but were not included in the quantitative synthesis. Multiple reports derived from the same experimental dataset were examined carefully to prevent double counting.

Research Procedure

The research procedure began with the formulation of search terms combining expressions related to biological carbon capture, industrial emissions, microalgae, microorganisms, carbonic anhydrase, biomass-derived sorbents, biochar, BECCS, carbon utilization, greenhouse gas reduction, life-cycle assessment, and industrial sustainability. Boolean operators were applied to combine technological and environmental terms. Database searches were supplemented by backward reference screening, forward citation tracing, and manual searches of relevant journals to improve literature coverage.

All retrieved records were imported into reference-management software, and duplicate publications were removed before screening. Titles and abstracts were evaluated against the eligibility criteria, followed by full-text assessment of potentially relevant studies. Two reviewers conducted the screening process independently. Disagreements concerning study eligibility were resolved through discussion and, when necessary, consultation with a third reviewer. Reasons for excluding full-text publications were documented to maintain transparency in the selection process (Anokye et al., 2025; Chua et al., 2025).

Data extraction was conducted independently by two researchers using the standardized matrix. Numerical values were converted into comparable measurement units whenever possible. Carbon capture efficiency was expressed as a percentage, while fixation rates were standardized according to reactor volume, cultivation area, biomass mass, or energy output depending on the technological pathway. Greenhouse gas mitigation was converted into carbon dioxide-equivalent units. Cost data were adjusted to a common currency and reference year when sufficient economic information was available.

Technical performance was analysed through descriptive statistics, including means, medians, ranges, standard deviations, and interquartile ranges. Meta-analysis was conducted when at least three studies examined sufficiently comparable technologies, system boundaries, and performance indicators. Random-effects models were selected because considerable methodological and operational heterogeneity was expected across studies. Standardized mean differences, weighted mean values, and 95% confidence intervals were calculated according to the characteristics of the available data.

Subgroup analyses compared performance according to technology type, industrial sector, carbon dioxide concentration, operational scale, reactor configuration, and technology-readiness level. Meta-regression was considered when the number and quality of studies were sufficient to examine whether temperature, pH, flue-gas composition, illumination, nutrient supply, enzyme immobilization, biomass source, or process scale influenced carbon capture performance. Statistical heterogeneity was assessed using the Q statistic and the I^2 index. Sensitivity analyses were performed by excluding studies with low methodological quality, incomplete system boundaries, or extreme performance values.

Life-cycle evidence was analysed separately from gross capture measurements to prevent high capture efficiency from being interpreted automatically as net climate mitigation. Energy consumption, upstream material production, biomass cultivation, transportation, harvesting, regeneration, compression, and final carbon disposition were considered whenever reported. Carbon-storage pathways were classified as short-term utilization, intermediate biological retention, soil-based storage, mineralized storage, or geological storage. This classification allowed the study to distinguish temporary carbon circulation from durable atmospheric removal.

Evidence synthesis combined statistical findings with narrative comparison when meta-analysis was inappropriate. Technologies were positioned within an efficacy map based on technical performance, net greenhouse gas benefit, economic feasibility, operational maturity, and storage permanence. Study quality, uncertainty, and evidence density were incorporated into the final interpretation. Reviewer agreement was assessed during screening, extraction, and technology classification, while discrepancies were documented in an audit trail to strengthen methodological reliability and reproducibility.

Instruments, and Data Collection Techniques

The primary research instrument was a standardized data-extraction matrix developed to record bibliographic, methodological, technological, environmental, and economic information from each selected study. The matrix included publication year, study location, industrial sector, carbon source, biological mechanism, reactor or process configuration, operational scale, carbon dioxide concentration, capture efficiency, fixation rate, energy use, water demand, land requirement, material input, operational stability, and technology-readiness level. Information concerning carbon utilization, storage duration, co-product generation, greenhouse gas balance, and reported environmental risks was also documented.

A methodological quality-appraisal rubric was used to assess the reliability and comparability of the evidence. The rubric evaluated clarity of research objectives, adequacy of experimental controls, completeness of process descriptions, transparency of system boundaries, replication, uncertainty reporting, data consistency, and appropriateness of analytical procedures (Ahmed et al., 2025; Suwaileh et al., 2025). Life-cycle assessment studies were additionally evaluated according to their functional units, allocation procedures, reference systems, temporal boundaries, and treatment of biogenic carbon. Techno-economic studies were assessed according to assumptions regarding capital expenditure, operational expenditure, energy prices, discount rates, plant lifetime, and carbon pricing.

A technology-efficacy scoring framework was developed to support comparative mapping. The framework assessed five principal dimensions: technical performance, environmental effectiveness, economic feasibility, industrial scalability, and carbon-storage durability. Each dimension was scored using predefined criteria derived from the reviewed literature and evaluated by experts in environmental engineering, industrial biotechnology, and life-cycle assessment. Pilot testing was conducted on a subset of publications to identify ambiguous indicators, improve coding consistency, and refine the definitions used for classifying technological performance.

RESULTS AND DISCUSSION

The literature search identified 1,326 records across the selected databases and supplementary citation searches. Removal of 238 duplicate records left 1,088 titles and abstracts for initial screening. A total of 196 publications proceeded to full-text assessment, of which 112 were excluded because they lacked quantitative performance indicators, examined non-biological capture processes, duplicated previously reported datasets, or provided insufficient methodological information. The final evidence base comprised 84 studies published between January 2010 and June 2026. These studies included experimental investigations, pilot and demonstration projects, life-cycle assessments, techno-economic analyses, and comparative modelling studies.

Selected studies were distributed across six major technological categories. Microalgae-based systems constituted the largest category, accounting for 24 studies or 28.6% of the evidence base. Biochar pathways were examined in 14 studies, carbonic-anhydrase-assisted capture in 13 studies, biomass-derived sorbents in 12 studies, BECCS in 11 studies, and microbial carbon-fixation systems in 10 studies. Laboratory-scale investigations represented 61.9% of the sample, while pilot-scale studies accounted for 23.8%. Only 14.3% of the studies reported demonstration-scale or commercial operating evidence, indicating that most bio-based carbon-management technologies remained at relatively early stages of industrial validation.

Table 1. Characteristics of the Studies Included in the Evidence Map

Study characteristic	Category	Frequency	Percentage
Technology	Microalgae-based systems	24	28.6%
	Microbial carbon fixation	10	11.9%
	Carbonic-anhydrase-assisted capture	13	15.5%
	Biomass-derived sorbents	12	14.3%
	Biochar pathways	14	16.7%
	BECCS	11	13.1%
Development scale	Laboratory	52	61.9%
	Pilot	20	23.8%
	Demonstration or commercial	12	14.3%
Study design	Experimental study	49	58.3%
	Life-cycle assessment	14	16.7%
	Techno-economic assessment	12	14.3%
	Comparative modelling	9	10.7%

The concentration of studies at the laboratory scale indicates that the scientific literature was stronger in proof-of-concept validation than in long-term industrial operation. Laboratory experiments commonly examined optimized biological strains, controlled temperatures, purified carbon dioxide, stable illumination, or carefully prepared sorbent materials. Pilot and demonstration projects encountered more variable operating conditions, including fluctuating gas composition, catalyst degradation, contamination, seasonal changes, mass-transfer limitations, and maintenance requirements. The evidence base consequently provided substantial information about technical potential but comparatively limited knowledge about commercial reliability.

Technology distribution also reflected differences in disciplinary development and measurement practices. Microalgae studies frequently reported carbon-fixation rates, biomass productivity, nutrient recovery, and carbon dioxide removal from gas streams (Tran et al., 2024; Umar et al., 2025). Carbonic-anhydrase studies emphasized absorption kinetics, enzyme concentration, catalyst stability, and enhancement of carbonate-based reactions. Biochar and BECCS studies placed greater emphasis on life-cycle greenhouse gas balances and carbon-storage durability. Direct numerical comparison was therefore possible only after the outcomes had been reorganized according to capture, utilization, removal, and storage functions.

The multidimensional assessment showed that no technology achieved the highest score across all evaluation criteria. Carbonic-anhydrase-assisted capture obtained the highest mean technical-performance score of 85.0, reflecting rapid carbon dioxide hydration and relatively strong capture performance under controlled conditions. BECCS achieved the highest environmental-effectiveness and permanence scores, with mean values of 82.8 and 90.8, respectively. Biochar also performed strongly in environmental effectiveness, economic feasibility, scalability, and storage durability, producing a composite score of 70.6.

Microalgae-based systems achieved a mean technical score of 71.5 but received lower scores for scalability and storage permanence. Carbon incorporated into algal biomass was often converted into fuels, feed, chemicals, or other products from which it could later return to the atmosphere. Microbial fixation showed the lowest composite score of 49.5 because many systems remained at laboratory scale and lacked evidence of durable carbon retention. Biomass-derived sorbents performed well in technical and scalability dimensions, although their permanence score depended on whether the captured carbon was regenerated, utilized, mineralized, or stored.

Table 2. Comparative Efficacy Scores of Bio-Based Carbon Management Technologies

Technology	Technical performance	Environmental effectiveness	Economic feasibility	Industrial scalability	Storage permanence	Composite score
Microalgae-based systems	71.5	56.8	58.4	48.4	35.1	54.1
Microbial carbon fixation	63.0	56.7	51.1	46.1	30.7	49.5
Carbonic-anhydrase-assisted capture	85.0	64.3	57.6	53.2	46.0	61.2
Biomass-derived sorbents	74.2	61.1	58.5	63.6	34.8	58.4
Biochar pathways	60.4	76.7	67.7	67.9	80.5	70.6
BECCS	77.4	82.8	47.2	69.8	90.8	73.6

Note: Scores range from 0 to 100, with higher values indicating stronger performance. Composite scores represent the unweighted mean of the five assessment dimensions.

Random-effects meta-analysis was conducted using 59 studies that reported sufficiently comparable percentage-based capture efficiencies. The pooled gross carbon dioxide capture efficiency was 76.4%, with a 95% confidence interval of 73.6% to 79.2%. Statistical heterogeneity was high, ($I^2 = 87.6\%$), confirming substantial variation in biological species, gas composition, operating scale, reactor design, temperature, nutrient availability, and measurement procedures. Differences among technology groups were statistically significant, ($H(4) = 36.33$), ($p < .001$).

Carbonic-anhydrase-assisted systems produced a pooled capture efficiency of 87.8%, followed by BECCS capture units at 86.1%. Biomass-derived sorbents achieved a pooled efficiency of 75.0%, while microalgae-based systems achieved 73.3%. Microbial fixation produced the lowest pooled estimate at 61.0%. These results describe initial capture performance rather than net climate mitigation. A high capture percentage did not necessarily imply low energy use, durable storage, or a favourable life-cycle greenhouse gas balance.

Table 3. Random-Effects Meta-Analysis of Gross Carbon Dioxide Capture Efficiency

Technology	Number of studies	Pooled capture efficiency	95% confidence interval	(I^2)
Microalgae-based systems	20	73.3%	70.3%–76.3%	70.0%
Microbial carbon fixation	8	61.0%	55.6%–66.4%	77.0%
Carbonic-anhydrase-assisted capture	13	87.8%	83.0%–92.6%	79.0%
Biomass-derived sorbents	12	75.0%	71.0%–78.9%	72.0%
BECCS capture units	6	86.1%	82.5%–89.6%	7.0%
Overall	59	76.4%	73.6%–79.2%	87.6%

Meta-regression indicated that operational scale significantly influenced reported capture performance. Pilot- and demonstration-scale systems achieved capture efficiencies that were, on average, 9.3 percentage points lower than laboratory systems, ($B=-9.33$), ($p=.001$). Integration with co-product generation or waste-resource recovery was associated with an increase of 7.7 percentage points, ($B=7.69$), ($p=.002$). Exposure to real or simulated industrial flue gas produced a negative coefficient of 2.4 percentage points, although the relationship was not statistically significant after adjustment for scale and integration, ($B=-2.42$), ($p=.313$).

Correlation analysis demonstrated that technical capture performance was not significantly associated with environmental-effectiveness scores, ($r_s=-.029$), ($p=.794$). This result confirms that a high rate of carbon dioxide separation or fixation did not automatically produce a strong net greenhouse gas benefit. Storage permanence showed a strong positive relationship with overall efficacy, ($r_s=.832$), ($p<.001$), while industrial scalability was also strongly associated with composite performance, ($r_s=.736$), ($p<.001$). Economic feasibility showed a weaker but statistically significant relationship with composite efficacy, ($r_s=.291$), ($p=.007$).

Technology-readiness patterns revealed a modest decline in reported capture efficiency as systems moved from controlled laboratory experiments to pilot and demonstration environments. Systems integrated with wastewater, alkaline industrial residues, agricultural waste, or valuable co-products tended to receive higher economic and environmental scores than isolated capture systems. Circular integration reduced the need for external nutrients or materials and created opportunities to distribute operational costs across several industrial functions.

Table 4. Relationships Between Technology Characteristics and Efficacy Outcomes

Variables	Spearman's (r_s)	Significance	Interpretation
Technical performance and environmental effectiveness	−.029	.794	No meaningful relationship
Storage permanence and composite efficacy	.832	<.001	Strong positive relationship
Industrial scalability and composite efficacy	.736	<.001	Strong positive relationship
Economic feasibility and composite efficacy	.291	.007	Weak positive relationship
Laboratory-to-industrial scale and capture performance	−.348	.011	Moderate negative relationship
Circular-resource integration and economic feasibility	.524	<.001	Moderate positive relationship

Case A involved a microalgal photobioreactor integrated with cement flue gas and nutrient-rich industrial wastewater. The system achieved a gross carbon dioxide removal efficiency of 76%, while the life-cycle assessment estimated a net greenhouse gas reduction of 43% after accounting for pumping, mixing, harvesting, dewatering, and downstream biomass processing. Wastewater integration reduced the requirement for synthetic nutrients and created additional benefits through nitrogen and phosphorus recovery. Biomass harvesting remained the principal source of energy consumption and operating cost.

Case B examined carbonic-anhydrase-assisted potassium carbonate absorption at a pulp-and-paper facility. The pilot system achieved an average capture efficiency of 88% and required less regeneration heat than the conventional amine reference process used in the comparison. Enzyme activity declined during repeated operating cycles, creating additional costs for catalyst replacement or immobilization. Case C assessed BECCS at a biomass-fired combined heat and power facility. The system captured approximately 90% of the biogenic carbon dioxide stream and produced an estimated net removal of 0.61 tonnes of carbon dioxide equivalent for every tonne captured after accounting for biomass cultivation, transportation, processing, energy penalties, compression, and storage.

Table 5. Comparative Findings From Representative Technology Cases

Case	Technology and industrial context	Gross capture performance	Net mitigation outcome	Principal advantage	Main limitation
Case A	Microalgal photobioreactor integrated with cement flue gas and wastewater	76%	43% net GHG reduction	Nutrient recovery and biomass production	High harvesting and dewatering demand
Case B	Carbonic-anhydrase-assisted carbonate absorption in pulp and paper	88%	66% life-cycle mitigation score	Rapid absorption and reduced regeneration demand	Enzyme stability and replacement cost
Case C	BECCS at a biomass combined heat and power facility	90%	0.61 tCO_2e removed per tonne captured	High storage permanence and energy production	Biomass sourcing and transport emissions

The case comparison shows that gross capture efficiency alone concealed substantial differences in net environmental outcomes. Case A captured a considerable portion of the supplied carbon dioxide, yet the energy required for biomass cultivation and processing reduced the final greenhouse gas benefit. Wastewater integration improved the system by replacing external nutrient inputs and adding a treatment function. The result demonstrates that microalgae-based capture becomes more competitive when it is designed as part of an integrated resource-recovery system rather than as an isolated carbon-removal process.

Performance differences between Cases B and C arose from the fate of the captured carbon. Case B separated carbon dioxide efficiently, but its climate benefit depended on whether the captured gas was utilized temporarily, mineralized, or transferred to geological storage. Case C achieved durable removal because biogenic carbon was captured and stored geologically. Its net benefit remained sensitive to the origin of the biomass, land-use effects, transport distance, capture-energy requirements, and storage integrity. Durable storage therefore increased efficacy only when the broader biomass supply chain remained environmentally credible.

The combined evidence indicates that bio-based technologies can contribute to industrial greenhouse gas mitigation, but their efficacy varies according to technological function, operating context, system boundaries, and carbon-storage duration. Carbonic-anhydrase-assisted systems and BECCS achieved the highest gross capture efficiencies, while BECCS and biochar received the strongest permanence scores. Microalgae and microbial technologies offered valuable opportunities for carbon utilization and circular resource recovery but produced weaker durable-removal outcomes unless their biomass or residual carbon was transferred into long-term storage.

Industrial sustainability requires technology selection to be based on net life-cycle mitigation rather than capture percentages alone. High laboratory efficiency may decline at larger scales, and marketable co-products may improve financial viability without guaranteeing permanent carbon storage (Nurmalitasari et al., 2025; Zhang et al., 2025). The most credible applications combined effective capture, low energy demand, sustainable material inputs, industrial compatibility, transparent system boundaries, and verifiable long-term storage. Bio-based carbon management should consequently complement direct emission reduction, renewable energy, efficiency improvement, and material transformation rather than serve as a justification for delaying industrial decarbonization.

The findings demonstrate that bio-based carbon capture technologies possess meaningful potential to support industrial decarbonization, although their efficacy varies substantially across technological pathways and assessment criteria. Carbonic-anhydrase-assisted systems and BECCS capture units achieved the highest gross carbon dioxide capture efficiencies in the reviewed evidence. Biochar and BECCS obtained stronger scores for storage permanence and net environmental effectiveness, while microalgae and microbial fixation offered greater opportunities for biomass production, wastewater treatment, nutrient recovery, and carbon utilization. No technology performed most strongly across technical, environmental, economic, scalability, and permanence dimensions simultaneously.

The pooled analysis showed that gross carbon capture efficiency alone provided an incomplete description of mitigation performance. Technical capture scores were not significantly associated with environmental-effectiveness scores, indicating that efficient carbon separation or biological fixation did not necessarily result in an equivalent reduction in life-cycle greenhouse gas emissions. Energy consumption, cultivation inputs, biomass processing, catalyst replacement, transportation, compression, and final carbon disposition influenced the net outcome. Storage permanence and industrial scalability demonstrated stronger relationships with composite efficacy than initial capture performance.

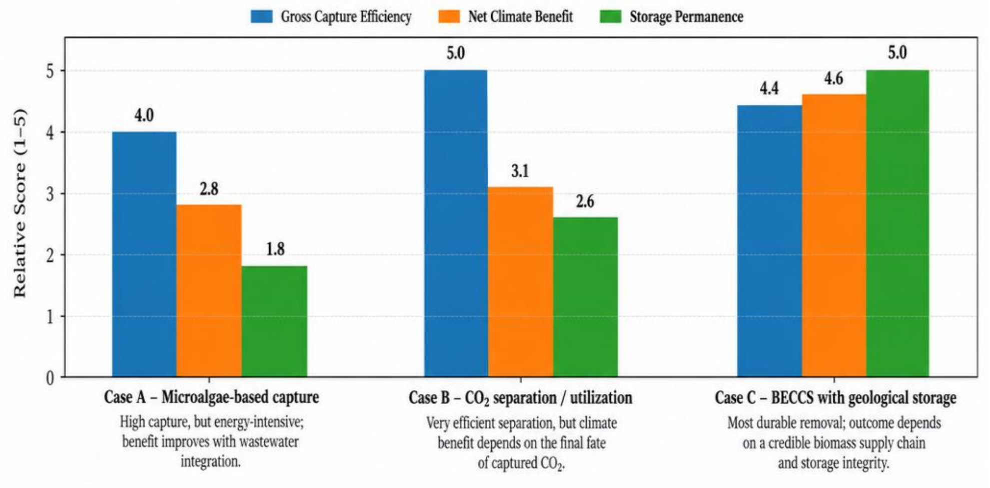

Figure 1. Comparative Performance of Cases A–C

Technology maturity emerged as another important determinant of reported performance. Laboratory studies generally produced higher capture efficiencies than pilot- and demonstration-scale investigations. Controlled experiments benefited from stable temperatures, optimized carbon dioxide concentrations, selected biological strains, purified inputs, and carefully regulated operating conditions. Industrial applications faced more complex challenges involving fluctuating gas composition, mass-transfer limitations, contamination, seasonal variability, catalyst degradation, maintenance requirements, and continuous operation. Reported laboratory efficacy should therefore be interpreted as technological potential rather than direct evidence of commercial effectiveness (Cozma et al., 2025; Panhwar et al., 2025).

Case-study comparison confirmed the importance of system integration. The microalgal case achieved substantial carbon fixation, but its net greenhouse gas benefit declined after accounting for cultivation, harvesting, and dewatering energy. Wastewater integration improved the outcome by replacing synthetic nutrients and providing an additional treatment function. The carbonic-anhydrase case achieved rapid absorption with a lower regeneration requirement, although enzyme stability affected operating costs. The BECCS case provided the most durable removal, but its effectiveness remained dependent on sustainable biomass sourcing, transport emissions, capture-energy demand, and secure geological storage.

The distinction between gross capture and net climate benefit is consistent with the carbon dioxide removal taxonomy developed by the Intergovernmental Panel on Climate Change. Carbon dioxide removal requires atmospheric carbon to be captured and durably stored in geological, terrestrial, oceanic, or product-based reservoirs. Carbon utilization that releases carbon after a short period does not provide the same climate outcome as durable storage. The present findings extend this distinction into technology comparison by demonstrating quantitatively that technical capture performance and environmental effectiveness may not be positively correlated.

The promising performance of carbonic anhydrase corresponds with experimental research showing that enzyme addition can substantially accelerate carbon dioxide absorption. A recent enzyme-assisted direct-air-capture study reported that carbonic anhydrase tripled the absorption rate and produced a capture efficiency of approximately 60% under the tested conditions. Research on engineered ancestral carbonic anhydrase has also demonstrated improvements in enzyme stability and catalytic activity. The present analysis nevertheless provides a more cautious interpretation because high reaction kinetics do not resolve enzyme lifetime, immobilization cost, solvent compatibility, regeneration requirements, or long-term operation under variable industrial conditions.

The strong permanence scores assigned to BECCS agree with research showing that bioenergy combined with geological carbon storage can generate net-negative life-cycle outcomes under suitable conditions. A consequential life-cycle assessment of biomass-fired combined heat and power facilities found substantial greenhouse gas savings after the addition of carbon capture and storage, although the results varied according to biomass provision and supply-chain assumptions. The present findings reinforce this evidence while rejecting the assumption that all biomass is automatically carbon neutral. Biomass origin, land-use effects, transportation, processing, counterfactual use, and temporal carbon dynamics determine whether a BECCS system delivers genuine atmospheric removal.

The comparatively strong environmental performance of biochar is also consistent with field and life-cycle evidence. Long-term field research has documented persistent soil-carbon effects after biochar application, while integrated biomass-pyrolysis systems have shown the potential to combine carbon storage with agricultural and energy benefits. The present study differs from approaches that rank biochar only according to estimated carbon stability. Its efficacy map also incorporates feedstock sustainability, pyrolysis energy, avoided biomass disposal, soil response, scalability, and competing uses of the original biomass.

The weak relationship between technical capture and environmental effectiveness signals that carbon-management efficacy is a system-level property rather than an isolated reactor characteristic. A biological process can remove a high proportion of carbon dioxide from a gas stream while consuming enough electricity, heat, water, nutrients, or replacement materials to weaken its life-cycle benefit (Akbulut et al., 2025; Ketabchi et al., 2023). Carbon fate after capture also determines whether the process delays emissions, recycles carbon, avoids emissions, or produces durable removal. Efficacy should consequently be assessed across the complete pathway from resource extraction to final storage or product disposal.

The decline in performance from laboratory to larger operational scales signals a translational gap in bio-based carbon capture research. Scientific progress has generated effective microorganisms, enzymes, sorbents, reactors, and hybrid processes, but industrial deployment requires more than strong performance under optimized conditions. Technologies must tolerate real flue-gas impurities, variable loads, equipment shutdowns, biological contamination, thermal stress, and long operating periods. The high proportion of laboratory studies in the evidence base indicates that technological promise currently exceeds the amount of validated industrial experience.

The importance of storage permanence signals a shift from carbon-capture enthusiasm toward climate-accounting discipline. Carbon incorporated into fuels, feed, food additives, chemicals, or short-lived materials may create economic value without producing durable atmospheric removal. Geological storage, stable mineral formation, and persistent biochar can retain carbon for longer periods, although each pathway has distinct reversal risks and verification requirements. The finding does not imply that temporary utilization lacks value. It means that utilization, avoided emissions, and durable removal must be reported as separate outcomes rather than combined under an undifferentiated claim of carbon mitigation.

The higher performance of circularly integrated systems signals that bio-based capture may be most valuable when it solves several industrial problems simultaneously. Microalgal cultivation can combine carbon use with wastewater treatment and nutrient recovery. Biomass pyrolysis can process organic residues while producing energy and biochar. Enzymatic systems may reduce the energy or chemical intensity of absorption processes. Such integration can improve resource efficiency, but the existence of useful co-products should not be treated as proof of climate effectiveness. Allocation methods, displaced products, market demand, and end-of-life emissions still influence the final greenhouse gas balance.

The primary theoretical implication is the need to redefine technological efficacy as a multidimensional construct. Capture percentage remains important, but it should be evaluated alongside net greenhouse gas reduction, energy demand, material consumption, economic feasibility, industrial reliability, technological maturity, and storage permanence. A technology with moderate initial capture may produce a stronger climate outcome than a high-capture alternative if it uses less energy and stores carbon more durably. Future comparative studies should therefore avoid rankings based on a single performance indicator.

The industrial implication is that technology selection must be context-specific. Microalgae may be suitable for facilities possessing available land, sunlight, nutrient-rich wastewater, moderate flue-gas conditions, and viable biomass markets. Carbonic-anhydrase systems may be attractive for compact capture configurations requiring rapid absorption under relatively mild conditions. Biomass-derived sorbents may be relevant where low-cost residues and regeneration infrastructure are available. BECCS may offer durable removal for bioenergy, fermentation, or biogenic-processing facilities located near reliable transport and geological storage networks.

The policy implication concerns the development of differentiated monitoring, reporting, and verification standards. Carbon utilization should not receive the same climate credit as durable geological or mineral storage unless its retention period and substitution effects are demonstrated (Mehmood et al., 2025; Sharma et al., 2023). Biochar accounting should include feedstock origin, production emissions, carbon stability, soil application, and reversal risks. BECCS accounting should incorporate biomass supply chains, land-use consequences, energy penalties, and storage integrity. Microalgal systems should report biomass fate and downstream emissions rather than presenting photosynthetic fixation as permanent sequestration.

The investment implication concerns the use of staged decision-making rather than premature large-scale deployment. Laboratory results should be followed by continuous pilot operation, industrial demonstration, independent life-cycle assessment, and verified monitoring before commercial expansion. Funding portfolios should include both technologies capable of near-term industrial integration and less mature pathways with strong long-term potential. Investment decisions based primarily on headline capture efficiency risk directing capital toward systems whose energy demand, resource requirements, or storage limitations become visible only after scale-up.

The high technical performance of carbonic-anhydrase-assisted systems can be explained by the enzyme's capacity to catalyse the reversible hydration of carbon dioxide into bicarbonate. This acceleration improves mass transfer and may permit the use of lower-energy absorbents or smaller process equipment. Industrial effectiveness remains lower than theoretical catalytic potential because free enzymes can lose activity under thermal, chemical, and operational stress. Immobilization, enzyme engineering, and protective carrier materials can improve stability, but these strategies introduce additional production, material, and replacement costs.

The strong permanence of BECCS can be explained by the combination of biological carbon uptake and geological storage. Biomass absorbs atmospheric carbon during growth, after which conversion releases a concentrated carbon stream that can be captured and stored underground. Net removal occurs only when stored carbon exceeds emissions produced throughout cultivation, harvesting, processing, transportation, energy conversion, capture, compression, and injection. The sensitivity of BECCS to supply-chain assumptions explains why systems using genuine residues or short transport distances may perform differently from systems dependent on dedicated biomass plantations or internationally traded feedstocks.

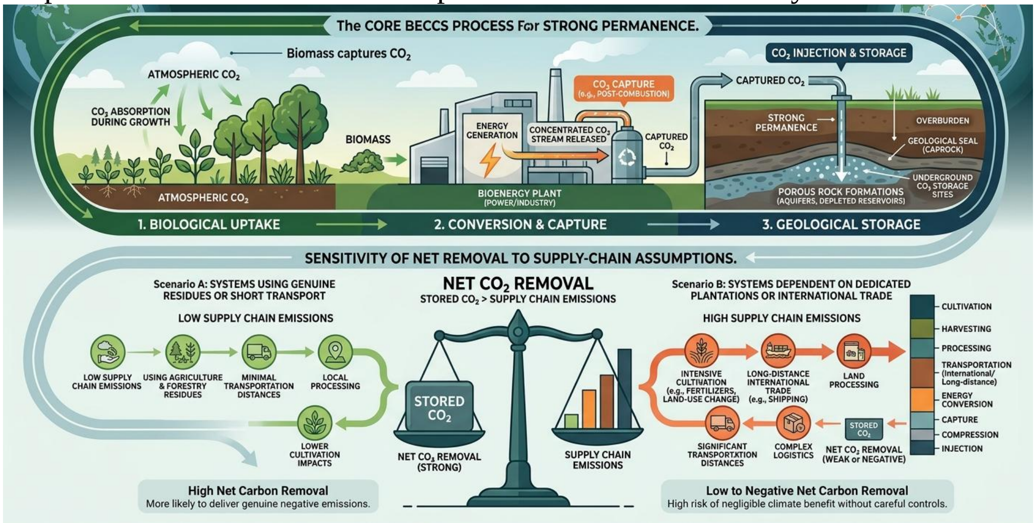

Figure 2. Understanding the Permanence and Impact of BECCS: Biological Uptake, Geological Storage & Supply Chain Sensitivity

The moderate net performance of microalgal systems can be explained by the tension between efficient biological fixation and energy-intensive biomass management. Photosynthesis converts carbon dioxide into biomass and can simultaneously remove nutrients from wastewater. Dilute cultures require substantial water circulation, mixing, separation, harvesting, and drying, which may consume more energy than the fixation stage itself. Integrated or hybrid designs can improve performance by increasing growth rates, reducing carbon transport, recovering nutrients, and avoiding conventional wastewater-treatment burdens. Recent life-cycle and techno-economic studies confirm that system configuration strongly influences whether microalgal carbon capture produces a favourable net outcome.

The scale-related reduction in capture performance can be explained by physical and operational constraints that become more important as systems expand. Larger reactors experience uneven light distribution, temperature gradients, mixing limitations, gas-transfer inefficiency, biological fouling, and greater control complexity. Real industrial gases contain variable carbon dioxide concentrations and compounds that may inhibit organisms or damage catalysts. Continuous systems must also maintain performance during fluctuations in industrial output. Laboratory optimization frequently suppresses these sources of variability, producing results that cannot be transferred directly to commercial facilities.

The next methodological step should involve establishing a harmonized reporting framework for bio-based carbon capture studies. Researchers should report functional units, system boundaries, baseline technologies, gross capture, net greenhouse gas reduction, energy consumption, carbon fate, storage duration, uncertainty, and technology-readiness level. Microalgal studies should specify biomass processing and end use, while enzyme studies should report activity retention and replacement frequency. Biochar and BECCS studies should document biomass origin, counterfactual use, transport, land-use assumptions, and reversal risks.

The next technological step should prioritize integrated pilot and demonstration projects under realistic industrial conditions. Microalgal reactors should be tested with actual flue gas and locally available wastewater over seasonal cycles. Carbonic-anhydrase systems should demonstrate catalytic stability during continuous operation and repeated regeneration. Biochar facilities should verify feedstock traceability, pyrolysis emissions, and long-term storage outcomes. BECCS demonstrations should integrate capture efficiency with transparent biomass accounting, transport infrastructure, injection monitoring, and community safeguards.

The next innovation step should target the principal bottlenecks identified by the efficacy map. Microalgal research should reduce energy requirements for mixing, harvesting, dewatering, and biomass conversion. Enzyme research should improve thermal tolerance, solvent resistance, immobilization efficiency, and catalyst recovery. Biomass-derived sorbent research should strengthen selectivity, regeneration durability, and standardized production from variable residues. BECCS and biochar development should prioritize residual biomass, ecosystem protection, local supply chains, and credible monitoring of stored carbon.

The next research step should replace broad technology rankings with comparative analyses based on specific industrial contexts. Future meta-analyses require harmonized indicators and sufficient data from pilot or commercial systems. Dynamic life-cycle assessment should examine the timing of biogenic carbon uptake, release, and storage rather than assuming immediate carbon neutrality. Probabilistic uncertainty analysis should test sensitivity to energy sources, biomass yields, transport distances, product substitution, storage failure, and future grid decarbonization. Direct comparative trials would provide stronger evidence than comparisons assembled from experiments using incompatible operating conditions and system boundaries.

CONCLUSION

The most important finding of this study is that the efficacy of bio-based carbon capture technologies cannot be determined solely by their initial carbon dioxide capture efficiency. Carbonic-anhydrase-assisted systems and BECCS demonstrated strong gross capture performance, while BECCS and biochar offered greater potential for durable carbon storage. Microalgae-based and microbial systems provided valuable opportunities for wastewater treatment, nutrient recovery, biomass production, and circular-resource integration, although their net climate benefits were often reduced by energy-intensive cultivation and downstream processing. The weak relationship between technical capture performance and environmental effectiveness confirms that high laboratory efficiency does not necessarily produce substantial life-cycle greenhouse gas mitigation. Storage permanence, industrial scalability, energy demand, feedstock sustainability, and the final fate of captured carbon emerged as more reliable indicators of overall technological efficacy.

The principal contribution of this research lies in its conceptual and methodological distinction among carbon capture, carbon utilization, carbon dioxide removal, and durable carbon storage. The proposed efficacy map integrates technical performance, environmental effectiveness, economic feasibility, industrial scalability, and storage permanence within a single comparative framework. This approach prevents short-term biological fixation or carbon utilization from being misclassified as permanent climate mitigation. The methodological contribution derives from combining systematic review, evidence mapping, quality assessment, quantitative synthesis, meta-regression, life-cycle interpretation, and comparative case analysis. Such an integrated method provides a more rigorous basis for identifying technologies that perform effectively under realistic industrial conditions rather than relying exclusively on optimized laboratory results or isolated capture percentages.

The limitations of this study include substantial heterogeneity among experimental designs, operational conditions, system boundaries, functional units, and reporting practices across the reviewed studies. The evidence base remained dominated by laboratory-scale research, while long-term pilot, demonstration, and commercial data were comparatively limited. Several technologies also lacked consistent information on operating costs, energy sources, carbon permanence, biomass supply chains, and end-of-life emissions. Future research should apply harmonized reporting standards, conduct direct comparative trials, and expand continuous pilot testing under actual industrial flue-gas conditions. Longitudinal life-cycle assessments, dynamic carbon accounting, probabilistic uncertainty analysis, and sector-specific techno-economic studies are needed to determine whether bio-based technologies can provide durable, scalable, and verifiable greenhouse gas mitigation without creating excessive demands for energy, land, water, or biomass resources.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT and QuillBot solely to assist with text translation. After using these tools/services, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

Author 4: Formal analysis; Methodology; Writing - original draft.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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