Carbon dioxide removal: technologies, MRV and carbon markets, a reliability-first review

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Abstract

Carbon dioxide removal (CDR) is increasingly treated as a necessary complement to rapid emissions reduction, yet the term is often applied to activities that capture concentrated carbon dioxide, avoid emissions, or store carbon only temporarily. This review examines CDR as an end-to-end system comprising atmospheric capture, transport and storage, life-cycle emissions, measurement, reporting and verification (MRV), and the carbon-market claim. It compares land-based biological removal, bioenergy with carbon capture and storage, direct air capture with storage, biochar, enhanced rock weathering, ocean alkalinity enhancement, and mineralization pathways. The central synthesis is that nominal capture capacity is not equivalent to a verified carbon dioxide removal credit: a credible claim must demonstrate a counterfactual baseline, additionality, net atmospheric removal, storage durability, monitoring adequacy, safeguards and controlled issuance. A mass-balance formulation is presented for net removal, and a closed-loop MRV architecture is proposed in which uncertainty, leakage, reversal risk and ecological monitoring continuously feed back into issuance decisions. The review also compares voluntary markets, compliance-oriented frameworks and emerging certification approaches, including the EU Carbon Removals and Carbon Farming Regulation. The analysis finds that CDR pathways differ more in measurement burden, permanence and externality profile than in headline removal potential. Durable engineered and mineral pathways offer stronger permanence claims but face energy, material, permitting and cost barriers; biological pathways can scale more rapidly but carry substantial reversal, land-use and monitoring risks. Carbon markets can help finance deployment, but should be treated as a mechanism for rewarding verified climate outcomes rather than as proof that a project is climate-positive. The paper concludes with a decision framework for project developers, buyers, verifiers and regulators.

Keywords: carbon dioxide removal; negative emissions; measurement, reporting and verification; permanence; additionality; carbon markets; life-cycle assessment; climate integrity

1. Introduction

Limiting warming requires deep and sustained reductions in greenhouse-gas emissions. CDR has a narrower role: it removes carbon dioxide from the atmosphere and stores it durably in geological, terrestrial, oceanic reservoirs or products. The IPCC therefore treats CDR as complementary to mitigation, not as a substitute for avoiding emissions [1]. This distinction is material because a tonne of carbon dioxide captured from a concentrated industrial stream is not automatically a tonne removed from the atmosphere, and a tonne of gross biogenic uptake is not automatically a tonne of net durable removal.

The CDR field spans technologies with very different carbon reservoirs, time scales, energy requirements and environmental risks. Reforestation and soil-carbon enhancement operate through biological cycles; biochar converts biomass carbon into a more persistent solid; bioenergy with carbon capture and storage (BECCS) combines biological uptake with engineered capture; direct air capture with geological storage (DACCS) uses chemical separation from dilute ambient air; enhanced weathering and ocean alkalinity enhancement accelerate geochemical pathways; and mineralization converts carbon dioxide into stable carbonate minerals. Comparing these approaches using a single cost or potential number can conceal decisive differences in additionality, reversibility, land competition, water demand, ecological disturbance and verification confidence [2–6].

The market dimension adds a second layer of complexity. Carbon credits are accounting instruments representing quantified climate claims under a defined standard; they are not physical containers of carbon. The credibility of a credit depends on the rules used to define the baseline, quantify net removal, manage uncertainty, allocate responsibility for reversals, prevent double counting and disclose the claim. The EU CRCF Regulation, for example, establishes a voluntary certification framework based on quality criteria and monitoring requirements, while voluntary-market initiatives increasingly distinguish durable removal from avoidance and short-lived storage [7–9].

This review addresses three linked questions: (i) what are the principal CDR technology families and their engineering bottlenecks; (ii) how should MRV convert a physical intervention into a conservative net-removal estimate; and (iii) under what conditions can carbon markets finance CDR without weakening climate integrity? The review adopts a reliability-first lens and contributes an integrated comparison, a net-removal equation, a closed-loop MRV architecture and a market-integrity ladder.

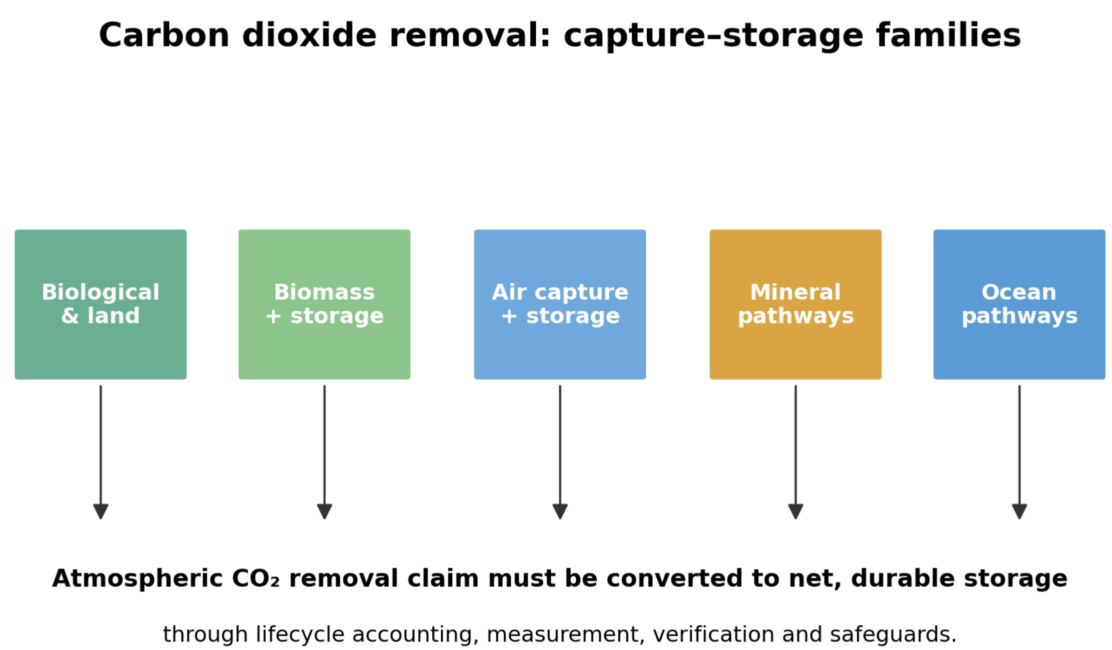

Figure 1. Carbon dioxide removal technology families and the requirement to convert capture potential into net, durable storage

Figure 1 is intentionally organized around the storage outcome rather than the capture device. This avoids a common category error in which the presence of a capture process is taken as evidence of atmospheric removal. The same device can produce a removal, an avoided emission, or no climate benefit depending on the carbon source, counterfactual, energy supply and storage fate.

2. Review approach and evidence boundaries

The review was structured using the carbon-capture review prompt located in Google Drive, adapted from a JECE-style review workflow. The scope was defined before synthesis around CDR technologies, MRV, carbon-market integrity and implementation. Evidence was prioritized from the IPCC, the State of CDR assessment, peer-reviewed studies, official regulatory texts and recognized carbon-integrity bodies. Technology claims were retained only when their system boundary and storage pathway could be identified. Project-specific performance numbers were not generalized across technologies.

A quantitative meta-analysis was not attempted because the literature combines unlike functional units, system boundaries, storage durations, energy systems, geographical conditions and maturity levels. Instead, the paper uses structured comparative synthesis and decision-relevant metrics. Values in the comparison tables are qualitative maturity judgements unless explicitly labelled as a range or scenario. This is important because a cost estimate based on a first-of-a-kind plant, a modelled future plant and an avoided-emission project cannot be pooled as if they were observations of one variable.

Table 1. Evidence architecture used in this review. The approach is evidence mapping rather than pooled-effect meta-analysis.

Evidence question	Preferred evidence	Interpretive rule
Definition and role of CDR	IPCC assessment and expert reports	CDR must remove atmospheric CO_2 and store it durably; capture alone is insufficient.
Technology performance	Peer-reviewed LCA, process and field studies	Report system boundary, functional unit, storage fate and uncertainty.
MRV and crediting	Methodologies, standards, verification rules	Separate monitoring feasibility from demonstrated net removal.
Market and policy	Official regulation and integrity frameworks	Treat certification as a governance process, not a scientific measurement.
Environmental and social effects	Field evidence, impact assessment and safeguards	Do not infer co-benefits from the carbon claim alone.

The review follows a structured evidence selection process to ensure that each aspect of carbon dioxide removal is evaluated using the most appropriate and reliable sources rather than relying on isolated findings. Table 1 presents the evidence architecture adopted in this study, illustrating how different evidence types support the assessment of technologies, MRV practices, market frameworks, and environmental safeguards.

3. What counts as carbon dioxide removal?

3.1 A process definition

A CDR activity has four necessary elements: atmospheric origin, human intervention, durable storage and net climate benefit. Atmospheric origin means that the carbon removed is ultimately drawn from ambient air through biological uptake, direct air capture or accelerated natural chemistry. Human intervention means that the removal would not occur in the claimed form without the project. Durable storage means that the carbon remains outside the atmosphere for a stated period appropriate to the claim. Net climate benefit requires deduction of emissions caused by materials, energy, transport, land-use change, processing, monitoring and end-of-life events.

The following distinction is useful: capture is a physical operation; removal is a climate-system outcome; a credit is a verified accounting claim. A project can capture biogenic CO_2 from a fermentation stream but deliver no removal if the gas would otherwise have been released and the storage system later leaks. Conversely, a project may remove atmospheric CO_2 through enhanced weathering without ever isolating a concentrated gas stream. The term "negative emissions" should therefore be reserved for net system-level removal, not gross uptake or gross capture.

3.2 Permanence and durability

Durability is not binary. Geological storage is generally described as long-duration storage when site characterization, injection integrity and monitoring support retention over centuries to millennia. Mineral carbonates are also potentially highly durable, although reaction completion and lifecycle emissions must be demonstrated. Terrestrial and biomass-based storage is vulnerable to fire, drought, pests, harvest, land-use change and management reversal. Ocean storage may be long-lived in chemical form but requires careful treatment of equilibration time, transport, ecological effects and attribution.

A robust crediting system should disclose both the expected storage duration and the mechanism for handling reversal. Possible tools include temporary crediting, pooled buffer reserves, insurance, replacement obligations, discounting, or liability carried by the project operator or buyer. None is a substitute for monitoring; a buffer can distribute risk but cannot measure an unobserved reversal.

4. Technology families and engineering bottlenecks

4.1 Land-based biological removal

Afforestation, reforestation, agroforestry, improved forest management, soil-carbon management and wetland restoration remove carbon through photosynthesis and allocation to biomass or soil pools. They are comparatively deployable because they use existing land-management systems and can deliver biodiversity, water, soil and livelihood benefits when well designed. Their limitations are equally fundamental: carbon stocks are spatially heterogeneous, additionality is difficult where practices are already profitable or legally required, and storage is exposed to climate and land-use disturbance.

MRV generally combines remote sensing, field plots, biomass allometry, soil sampling, activity records and models. The key question is not whether vegetation is present but whether the project caused an incremental stock increase relative to a credible counterfactual and whether that increase persists. Sampling intensity and model uncertainty should be reflected in issuance, especially where a project claim changes smaller than the uncertainty of the stock estimate.

4.2 Biochar

Biochar converts biomass through pyrolysis or gasification into a carbon-rich solid that can be applied to soils or placed in durable products. The climate outcome depends on feedstock sustainability, avoided alternative uses, pyrolysis energy, char-carbon stability, application fate and methane or nitrous-oxide effects. The carbon content of a char is not itself the removals quantity. A defensible calculation requires a stable-carbon fraction, a defined storage period, lifecycle deductions and evidence that biomass procurement does not displace another carbon sink.

Biochar has an important MRV advantage: production batches can be weighed, sampled and chemically characterized. However, permanence after soil application remains context-dependent. Standards therefore need clear rules for feedstock eligibility, contamination, hydrogen-to-carbon ratio or equivalent stability indicators, application records, chain of custody and end-use monitoring. The EU's emerging certification work illustrates the movement toward pathway-specific requirements rather than one generic "biochar credit" [7].

4.3 BECCS

BECCS couples biomass uptake with capture and geological storage. In principle, it can deliver durable removal while producing electricity, heat, fuels or materials. In practice, its performance is governed by biomass supply, land-use change, transport, capture energy penalty, CO_2 conditioning, storage integrity and the counterfactual use of the biomass. Large-scale deployment can generate pressure on land, food systems, water and biodiversity, and the "negative" result can disappear when indirect effects are included.

The most decision-relevant BECCS metric is not capture rate at the plant but net tonnes removed per tonne of sustainable biomass under a stated system boundary. MRV must connect feedstock origin, carbon content, process emissions, capture flow, transport, injection and storage monitoring. Co-produced energy and materials also require allocation rules that prevent the same climate benefit being counted twice.

4.4 Direct air capture with storage

DACCS separates CO_2 from ambient air using solid sorbents, liquid solvents or related process configurations, followed by compression and permanent storage. Its conceptual strength is source independence: the carbon is atmospheric and the plant can be located near low-carbon energy and storage. Its central barriers are the low concentration of CO_2 in air, energy demand, sorbent or solvent degradation, water requirements, capital intensity, siting and the need for verified storage.

DACCS is unusually amenable to process measurement because airflow, CO_2 concentration, regeneration energy, product flow and injection can be instrumented. That does not eliminate uncertainty: electricity carbon intensity, upstream material production, heat source, plant degradation and storage leakage remain material. A plant with high capture efficiency can still have low or negative net removal if powered by carbon-intensive energy or if captured CO_2 is used in a short-lived product.

4.5 Enhanced rock weathering and mineral pathways

Enhanced rock weathering accelerates the reaction of silicate minerals with atmospheric or soil CO_2, producing dissolved bicarbonate and ultimately carbonate alkalinity. Mineralisation can also react concentrated or atmospheric CO_2 with alkaline solids to form stable carbonates. These pathways offer potentially durable storage and may provide soil or industrial co-benefits, but reaction rates, transport, trace contaminants, alkalinity fate and lifecycle emissions are highly site-dependent.

Measurement is challenging because the removal signal is distributed across solid, soil-water and aquatic carbon pools. Suitable MRV may combine mineral mass balances, mineralogy, alkalinity and dissolved inorganic carbon measurements, cation tracers, soil and water sampling, geochemical models and conservative uncertainty discounts. The WAE material in the user's Drive correctly highlights that theoretical stoichiometric capacity is not verified removal: unreacted mineral, secondary precipitation and upstream emissions must be deducted.

4.6 Ocean alkalinity enhancement and marine CDR

Ocean alkalinity enhancement adds alkalinity to seawater so that more atmospheric CO_2 can enter the ocean carbonate system as bicarbonate and carbonate. Related approaches include electrochemical processing, mineral dissolution and alkalinity generation from industrial streams. The theoretical reservoir is large, but the field is early-stage and requires evidence on mixing, equilibration, residence time, pH perturbations, trace contaminants, ecological effects and attribution against natural variability.

Marine CDR should not be credited from alkalinity addition alone. The project must demonstrate where the additional carbon is, when it entered the ocean, how much would have entered without the intervention, and whether the intervention produced unacceptable local effects. A receiving-water monitoring plan should include pH, alkalinity, dissolved inorganic carbon, pCO_2, oxygen, temperature, salinity, nutrients and relevant contaminants, with spatial and temporal sampling designed around the plume and background variability.

Table 2. Comparative technology map. The maturity and MRV descriptions are directional judgements; they should not be read as universal performance rankings.

Pathway	Primary storage	Main strength	Dominant failure mode	MRV burden
Afforestation / soil	Biomass and soil	Near-term deploy ability and co-benefits	Fire, drought, land-use reversal	High spatial sampling and permanence monitoring
Biochar	Stable solid carbon	Batch traceability and product options	Unstable fraction, feedstock displacement	Moderate–high; chemistry plus chain of custody
BECCS	Geological storage	Potential energy plus durable removal	Unsustainable biomass or lifecycle emissions	High; biomass-to-injection chain
DACCS	Geological storage	Atmospheric source and	Energy/material intensity	High but

		process control		instrument-rich
Enhanced weathering	Dissolved inorganic carbon / carbonate	Potential durability and land co-benefits	Slow kinetics, contaminants, attribution	Very high; distributed geochemistry
Ocean alkalinity	Ocean bicarbonate/carbonat e	Large theoretical sink	Mixing, ecological effects, permanence attribution	Very high; ocean observation and models
Mineralization	Carbonate minerals	Potentially very durable	Energy and mineral supply	High; mass balance and reaction completion

The comparison highlights that carbon dioxide removal pathways differ not only in how carbon is stored but also in the level of technical complexity and verification required to demonstrate long-term climate benefits. Table 2 summarizes these differences by comparing storage mechanisms, key strengths, potential limitations, and the corresponding MRV requirements across the major CDR technologies.

5. Net-removal accounting and MRV

5.1 A conservative accounting equation

A project-level net-removal estimate can be represented as:

Net CDR = Gross atmospheric carbon stored − project and supply-chain emissions − leakage and displacement − reversal adjustment − uncertainty deduction − non-CO_2 climate effects.

In a more explicit notation, for a monitoring period t:

$N_t = G_t - E_t - L_t - R_t - U_t - H_t$

where G is the increment in atmospheric carbon stored, E includes energy, material, transport and construction emissions, L covers leakage or displaced sinks, R is expected or realised reversal, U is a conservative uncertainty deduction, and H captures material non-CO_2 effects expressed in the chosen accounting metric. The equation is a bookkeeping structure, not a universal methodology. Each term must be operationalised for the pathway and justified with measurements or conservative defaults.

5.2 MRV as a closed-loop control system

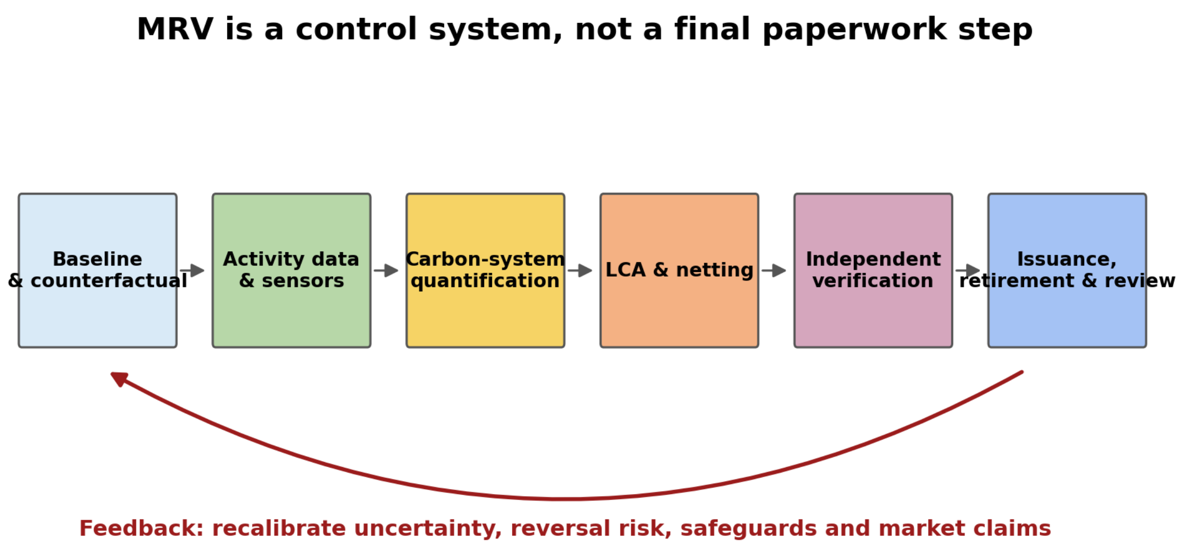

Figure 2. Closed-loop MRV architecture linking baseline, activity data, carbon-system quantification, lifecycle netting, verification and issuance control

Figure 2 shows why MRV should be designed before commercial operation. Baseline design determines what counts as additional; sensors determine whether the activity occurred; carbon-system measurements determine the storage signal; lifecycle accounting determines whether the result is net; and verification determines whether the evidence is sufficiently reliable for issuance. The loop must remain active after issuance because reversals, sensor drift, feedstock changes and regulatory decisions can alter the claim.

5.3 Baseline and additionality

The baseline is the best-supported estimate of what would have happened without the project. Additionality is the claim that the removal is caused by the project and would not have occurred at the credited scale under the baseline. Financial tests, regulatory tests, common-practice tests and barrier analyses can provide evidence, but none alone proves atmospheric removal. A project that is legally required to operate, already profitable without carbon income, or already implemented before crediting may fail additionality even if it stores carbon.

Baseline uncertainty is often asymmetric. Over-crediting creates a climate liability, whereas under-crediting reduces revenue but does not create a false removal claim. Conservative baselines should therefore be preferred where counterfactual uncertainty is large. Baseline assumptions should be version-controlled and revisited when policy, prices, land use, energy supply or operating practice changes.

5.4 Measurement and data quality

A decision-grade MRV plan specifies the variable, instrument, calibration frequency, sampling location, temporal resolution, detection limit, quality-control rule, missing-data treatment and responsible owner. Typical measurements include biomass plots and remote sensing; feedstock mass, moisture and carbon content; electricity and heat consumption; CO_2 flow and purity; injection pressure and plume behaviour; mineral dissolution; alkalinity and dissolved inorganic carbon; and ecological indicators.

- Calibrate instruments against traceable standards and retain calibration certificates.
- Keep raw data, transformations, rejected observations and imputation decisions in an immutable audit trail.
- Use independent duplicate samples and laboratory blanks where chemical measurements determine credits.
- Define stop-work thresholds for pH excursions, contamination, abnormal mass balance, sensor drift or storage anomalies.
- Propagate measurement error through the net-removal calculation rather than reporting only a point estimate.

5.5 Uncertainty, leakage and reversals

Uncertainty should be reported as a range or distribution, not hidden in a generic discount. Correlated uncertainty matters: flow-meter error and concentration error may jointly affect a mass balance; model error and sampling error may not be independent; and an uncertain baseline can dominate a precise activity measurement. A conservative issuance quantity can be expressed as the lower confidence bound of N_t, subject to methodology-specific rules.

Leakage includes displaced biomass use, indirect land-use change, market-mediated effects and emissions outside the project boundary that are causally linked to the intervention. Reversal is a loss of previously stored carbon. Both are different from measurement error: an uncertain measurement can be improved with data, whereas a reversal is a physical change requiring replacement, buffer or cancellation action.

6. Carbon markets and claim integrity

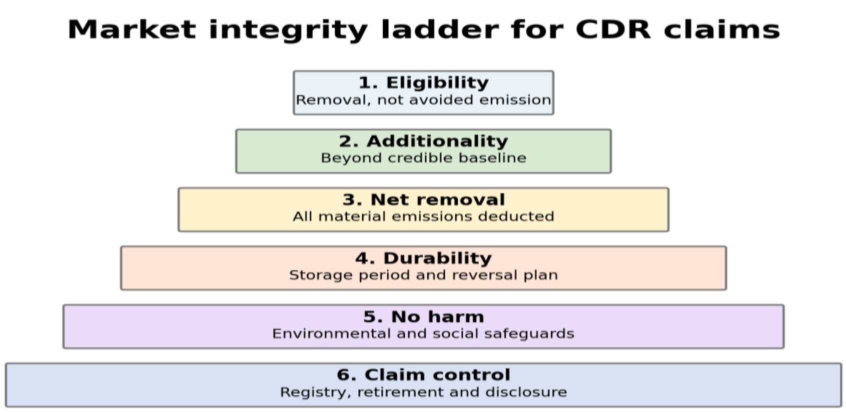

Figure 3. A market-integrity ladder for translating a measured intervention into a defensible CDR claim

The market-integrity ladder in Figure 3 reflects the minimum sequence a buyer should expect. Eligibility comes first; a project should not use a removal label for an avoided-emission activity. Additionality and net accounting follow. Durability determines the appropriate claim period and liability arrangement. Safeguards address harms that cannot be represented by a carbon tonne. Finally, registry issuance, retirement and disclosure prevent multiple parties from claiming the same outcome.

6.1 Voluntary and compliance contexts

Voluntary carbon markets generally connect project developers and buyers through standards, registries, independent validation and verification, and contractual claims. Their flexibility can support innovation, but methodologies vary and buyers may compare non-equivalent units. Compliance systems operate under legal caps or obligations and may impose more prescriptive eligibility, monitoring and accounting rules. The same physical project can have different market eligibility depending on national authorisation, corresponding adjustments, NDC accounting and rules against double claiming.

The EU CRCF Regulation provides an important policy development by creating a voluntary EU-wide certification framework for permanent removals, carbon farming and carbon storage in products [7]. Its significance is institutional: it establishes common quality and monitoring criteria, but certification does not remove the need for project-specific measurement, lifecycle assessment, safeguards and transparent claims. Developers should not describe certification as a guarantee of additionality or permanence beyond the applicable methodology.

6.2 Additionality, double counting and claims

A carbon-market claim should state who owns the removal, which registry issued the unit, whether the unit has been retired, the storage duration, whether national accounting adjustments apply, and what the buyer is claiming. Double counting can occur as double issuance, double use, double claiming or double representation across inventories and markets. These risks are especially important for removals because governments, project developers, buyers and product labels may all seek to attribute the same tonne.

A high-integrity buyer should ask for a pathway-specific methodology, a public monitoring report, verifier scope and competence, uncertainty treatment, reversal policy, feedstock or land safeguards, storage evidence and retirement record. A low price is not automatically evidence of poor quality, but a high price is not evidence of quality. Quality is a property of the evidence and governance chain.

Table 3. Minimum evidence for a credible CDR market claim. The table is intended as a practical screening tool, not a substitute for a registry methodology.

Integrity criterion	Minimum evidence	Common weak claim	Recommended control
Atmospheric origin	Carbon-source and counterfactual analysis	"Captured CO_2 equals removal"	Define source, baseline and storage fate
Net accounting	Energy, materials, transport and process emissions	Gross tonnes reported as net	Publish a transparent lifecycle boundary
Additionality	Regulatory, financial and common-practice evidence	Project would happen anyway	Use conservative tests and periodic reassessment
Durability	Storage mechanism, duration and monitoring	"Permanent" without liability plan	State duration and reversal remedy
MRV quality	Raw data, calibration, uncertainty and QA/QC	Annual totals without raw traceability	Digital audit trail and independent verification
Safeguards	Environmental and social risk assessment	Co-benefits assumed from technology label	No-harm thresholds and grievance mechanism
Claim control	Registry, retirement and disclosure	Multiple claims by seller and	Unique serialisation and claim

		buyer	language

Establishing confidence in carbon removal projects requires consistent evidence that extends beyond reported removal quantities and includes transparent monitoring, verification, and governance practices. Table 3 outlines the essential evidence needed to support credible CDR claims while identifying common weaknesses and the controls that can improve claim integrity.

7. Comparative synthesis: what can be scaled and trusted?

The technology comparison reveals a recurring trade-off. Pathways with relatively accessible deployment forestry, soil carbon and some biochar systems often have distributed carbon stocks, higher reversal exposure and greater baseline dependence. Pathways with more durable storage—DACCS, BECCS with geological storage and mineralization offer clearer storage endpoints but require more energy, infrastructure, materials and permitting. Ocean and weathering pathways may have large theoretical potential, yet their MRV and ecological evidence are still developing.

This trade-off does not justify a single universal ranking. A project should be selected against the decision context: available low-carbon energy, sustainable feedstock or mineral supply, storage geology, water and land constraints, monitoring capability, regulatory permissions, local ecological sensitivity and the buyer's required durability. A technology with a lower modelled cost can be the worse project if its baseline uncertainty, reversal exposure or lifecycle emissions are poorly controlled.

Current CDR deployment is also far below the scale implied by climate pathways. The 2026 State of CDR assessment reports total removal of approximately 2.2 $GtCO_2$ per year, dominated by conventional land-based activities, while novel CDR remains a very small fraction of the total [10]. This headline total should not be mistaken for the volume of durable, registry-ready, novel removal. The relevant gap for markets is the gap between verified durable removals and the much larger future requirement, not simply the difference between all biological uptake and future scenarios.

Table 4. Decision-oriented comparison of CDR families. "High" or "moderate" describes evidence and governance burden, not climate value by itself.

Decision dimension	Land / biological	Biochar / BECCS	DACCS / mineral	Ocean / alkalinity
Atmospheric attribution	Moderate; baseline-sensitive	Moderate–high with traceable feedstock	High at capture point	Low–moderate until field attribution improves
Durability	Variable; often reversible	Moderate to high, pathway-specific	High if geological storage is verified	Potentially high but fate is system-dependent
Energy/material burden	Low–moderate operationally	Moderate; feedstock and heat matter	High today; electricity and heat critical	Variable; minerals/electrochemistry can be material
MRV complexity	High spatial and temporal variability	Moderate–high; batch plus end use	High but instrument-rich	Very high; ocean background and models
Main governance risk	Land rights, leakage, reversal	Feedstock displacement and char fate	Energy lock-in, storage liability	Ecological effects and public consent

Most appropriate near-term use	Carefully governed land restoration	Traceable waste-residue systems	Demonstration with low-carbon energy	Research and tightly monitored pilots

No single carbon dioxide removal pathway is suitable for every application because technical feasibility, durability, monitoring effort, and governance requirements vary considerably across project settings. Table 4 provides a decision-oriented comparison of the major CDR families, helping readers understand the practical trade-offs that influence technology selection and implementation.

8. Implementation framework for developers and buyers

8.1 Project development gates

- Gate 1—Define the claim: removal, avoided emission, storage product or process benefit. Do not combine them without separate accounting.
- Gate 2—Prove the pathway: identify carbon source, storage reservoir, expected duration, boundary and counterfactual.
- Gate 3—Test feasibility: energy, materials, land, water, storage, permitting, logistics, local stakeholders and ecological risks.
- Gate 4—Design MRV before operation: sensors, sampling, calibration, QA/QC, uncertainty, data governance and verification access.
- Gate 5—Run a pilot: demonstrate mass balance, operating stability, environmental thresholds and data completeness.
- Gate 6—Register and verify: use an appropriate standard, disclose limitations and issue conservatively.
- Gate 7—Manage the credit: retirement, claims, reversal response, monitoring after issuance and public reporting.

8.2 India-facing considerations

For Indian developers, the project should be screened simultaneously against the environmental approval pathway, consent conditions, land and water permissions, national carbon-market rules, potential Article 6 accounting and voluntary-market requirements. The wastewater alkalinity material in the user's Drive provides a useful practical lesson: where a domestic methodology is not yet approved, carbon revenue should be treated as upside and the pilot should be justified by a genuine operational or environmental benefit. This principle generalizes to emerging CDR pathways: the project should remain technically and economically meaningful if credit issuance is delayed.

A practical Indian CDR pilot should therefore secure a host site, define the primary non-carbon value, establish baseline water/soil/land/energy conditions, assess local contaminants and ecological thresholds, identify the relevant registry or certification route, and obtain independent review of the net-removal equation. Feedstock and mineral sourcing should include traceability and testing for contaminants. The project should not make a domestic offset claim merely because an international standard accepts a similar pathway elsewhere.

8.3 Economic interpretation

CDR economics are highly sensitive to first-of-a-kind capital, energy price, storage distance, feedstock cost, financing, MRV frequency, verification fees, credit price and revenue from co-products or services. A carbon price alone cannot determine viability because the credit may be issued years after expenditure and may be discounted for uncertainty or durability. Developers should model at least three cases—no credit revenue, conservative credit revenue and upside credit revenue—and include a stop condition when measured net removal or environmental performance falls below the agreed threshold.

9. Research gaps and future agenda

The next phase of CDR research should move from technology advocacy toward comparable evidence. First, pathway-specific MRV must be tested in field conditions, including missing data, sensor drift, seasonal variation and operational change. Second, lifecycle assessments should use transparent, harmonized boundaries while preserving site-specific evidence. Third, durability should be represented in claims and procurement contracts rather than reduced to a single adjective. Fourth, environmental and social safeguards need the same evidentiary status as carbon accounting. Fifth, registries and governments should align project records, national inventories and corporate claims so that a verified tonne is not claimed multiple times.

For ocean, alkalinity and weathering pathways, the most urgent gap is not another theoretical potential estimate but field evidence on attribution, equilibration, ecological effects and uncertainty. For biological CDR, the priority is improved counterfactuals, permanence monitoring and land-use safeguards. For DACCS and BECCS, the priority is low-carbon energy, durable storage, supply-chain emissions and transparent process data. For biochar, the priority is end-use stability and feedstock displacement. Across all pathways, open data and independent replication would improve market confidence more effectively than promotional deployment numbers.

10. Conclusions

CDR should be understood as a chain from atmospheric capture to durable storage and verified climate claim. The chain fails if any material link is missing. Gross capture, biomass uptake, alkalinity addition, mineral dosing or carbon-rich product formation can all be scientifically meaningful without qualifying as net atmospheric removal. A credible CDR unit therefore requires an explicit baseline, additionality evidence, lifecycle netting, storage-duration statement, uncertainty treatment, reversal management, safeguards and controlled claims.

The technology landscape contains no universally superior pathway. Biological methods offer near-term deployment and co-benefits but require strong land, baseline and permanence governance. Biochar and BECCS can provide more traceable or durable storage under specific conditions, but feedstock and lifecycle effects are decisive. DACCS and mineral pathways may support high-durability claims but remain constrained by energy, materials, infrastructure and cost. Ocean and alkalinity approaches require cautious, monitored field development before large-scale crediting.

Carbon markets can accelerate learning and deployment when they reward measured, net and durable outcomes. They become harmful when a credit label substitutes for evidence or allows removal claims to delay emissions reduction. The recommended decision rule is simple: treat carbon revenue as payment for verified climate performance, not as the justification for an unproven intervention. A reliability-first MRV loop provides the practical bridge between CDR science, engineering deployment and credible carbon markets.

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Author's note on evidence status

This is an original, detailed review-paper draft prepared from authoritative sources and the user-supplied Google Drive review workflow. It is suitable for technical development, internal review and journal-specific refinement. Before submission, the author should run a final reference audit against the target journal database, update the literature search date, confirm every DOI and regulatory status, and replace any pathway-specific qualitative judgement with a documented extraction table if a systematic review protocol is required.