



Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET 6 DELIVERED BY ISMC, UNIOVI, PAS, LURTEK, ICAMCYL

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR): ARTIFICIAL SOILS

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, **European leaders endorsed the objective of achieving a climate-neutral Europe (EU) by 2050**. This followed the commitments made by all European member states that ratified the Paris Agreement in 2015 (United Nations Framework Convention on Climate Change [UNFCCC], 2016). The Agreement is a legally binding international treaty that sets long-term goals to guide all nations to substantially reduce greenhouse gas (GHG) emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, recognizing that this would significantly **reduce the risks and impacts of climate change**.

The European Climate Law (European Parliament & Council, 2021) proposed in 2020, as a part of the European Green Deal (European Commission, 2019), the strategy through which to achieve EU climate neutrality by 2050. It legally binds the EU to reduce net greenhouse gas (GHG) emissions. It establishes an intermediate milestone, requiring a reduction in net greenhouse gas emissions of at least 55% by 2030 compared with 1990 levels. To adopt these ambitious climate goals, particularly with its proposed 90% net GHG reduction target for 2040, the implementation of **technologies, practices, and approaches for actively carbon dioxide removal (CDR) and durably store existing carbon dioxide from the atmosphere and drastically cutting emissions** by switching to renewables and improving energy efficiency. Combining emission reductions with carbon removal is essential because cutting emissions alone is not enough to reverse current atmospheric CO₂ levels, to

meet 2050 net-zero and net-negative emission goals.

CDR is primarily needed to offset emissions from hard-to-decarbonize sectors (like cement, aviation, heavy industry) that cannot be eliminated entirely, and to counter declining natural carbon sinks, making **CDR a climate necessity and strategic opportunity for jobs and innovation**, supported by EU policies like the Carbon Removal Certification Framework (CRCF).

This involves developing strategies for both land-based (forests, agriculture) and industrial (Direct Air Capture, Bioenergy with CCS) methods, setting up certification frameworks like the EU's Carbon Removals Regulation, and creating incentives through mechanisms like the EU Emissions Trading System (ETS) to scale up CDR as a vital economic opportunity and strategic necessity. The EU ETS is a cornerstone of the Union's climate policy and constitutes its key tool for reducing greenhouse gas emissions in a cost-effective way.

The C-SINK project funded by Horizon Europe aims to establish the foundations to build a standardized and transparent European CDR market to contribute to the implementation of climate change mitigation measurements through the responsible employment of CDR technologies, by complementing existing EU and international mitigation efforts with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

CDR technologies is an umbrella term for techniques that can be used to capture



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carbon dioxide (CO₂) from the atmosphere and store durably in geological, terrestrial, or ocean reservoirs, or in products with varying CO₂ storage durations from decades to millennia (Brunner et al., 2024, Intergovernmental Panel on Climate Change [IPCC], 2018).

CDR technologies are divided into Nature-Based Solutions, Engineered Solutions and Hybrid Solutions:

- Nature-Based Solutions leverage natural processes, such as afforestation /reforestation (planting trees) and soil carbon sequestration, to absorb and store CO₂.
- Engineered Solutions use advanced technologies and chemical processes, such as Direct Air Capture (DAC) and carbon mineralization, to remove and durably store CO₂.
- Hybrid Solutions combine aspects of both, often using natural systems to capture the CO₂ (e.g., biomass) and engineered processes to ensure more durable storage.

Nature-based solutions stand out as more cost-effective and viable in the short run, while some technological alternatives have potential to become more relevant later this century. The European Commission recognises the crucial role of CDR and intends to focus on nature-based options.

Examples of CDR include:

- Afforestation/reforestation: transforming non-forested areas into woodland by planting trees to capture and store CO₂.
- Soil carbon sequestration: natural process where plants convert CO₂ from the air into organic matter through photosynthesis, that gets stored in the soil as stable organic carbon when litter is incorporated into soil.
- Peatland restoration: rewetting and revegetation of degraded peatlands can capture CO₂, with CO₂ stored in soils.

- Biochar: a charcoal-like substance created from plant matter which can store carbon; it can be used on agricultural land (with benefits for the soil and crop yields), or in products.
- Enhanced rock weathering: crushed silicate rock such as basalt can be spread on agricultural land (with benefits for the soil and crop yields) to capture and store CO₂.
- Bioenergy with Carbon Capture and Storage (BECCS): biomass (purpose-grown crops or agricultural/forestry residues) captures CO₂ from the atmosphere as it grows; when the biomass is burned to generate electricity or heat, CO₂ is captured and stored.
- Direct Air Carbon Capture and Storage (DACCS): captures CO₂ from the atmosphere using industrial chemical processes and stores it durably in geological storage or products.
- Marine-based techniques such as ocean alkalisation and coastal wetland management: there are a variety of methods that use geochemical or biological capture, and various forms of storage. A subset of CDR methods such as BECCS and DACCS make use of Carbon Capture and Storage (CCS) technologies to deliver net negative emissions (that is, to reduce overall levels of carbon dioxide in the atmosphere) but it is important to note that applying CCS technologies to emissions from fossil fuels can never result in carbon dioxide removal from the atmosphere. Therefore, the terms CDR and CCS are not interchangeable.

ARTIFICIAL SOILS

Natural soils retain and remove atmospheric CO₂ through the interaction of the soil-plant system, which plants absorb CO₂ from the atmosphere and convert it into organic matter when plant material decomposes, some of this carbon is incorporated into the soil as soil organic carbon (SOC) and other via is the hydrological/hydrogeological systems as inorganic C (bicarbonate in solution or carbonate minerals) (Beerling et

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al., 2020). Globally, it was recognized the significance of using soil processes to remove atmospheric CO₂ (Renforth et al., 2011), given that soil represents a carbon pool of up to 2,700 Gt in the top meter of soil globally, in the world's soils which is twice that of the atmosphere (730 Gt C) (Lal, 2003).

According to estimates from Sanderman et al. (2017) for the year 2010, the global SOC stocks were 1,824 Pg C in the upper 1 m of soil, and the global SIC stock was estimated at approximately 750 Pg in the top 1 m (Batjes, 1996) and more than 2300 Pg in the top 2 m (Le Quéré et al., 2016, Zamanian et al., 2021, Huang et al., 2021), which is similar to the organic carbon stocks found in the top 2 m of soil ~ 2400 Pg (Batjes, 1996). The potential of soils to store soil carbon and therefore its persistence in soils is the result of functional complexity arising from the interplay between spatial and temporal variation in molecular diversity and composition (Lehmann et al., 2020). The removal process of carbon from the biological carbon cycle involves two processes: carbonation (i.e. the formation of pedogenic carbonate minerals in soils) and enhanced rock weathering (ERW).

In the context of carbon removal captured in soil in organic and inorganic form, artificial soils designed with two purposes **carbon capture and recycling waste**.

Artificial soils are engineered soils created by combining selected organic and inorganic waste materials to produce a functional and healthy soil. The specific composition varies according to local resource availability and the desired physic-chemical properties. Typical components may include manure, sewage sludge, pruning residues, sawdust, biomass combustion ashes, paper mill sludge, food waste, and construction and demolition waste (CDW).

The final mixture is carefully designed to meet soil health criteria such as appropriate pH, nutrient availability, structure, and

texture. Artificial soils can be used for a range of purposes, including the regeneration of areas where soil has been degraded or lost, land decontamination, biomass production and green infrastructure (Deeb et al., 2020).

Artificial soils are classified as Technosols because they contain more than 20% human-made materials by volume within the upper 100 cm of the soil profile (Schad, 2015). Technosols encompass a broad range of soil types, from mine tailings and construction waste fills to land surfaces covered by geomembranes. While many Technosols are initially of low quality due to their origin, they can be purposefully engineered to address environmental challenges and significantly enhance soil health (Figure 1).



Figure 1. Diagram with examples of parent materials for artificial soil formulation

CURRENT STATE OF ARTIFICIAL SOILS AS CDR TECHNOLOGY

Artificial soils are currently situated largely in the research and development (R&D) stage, particularly with respect to their role as a carbon dioxide removal (CDR) option. While artificial soils are well established in land reclamation, urban landscaping, and brownfield restoration, their systematic design, monitoring, and optimisation for long-term carbon sequestration and stable ecosystem service delivery remain under active research.

At this stage, stability and predictability of policy and financial support are critical.



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Artificial soils require long-term experimentation to understand carbon accumulation rates, stabilization mechanisms (e.g. mineral-associated organic carbon formation), and interactions between physical structure, microbial activity, and vegetation. These processes unfold over years to decades, meaning that short funding cycles risk interrupting experiments before meaningful conclusions can be drawn. If R&D funding is withdrawn prematurely, artificial soil development risks becoming stranded before reaching demonstrable maturity or scalability.

Artificial soils also involve significant uncertainty regarding performance, as outcomes depend strongly on local materials (e.g. mine waste, construction residues, organic inputs), climate, and management practices. As a result, risk mitigation and risk absorption by public actors are essential, particularly where private actors have limited incentives to invest in uncertain, long-horizon soil-based CDR outcomes. Artificial soils still require upfront investment in site preparation, materials, monitoring, and long-term verification, with delayed and uncertain returns.

Beyond direct financial support, the deployment of artificial soils as a carbon dioxide removal (CDR) pathway requires enabling policy instruments and a stable regulatory environment to stimulate early-stage demand. This includes the formal inclusion of artificial soils within CDR research frameworks, land restoration and remediation policies, and soil carbon accounting and monitoring programmes. Explicit policy recognition of artificial soils as a credible CDR option would reduce institutional uncertainty, improve investment confidence, and accelerate technological development during the pre-commercial phase.

Artificial soils are currently transitioning into a demonstration phase, where pilot projects move from controlled research settings to

real-world applications, such as degraded land reclamation, mining sites, infrastructure corridors, and urban environments. At this stage, considerations of scale become increasingly important; however, capital deployment remains high-risk due to persistent uncertainties related to long-term carbon stability, permanence, and the robustness and standardisation of monitoring, reporting, and verification (MRV) protocols.

Demonstration projects typically involve hectare-scale deployments, integration of heterogeneous waste streams, and testing of monitoring, reporting, and verification (MRV) approaches under operational conditions. These projects are essential to bridge the gap between laboratory-scale understanding and broader deployment, yet they often lack immediate revenue streams, making them highly dependent on continued public support.

Political and social support are particularly important at this stage. Artificial soils often rely on the reuse of secondary materials (e.g. mine waste, construction residues, organic by-products), which can raise regulatory, public perception, and social acceptance challenges. Strong institutional backing can help ensure continuity of incentive mechanisms, facilitate permitting, and encourage early adopters such as municipalities, landowners, and industrial site operators.

Demonstration-stage support should therefore prioritise pilot funding, risk-sharing instruments, and public procurement, as well as visibility and learning effects. Successful demonstration projects can help reduce uncertainty, build trust among stakeholders, and establish credible performance benchmarks that are necessary for progression toward maturity.

In the mature stage, artificial soils would be deployed at scale as a recognised and reliable CDR and land management option, with scale becoming the dominant



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imperative. At this point, artificial soils would demonstrate predictable carbon sequestration performance, robust MRV methodologies, and co-benefits such as soil restoration, biodiversity enhancement, and reduced waste disposal.

For maturity to be reached, revenue streams must be sufficient to sustain deployment, including the costs of construction, maintenance, and long-term monitoring. Revenues could be drawn from a mix of public and private sources, land restoration funding, infrastructure development budgets, and circular economy incentives tied to waste valorisation. As deployment scales up, efficiency gains and learning effects should reduce per-unit costs, improving competitiveness relative to alternative CDR options.

Cost-effectiveness becomes increasingly important at this stage, given the potentially large land areas involved. Support mechanisms should therefore prioritise artificial soil applications while also accounting for additional benefits (e.g. remediation of degraded land, reduced erosion, enhanced ecosystem services) and potential trade-offs (e.g. material transport emissions or land-use conflicts).

Despite maturity, stability remains a core requirement. Incentive mechanisms must be durable, predictable, and capable of operating over multi-decadal timescales, reflecting the long-term nature of soil carbon storage. Over time, support should transition toward self-sustaining approaches, where artificial soils are integrated into standard land management, infrastructure, and restoration practices, rather than relying solely on direct government subsidies.

ARTIFICIAL PILOT DEVELOPED WITHIN THE C-SINK PROJECT

A field pilot trial with artificial soil was carried out at Pasek mine within the framework of C-sink project. The purpose of

this trial was to collect data to evaluate CDR with this technology by itself and when it is combined with EW and biochar. Six plots of 300 m² were implemented at David’s Mine from Pasek Minerale, in Landoi, Cariño, Spain (Figures 2 and 3).



Figure 2 Aerial view of the pilot in February 2025 (4 artificial soil plots, 1 control where fertilizer was applied and trees and grasses were planted, and other second control plot that was unplanted).



Figure 3 pictures that compare artificial soil plot (without amendments) with control



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plot (where fertilizer was applied) in February 2025.

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