CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

ARTIFICIAL SOILS (AF)

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, leaders of the European Union agreed on an ambitious goal: to make Europe climate-neutral by 2050. This means balancing the greenhouse gases we emit with actions that remove carbon dioxide from the atmosphere. This commitment builds on the promises made by EU countries when they signed the Paris Agreement in 2015, a global agreement to limit global warming to well below 2°C and ideally to 1.5°C above pre-industrial levels to reduce the worst impacts of climate change
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To turn this vision into law, the EU introduced the European Climate Law in 2020 as part of the European Green Deal. This law legally commits the EU to climate neutrality by 2050 and sets a clear milestone for 2030: cutting net greenhouse gas emissions by at least 55% compared with 1990 levels. Looking ahead, the EU has also proposed an even more ambitious target, a 90% reduction by 2040 ((EU) 2021/1119, 2025).

Reaching these goals will require more than just reducing emissions. Although switching to renewable energy and improving energy efficiency are essential, they are not enough on their own. Some sectors—such as aviation, cement, and chemicals and steel industry—are very difficult to fully decarbonize. That is why carbon dioxide removal (CDR) is becoming increasingly important. It involves actively removing carbon dioxide from the air and storing it safely and durably, helping to balance remaining emissions and reduce the overall amount of CO_2 in the atmosphere.

Carbon removal is also needed because natural carbon sinks, like forests and soils, are becoming less effective due to climate change and land-use pressures. When combined with strong emissions reductions, CDR can help the EU reach net-zero. Beyond its climate benefits, CDR also presents opportunities for innovation, new industries, and job creation.

The EU is developing policies to support both nature-based solutions, such as tree planting and climate-friendly farming, and industrial technologies, including direct air capture and bioenergy with carbon capture and storage. To ensure trust and environmental integrity, the EU is setting up clear rules and certification systems for carbon removal, including the Carbon Removals and Carbon Farming (CRCF) Regulation (EU 2024/3012).

Economic incentives also play a key role. The EU Emissions Trading System (ETS), the EU's main tool for reducing emissions cost-effectively—can help create demand for verified carbon removals and encourage investment in these solutions.

Within this context, the C-SINK project, funded by Horizon Europe, aims to help build the foundations for a transparent and reliable European carbon removal market. The project focuses on developing trustworthy methods to measure, report, and verify carbon removal, ensuring that CDR contributes responsibly and effectively to Europe's climate goals while complementing existing EU and international efforts.

CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

CDR is a general term for ways to take carbon dioxide (CO_2) out of the air and store it safely for a long time. The captured carbon can be stored underground in rock formations, in soils and plants, in the ocean, or in products that keep the carbon locked away for decades, centuries, or even longer.

CDR approaches fall into three main groups:

Nature-based solutions
These approaches use natural processes to absorb and store carbon.

- Planting trees (afforestation and

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reforestation) helps capture CO_2 as trees grow.

- Soil carbon storage improves farming and land-management practices so soils can hold more carbon.
- Peatland restoration involves rewetting damaged peatlands so they can store large amounts of carbon in the soil.

Engineered solutions

These rely on technology and industrial processes to remove carbon from the air.

- Direct Air Capture (DAC) uses machines and chemicals to pull CO_2 directly from the atmosphere.
- Carbon mineralisation locks CO_2 into solid rock so it cannot return to the air.

Hybrid solutions

These combine natural and technological approaches.

- Bioenergy with Carbon Capture and Storage (BECCS) uses plants to absorb CO_2 as they grow. When the plants are used to produce energy, the released CO_2 is captured and stored underground.
- Biochar is a charcoal-like material made from plant waste that stores carbon and can improve soil health when added to farmland.

Nature-based solutions are currently the most affordable and ready-to-use options, making them especially important in the near term. More advanced technological solutions are still developing but could play a bigger role later in the century. For this reason, the European Commission sees carbon removal as essential and is placing strong emphasis on nature-based approaches.

Other examples of carbon removal include:

- Enhanced rock weathering, where crushed rocks are spread on farmland to absorb CO_2 while also improving soil quality.
- Marine-based approaches, such as restoring coastal wetlands or adjusting ocean chemistry, which use natural ocean processes to capture and store carbon.

Some carbon removal methods, such as BECCS and Direct Air Carbon Capture and Storage (DACCS), use carbon capture and storage (CCS) technology to permanently store CO_2. These methods can lead to net negative emissions, meaning they reduce the overall amount of carbon dioxide in the atmosphere.

However, it is important to understand that CCS used on fossil fuel emissions only reduces emissions it does not remove carbon already in the atmosphere. For this reason, carbon capture and storage (CCS) and carbon dioxide removal (CDR) are related but not the same, and the terms should not be used interchangeably.

ARTIFICIAL SOILS

Soils play an important role in removing carbon dioxide (CO_2) from the air. Plants absorb CO_2 through photosynthesis, and some of that carbon ends up stored in soils. In addition, water moving through soil and underground systems can transform CO_2 into inorganic forms, such as dissolved carbon or solid minerals, which can remain stored for very long periods.

Soils are one of the largest carbon sinks on Earth. They hold about twice as much carbon as the atmosphere, making them a powerful but often overlooked part of the climate system. By contrast, when carbon is converted into inorganic forms, such as carbonate minerals, it can be locked away for much longer. This happens through natural processes like the formation of carbon-rich minerals in soils and through methods such as enhanced rock weathering, where crushed rocks help capture and store CO_2.

To strengthen carbon storage in soils, scientists are also developing artificial soils. These are specially designed soils created to both capture carbon and reuse waste materials. Artificial soils are made by carefully mixing organic and mineral wastes to create healthy, functioning soil. Depending on local needs and available materials, they can include items such as manure, food waste, plant trimmings, sawdust, ashes from biomass, sewage sludge, paper waste, or recycled construction materials.

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These materials are blended to achieve good soil quality, including the right balance of nutrients, structure, and acidity. Artificial soils can be used to restore damaged land, clean up polluted areas, and improve soil fertility. They can be added into existing soils to improve their functions e.g. water retention.

Because artificial soils contain a large share of human-made materials, they are classified as Technosols. This category includes many types of soils influenced by human activity, such as mine waste or construction fills and are designed for recycling waste materials (Figure 1).
Using engineered soils can help store carbon on land for long periods via soil-plant system offering a promising way to tackle CDR while reducing waste at the same time.

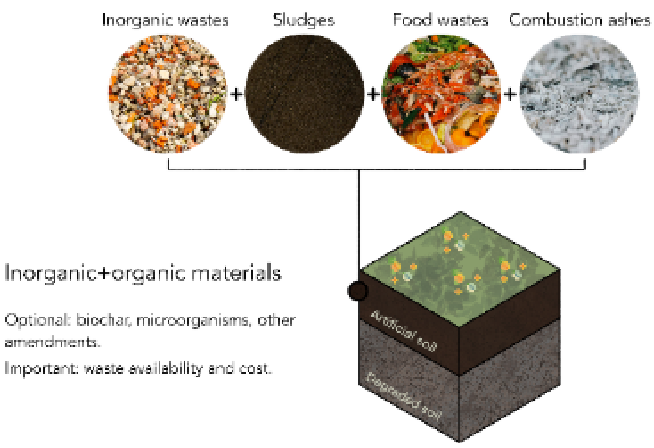

Figure 1. Diagram with examples of parent materials for artificial soil formulation

CURRENT STATE OF ARTIFICIAL SOILS AS CDR TECHNOLOGY

Artificial soils are made by carefully mixing natural and recycled materials- They are still mostly at the research and testing stage when it comes to removing carbon dioxide (CO_2) from the atmosphere. While they are already used to restore damaged land, green cities, and clean up polluted sites, scientists are still learning how to design and manage them specifically to store carbon for the long term and deliver reliable environmental benefits.

At this early stage, steady and long-term public support is very important. Artificial soils need years, and often decades, of testing to understand how much carbon they can store, how stable that carbon is, and how soil structure, microbes, and plants interact over time. Short-term funding can stop projects before useful results are achieved, slowing progress and innovation.

There is also uncertainty about how artificial soils will perform in different places. Results depend on local materials, climate, and how the soil is managed. Because of this uncertainty and the long time needed to see results, public institutions play a key role in sharing risks. Artificial soils still require upfront investment for site preparation, materials, monitoring, and long-term tracking, with benefits that may take years to appear.

Supportive policies are just as important as funding. Recognising artificial soils in climate research, land restoration plans, and soil-carbon programs helps create confidence and early demand. Clear policy signals can speed up learning and encourage innovation.

Artificial soils are now moving into a demonstration stage, where pilot projects are tested in real-world settings such as former mining areas, construction sites, roadsides, and urban spaces. These projects are larger than lab experiments but still risky, because long-term carbon storage and monitoring methods are not yet fully proven.

Demonstration projects help close the gap between research and wider use. They test how artificial soils perform at larger scales, how different waste materials can be safely reused, and how carbon storage can be measured in practice. Since these projects usually do not generate immediate income, they still rely heavily on public funding and support.

Public and political backing is especially important because artificial soils often use recycled materials like construction waste or mine residues, which can

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raise concerns about safety, regulation, and public acceptance. Strong institutional support can help overcome these barriers, simplify approvals, and encourage early users such as cities, landowners, and site managers.

At this stage, they would show carbon storage, trusted monitoring systems, and clear additional benefits such as healthier soils, better biodiversity, and less waste going to landfill.

To reach this stage, artificial soils need reliable sources of funding to cover construction, upkeep, and long-term monitoring. These could come from a mix of public and private sources, land restoration programs, infrastructure budgets, and incentives that reward recycling waste. As experience grows, costs are expected to fall, making artificial soils more competitive with other carbon-removal options.

Over time, artificial soils should become a normal part of land restoration, infrastructure development, and soil management reducing reliance on direct subsidies and becoming self-sustaining.

CONCLUSIONS FROM C-SINK PROJECT

A field pilot trial with artificial soils 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 also when is combined with EW and biochar. Six plots of 300 m2 were implemented at David's Mine from Pasek Minerales, 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 plot (where fertilizer was applied) in February 2025.

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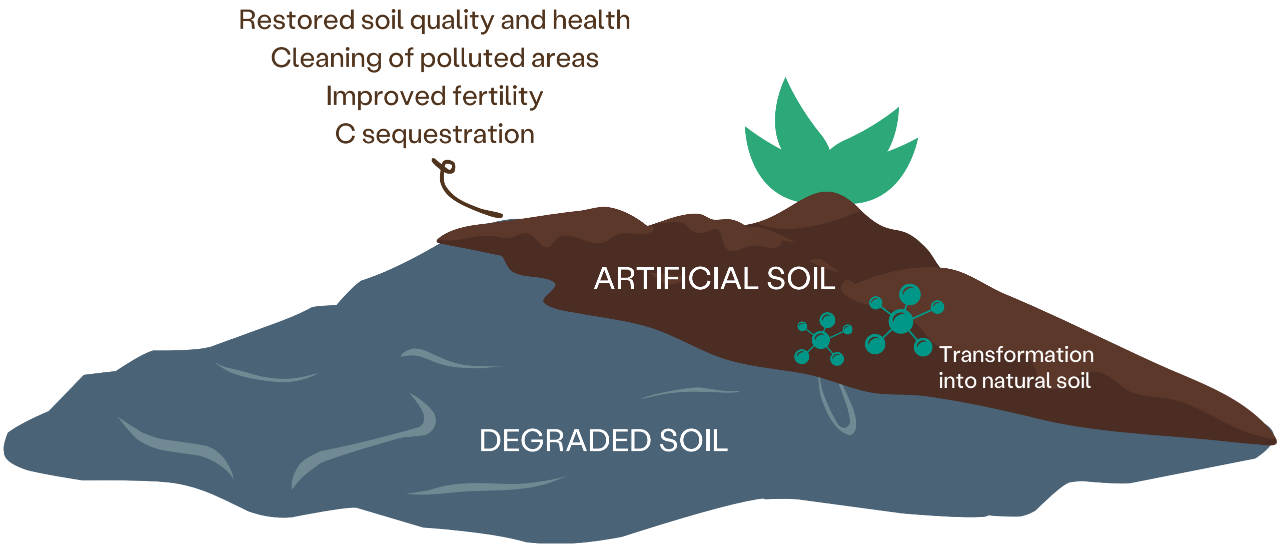

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