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ENGINEERED SOIL CARBON SYSTEMS FOR SUSTAINABLE CARBON CAPTURE AND STORAGE

Kalpana K[1], Backiyavathy M R[2*], Chitdeshwari T[3], Kalaiselvi T[4], Bharani A[5]

[1]PG Scholar, Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. E-mail: kalpana.k2282@gmail.com
[2]Professor (SS&AC), Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. E-mail: backiyavathy.mr@tnau.ac.in
[3]Professor (SS&AC), Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. E-mail: chitdeshwari@tnau.ac.in
[4]Professor (Agricultural Microbiology), Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. E-mail: tkalaiselvi@tnau.ac.in
[5]Professor and Head (Environmental Science), Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. E-mail: bharani.a@tnau.ac.in
*Corresponding author: backiyavathy.mr@tnau.ac.in

ABSTRACT
The escalating global carbon crisis is driving a shift from conventional, passive soil carbon sequestration towards actively engineered carbon management with greater efficiency and permanence. This review presents Engineered Soil Carbon Systems (ESCS), an emerging interdisciplinary approach combining enhanced rock weathering, engineered biological systems, advanced carbon-stabilizing materials, and digital monitoring technologies to strengthen terrestrial carbon capture and storage. Passive soil carbon sequestration remains constrained by finite mineral surface saturation, microbial priming, and the temporal instability of organic carbon pools. ESCS applies enhanced rock weathering using reactive silicate minerals such as basalt, olivine, and wollastonite to accelerate mineral dissolution, producing pedogenic carbonates and mineral-associated organic carbon that persist over long timescales. Alongside this, engineered biological approaches, including synthetic microbial consortia and CRISPR-based metabolic engineering, raise the rate of atmospheric CO_2 fixation and redirect carbon towards more stable biomass and soil carbon pools, while engineered nanomaterials and mineral-biochar composites further slow the breakdown of stored carbon. These advances are supported by IoT-enabled sensors, hyperspectral remote sensing, and machine learning, which allow soil carbon changes to be tracked and verified with greater accuracy, forming the basis for reliable monitoring, reporting, and verification. This review synthesizes these developments to position ESCS as a verifiable, efficient, and technologically grounded pathway for long-term soil carbon mitigation, while also highlighting the environmental, biosafety, and regulatory challenges that must be addressed for its wider field-scale adoption.

KEYWORDS: Engineered Soil Carbon Systems, Enhanced Rock Weathering, Synthetic Microbial Consortia, Monitoring, Reporting, and Verification, Carbon Stabilization

GRAPHICAL ABSTRACT

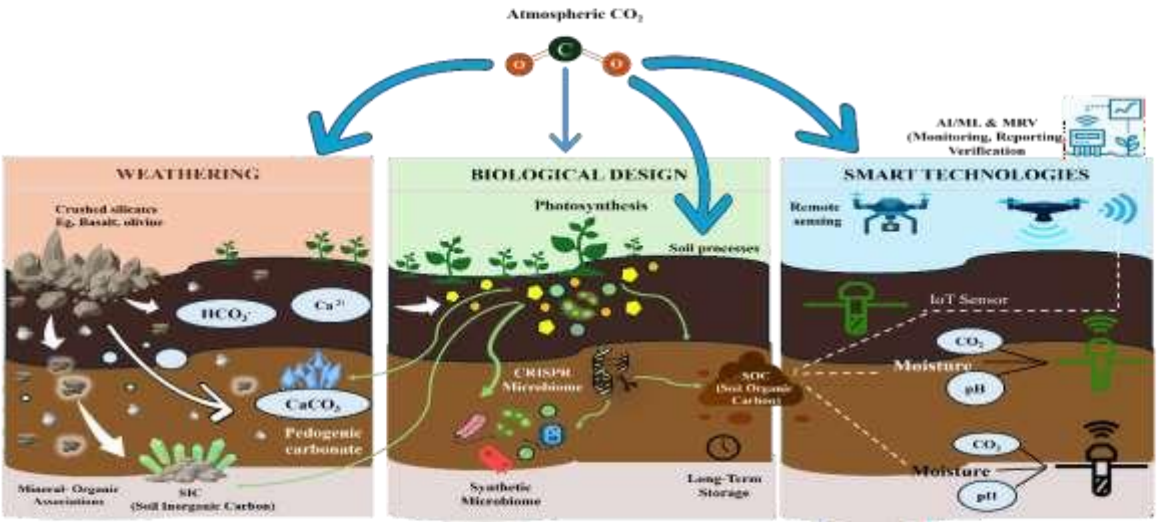

Figure 1. Overview of Engineered Soil Carbon Systems (ESCS), showing how mineralization, biological design, and smart technologies work together to capture and store atmospheric CO_2 in soil

1. INTRODUCTION

In the past few decades, climate change has become a major concern for the world, with research showing a gradual rise in the average temperature of the Earth (Rodrigues et al., 2023). Human activities have a major influence on the changes occurring in the Earth's climate. The role of modern agriculture is significant in this regard. Deforestation, changes in land use patterns, excessive use of fertilizers, and the use of fossil fuels are some of the activities that have an impact on the concentration of CO_2 in the atmosphere (Nazir et al., 2024). The Global Carbon Budget (2025) predicts that fossil fuel emissions will reach 38.1 Pg CO_2 annually, rising to 42.2 Pg CO_2 when including emissions linked to land use changes. Atmospheric CO_2 concentration is anticipated to rise to 425.7 ppm, significantly higher than the pre - industrial levels. These projections emphasize the necessity to design efficient carbon reduction strategies (Friedlingstein et al., 2025).

Of all the techniques available, carbon sequestration in soils has received significant interest as a viable option for reducing atmospheric CO_2 levels (Nazir et al., 2024). Soils function as a key reservoir of organic carbon in terrestrial systems, storing approximately 1,500 Pg C within the upper one metre of the soil profile and nearly 2,400 Pg C within the upper two metres, substantially greater than the atmospheric carbon pool of 830 Pg C. In addition, soil carbon stocks are significantly larger than annual carbon emissions from fossil fuel combustion, which are estimated at around 10 Pg C yr^{-1}. Managed soils play an important role in the global carbon cycle, with total carbon stocks in managed soils being 1,200 Pg of carbon (Paustian et al., 2016). This underscores their significant potential in the mitigation of climate change. Nevertheless, the sequestration capacity is subject to biophysical limitations, management practices, and carbon saturation thresholds.

Although soils possess substantial carbon storage capacity, activities such as agricultural intensification, deforestation, and unsustainable land-use practices have significantly reduced soil organic carbon levels over the past century (Bhargava et al., 2025). Soils retain carbon in stable forms for decades to centuries, and this capacity can be enhanced through conservation tillage, cover cropping, and biochar application, which collectively increase soil carbon stocks by 10–30% across agroecosystems, while biochar further contributes to carbon stabilization by reducing microbial degradation (Ghimirey et al., 2025). Sequestration of carbon in soil is still uncertain, and quantifying and verifying soil carbon sequestration is complex, which makes it difficult to reliably assess sequestration benefits (Das et al., 2025). To overcome these limitations, engineered soil carbon systems with higher stability and persistence are required to store carbon for longer time periods, providing measurable carbon storage in line with climate goals.

2. Fundamentals of soil carbon dynamics

2.1 Soil Organic Carbon: Stabilization Mechanisms and Persistence

Among terrestrial systems, soils constitute the largest carbon reservoir, holding more carbon than both the atmosphere and plant biomass combined. The stability of different SOC fractions, with labile SOC decomposing rapidly and recalcitrant pools persisting for decades to centuries determines how soils respond to variations in climate, land use, and management practices (Muñoz-Romero et al., 2017). SOC is derived from plant residues, root exudates, and microbial residues, and is grouped into labile and stable fractions based on turnover time (Lasota et al., 2020). Labile fractions including microbial biomass carbon (MBC), dissolved organic carbon (DOC), light fraction organic carbon (LFOC), and particulate organic carbon (POC) drive nutrient cycling and short-term fertility (Ghani et al., 2023).

MBC is the living fraction of SOC while DOC supports microbial metabolism and carbon transport. LFOC comprises rapidly decomposing residues, whereas POC serves as a nutrient reservoir responsive to management practices. In contrast, mineral-associated organic carbon (MAOC) and humic substances resist decomposition through chemical stability and organo-mineral associations, promoting long-term carbon stabilization (Liu et al., 2025). Overall, the relative proportion of labile and stable SOC fractions determines carbon persistence, ecosystem resilience, and long-term sequestration potential (Lavallee et al., 2020).

2.2 Soil Inorganic Carbon: Formation, Pathways and Environmental Controls

Soils store substantial inorganic carbon, accounting for 38% of total soil carbon, mainly as carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) compounds associated with calcium, magnesium, potassium, and sodium (Lal, 2016; Ling et al., 2023). SIC is classified as geogenic or pedogenic, and dominates arid and semi-arid regions, contributing over 90% of total soil C in these environments (Batool et al., 2024). Pedogenic carbonate formation involves dissolution of primary carbonates and biologically derived CO_2, producing bicarbonate and Ca^{2+}/Mg^{2+} species that reprecipitate as secondary carbonates under high alkalinity or evaporation conditions (Zamanian et al., 2016).

$$CaCO_3 + 2H_2O \rightleftharpoons Ca^{2+}_{(aq)} + 2OH^-_{(aq)} + H_2CO_{3(aq)} \quad (1)$$

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + CO_3^{2-} + CO_{2(aq)} + 2H^+ \quad (2)$$

This process is closely linked to the weathering of calcium and magnesium-bearing silicate minerals, driven by carbon dioxide from root and microbial respiration. Carbon dioxide reacts with silicates, releasing Ca^{2+} and forming dissolved inorganic carbon in soil solution (Eq.3); the released Ca^{2+} then combines with bicarbonate to precipitate as pedogenic $CaCO_3$ under favourable conditions (Eq.4), with sequestration efficiency depending on the calcium source (Batool et al., 2024):

$$CaSiO_3 + CO_2 + H_2O \downarrow \leftrightarrow H_4SiO_4 + 2HCO_3^{-} + Ca^{2+} \quad (3)$$
$$H_2CO_3^{-} + Ca^{2+} \leftrightarrow CaCO_3 + H_2O + CO_2 \uparrow \quad (4)$$

Pedogenic carbonate formation is described by four models (Monger, 2002): the per-descensum model, involving downward transport and subsurface precipitation of dissolved carbonates; the per-ascensum model reflecting upward movement of Ca^{2+} and bicarbonate via evaporation; the in-situ model, describing dissolution and reprecipitation of parent material within the soil profile; and the biogenic model, emphasizes carbonate formation mediated by roots, mycorrhizae, and soil fauna through biomineralization. In dryland regions carbonate formation is governed by interacting climatic drivers (moisture, evapotranspiration, biological activity) and soil properties (texture, mineralogy, parent material), which collectively regulate carbonate quantity, morphology, and long-term stabilization (Zamanian et al., 2016). Compared with SOC, SIC is more stable and can retain carbon over geological timescales, making it an attractive target for engineered carbonate formation and long-term storage.

2.3 Constraints on long-term carbon storage

While soils can store significant amounts of carbon in both organic and inorganic forms, their long-term stability and accumulation are constrained by several biophysical factors: mineral surface saturation, disturbance and climate stress, and microbial priming and carbon destabilization. Soils have a finite carbon saturation capacity governed by mineral texture, mineralogy, and surface area; as reactive mineral surfaces become occupied, MAOC stabilization progressively declines, limiting further carbon storage (Georgiou et al., 2025; Hassink & Whitmore, 1997; Six et al., 2002). Soil erosion by water and wind redistributes SOC across landscapes, disrupting aggregates and exposing protected carbon to microbial decomposition, thereby increasing CO_2 emissions (Lal, 2021). Climate warming further accelerates microbial metabolism and the mineralization of stable carbon pools, increasing the vulnerability of deep soil carbon (Hicks Pries et al., 2023). Additionally, the microbial priming effect describes accelerated SOC mineralization triggered by fresh organic inputs, which stimulate microbial activity and enzyme processes, increasing CO_2 release and destabilizing long-term carbon storage (Bernard et al., 2022), with environmental changes further weakening organo–mineral interactions and promoting MAOC destabilization and reducing long-term carbo persistence (Xu & Tsang, 2024). These natural constraints highlight the need for engineered soil carbon systems that can improve carbon stabilization and long-term carbon storage.

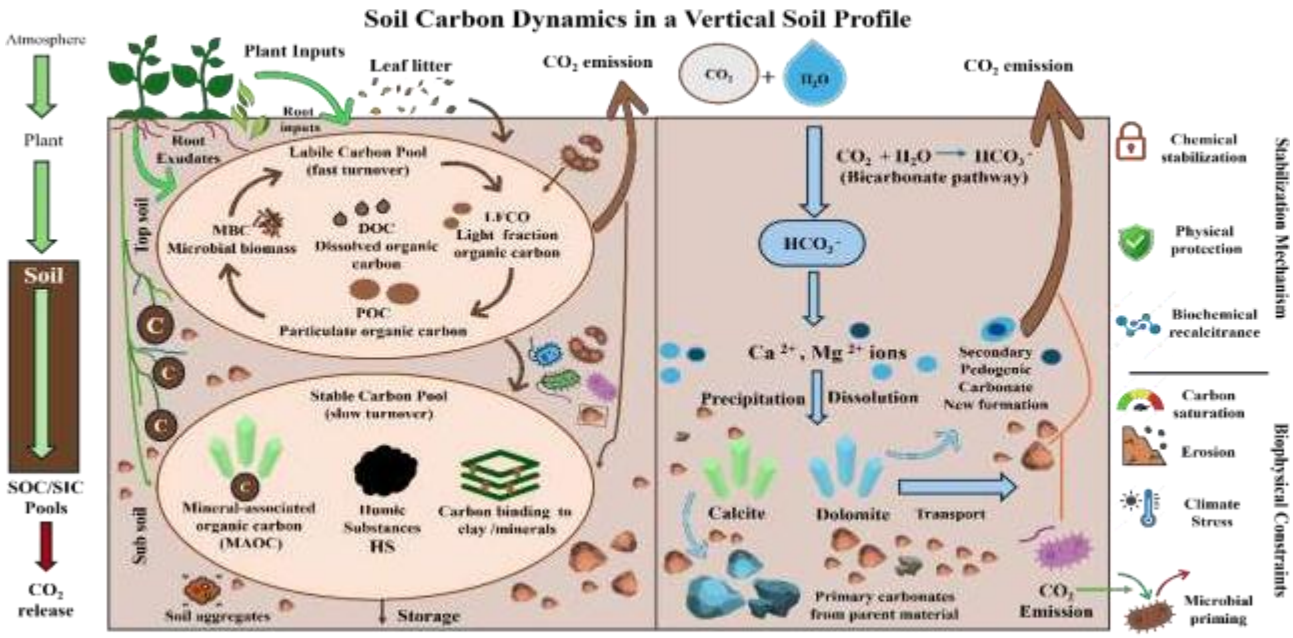

Figure 2. Vertical soil profile illustrating organic and inorganic carbon cycling, stabilization mechanisms, and CO_2 fluxes between soil and the atmosphere

3. Engineered Soil Carbon System

3.1 Enhanced Rock Weathering (ERW)

3.1.1 Geochemical Basis of Silicate Weathering and Carbonate Formation

Enhanced Rock weathering (ERW) is emerging as a viable approach for removing atmospheric carbon dioxide, gaining increasing attention in recent years. It relies on mineral carbonation - geochemical reactions in which silicate minerals interact with atmospheric CO_2, to form stable carbonate compounds, enabling long-term carbon sequestration (Abdalqadir et al., 2024). Enhanced weathering accelerates natural silicate weathering by applying crushed minerals to land or water, capturing CO_2 within human-relevant timescales while improving soil fertility in agricultural systems. The released nutrients Ca^{2+}, Mg^{2+}, and K^+, allow it to function as both a climate mitigation strategy and a crop productivity enhancing soil amendment (te Pas et al., 2023). Basalt, olivine, and serpentine are extensively studied in enhanced weathering owing to their widespread availability and strong reactivity with carbonic acid. Basalt, classified as a mafic igneous rock, composed mainly of plagioclase, pyroxene, and olivine, is rich in divalent cations, including Ca^{2+}, Mg^{2+}, and Fe^{2+}, which drive the formation of stable carbonate minerals. This process proceeds through three main geochemical stages (Owusu et al., 2025).

Dissolution and ionization of CO_2 in water

$CO_2\,(g) + H_2O\,(l) \rightleftharpoons H_2CO_{3(aq)}$

$H_2CO_{3(aq)} \rightleftharpoons HCO^{-3}{}_{(aq)} + H^+{}_{(aq)}$

$HCO^{3-}{}_{(aq)} \rightleftharpoons CO_2{}^{-3} + H^+$

The dissolution of plagioclase feldspar:

$CaAl_2Si_2O_8\,(s) + 8H^+ \rightarrow Ca^{2+} + 2Al^{3+} + 2Si\,(OH)_4$

The dissolution of the pyroxene:

$(Ca, Mg, Fe)\,SiO_3 + 2H^+ \rightarrow (Ca^{2+} + Mg^{2+} + Fe^{2+}) + SiO_2$

The precipitation of carbonates:

$Ca^{2+} + CO_3{}^{2-} \rightarrow CaCO_3$

$Mg^{2+} + CO_3{}^{2-} \rightarrow MgCO_3$

$Fe^{2+} + CO_3{}^{2-} \rightarrow FeCO_3$

These reactions support both soil nutrient enrichment and long-term carbon sequestration via bicarbonate and carbonate formation, with efficiency depending on mineral, soil, climatic, and biological factors. Comparing the two reactions above, pyroxene dissolution requires fewer bonds to break than feldspar's more polymerized aluminosilicate structure, indicating mineral structure-not surface area alone governs weathering rate.

3.1.2 Bio-enhanced Weathering

Microorganisms enhance mineral weathering by releasing organic acids, siderophores, and extracellular polymers that acidify and chelate mineral surfaces, increasing dissolution and mobilization of Ca, Mg, Fe, and P, thereby promoting nutrient cycling (Dong et al., 2022; Pradhan et al., 2025). Within enhanced weathering systems, these processes accelerate CO_2 conversion into bicarbonate and carbonate, enabling long-term sequestration. A key mechanism is microbially induced calcium carbonate precipitation (MICP), in which urea hydrolysis generates carbonate that reacts with Ca^{2+} to form calcite, with microbial cells and extracellular polymers acting as nucleation sites for crystal growth (Zhu & Dittrich, 2016). Several recent studies illustrate this microbial potential. *Bacillus subtilis* strain MP1, cultured in B4+ medium supplemented with plagioclase feldspar, increased Ca^{2+} and Mg^{2+} release and biofilm-mediated $CaCO_3$ precipitation achieving more than sixfold higher weathering rates, about 20% increase in SIC, and 2.02 t ha^{-1} yr^{-1} sequestration (Timmermann et al., 2025). Building on this an engineered *Bacillus subtilis* expressing carbonic anhydrase, which reduced CO_2 concentrations from 3800 ppm to 820 ppm and enhanced calcite and vaterite formation in $CaCl_2$ - urea media, confirmed by SEM and XRD (Gilmour et al., 2024). Beyond bacteria, urease-positive fungi isolated from alkaline soils promoted MICP and bio-cementation, showing high urease activity 8.42–10.06 µg mL^{-1} and hyphal $CaCO_3$ deposition confirmed by XRD and FESEM, indicating active nucleation for calcite formation (Devgon et al., 2024). Although both bacterial and fungal systems enhance mineral weathering, bacterial systems have shown measurable weathering-rate increases, whereas fungal hyphae offer extensive nucleation surfaces for carbonate formation, pointing to complementary contributions to microbially driven weathering. At the enzyme level, carbonic anhydrase from *Bacillus mucilaginosus*, expressed in *E. coli* (PCA4), enhanced wollastonite weathering, increasing dissolution rates (9.24×10^{-4} to 1.402×10^{-3} mg g^{-1} min^{-1}) and Ca release, and boosting carbonate formation by 15% under high CO_2 and from 0.005 to more than 0.020 g (419%) underscoring the role of microbial enzymes in driving CO_2 sequestration (Xiao et al., 2015). Overall, microbial pathways offer strong potential to accelerate carbonation, but field-scale evidence remains limited.

3.1.3 Field Evidence and Carbon Sequestration Potential

A growing body of experimental field studies has evaluated the carbon sequestration potential of ERW under laboratory, mesocosm, modelling and field conditions. Large-scale modelling indicates that applying basalt at 10-30 t ha^{-1} yr^{-1} on U.S croplands could remove about 0.16-0.30 Gt CO_2 yr^{-1}, nearly 10% of national emissions, with life-cycle analysis confirming net-negative outcomes despite processing emissions (Beerling et al., 2020). At smaller scales, laboratory weathering experiments show that tropical conditions significantly enhance mafic rock dissolution, with basalt and similar rocks removing 2.4 - 11.9 t CO_2 ha^{-1} yr^{-1} depending on mineral composition and soil properties (Vanderkloot et al., 2024). Consistent with this, rainfall simulation studies find that the reactive basalt minerals (augite, hortonolite) dissolve faster than stable phases, releasing Ca^{2+} and Mg^{2+}, that form calcite and dolomite, yielding a sequestration potential of approximately 9.73 t CO_2 ha^{-1} yr^{-1} (Tang et al., 2025). This consistency between the two estimates indicates that dissolution of reactive phases like augite and hortonolite, rather than bulk basalt composition, is the primary driver of variability across these studies. Beyond dissolution rate, weathering stage also shapes outcomes: a carbon-labelled straw incubation found that fresh olivine-rich basalt raised soil pH and produced 0.4% dissolved inorganic carbon and 4% SIC, yet reduced SOC by 17% through enhanced microbial decomposition, whereas weathered basalt caused smaller pH shifts and retained over 95% of stabilized carbon (Lei et al., 2025). Comparative column trails across five minerals - olivine, basalt, wollastonite, anorthite, and albite showed that all minerals increased soil pH, base saturation, and CEC, where olivine and wollastonite exhibited the highest sequestration potentials of 0.43 - 2.30 t CO_2 ha^{-1} and 0.45 - 1.78 t CO_2 ha^{-1}, respectively, while feldspars proved efficient only when normalized to specific surface (te Pas et al., 2023). This contrasts with the basalt-only estimates above - pure minerals like olivine outperform basalt per hectare, though basalt is still more practical at scale. Longer-term field-scale studies show more gradual but consistent gains. A mesocosm study using reactive transport modelling found that 50 t ha^{-1} basalt increased alkalinity and Mg without a significant increase in inorganic carbon within 99 days, with sequestration increasing from 0.77 t CO_2 ha^{-1} to 4.48 t CO_2 ha^{-1} over five years (Vienne et al., 2022). Supporting this trajectory, a Ti-based mass-balance (TiCAT) study in basalt-amended sorghum soils recorded Ca and Mg release alongside 1.44 ± 0.27 t CO_2 ha^{-1} removed over 235 days (Reershemius et al., 2023). Elsewhere, engineered and marine settings can further accelerate mineral carbonation. Batch experiments show citrate enhances serpentine dissolution under CO_2 exposure, reaching rates up to 3.43×10^{-7} cm s^{-1} at 120 °C (0.5 M), with rates declining at lower temperatures or citrate concentration (Krevor & Lackner, 2011). Collectively, laboratory, mesocosm modelling, and field studies demonstrate that ERW is a promising strategy for atmospheric CO_2 removal while simultaneously improving soil health and supporting long-term carbon sequestration. The reported sequestration rates span roughly 1 to 12 t CO_2 ha^{-1} yr^{-1}, a range shaped more by study duration and climate than by mineral type: multi-year and tropical trails show larger gains, while freshly applied basalt can temporarily lower organic carbon even as it builds inorganic stores.

3.2 Engineered Microbial System for Carbon Stabilization

3.2.1 Synthetic Microbial Consortia

Soil microbial communities convert plant-derived carbon and atmospheric CO_2 into microbial biomass and stable soil organic matter, forming a biological route to long-term carbon retention (Mason et al., 2023). This fixation proceeds through several routes- the Calvin-Benson - Bassham cycle, Wood–Ljungdahl pathway, and reductive TCA cycle (Ruan et al., 2025), yet natural fixation rates remain constrained by complex enzymatic systems and the low catalytic efficiency of RuBisCO (Bar-Even et al., 2010). Synthetic biology and microbial engineering offer a route around these constraints, though most engineered systems remain confined to laboratory – scale demonstrations without field validation. Rather than engineering single organisms, researchers now turn to constructing synthetic microbial consortia – multi-species communities built through the *design-build-test-learn (DBTL)* cycle using either top-down or bottom-up approaches. Distributing metabolic tasks across species improves resource use efficiency and community stability relative to monocultures (Liang et al., 2022), translating into measurable gains in CO_2 fixation and downstream bioconversion. Coupling photosynthetic and heterotrophic organisms enhances CO_2 fixation. A *Synechococcus elongatus* - *Vibrio natriegens* consortium in which cyanobacteria engineered carrying the *cscB* gene enabled sucrose transfer, increased CO_2 fixation by 31% and enabled rapid production of value-added compounds within 6–7 days (Wang & Dai, 2023), while *Chlorella vulgaris* HL02–bacterial consortium under 15% CO_2, showed even sharper gains: the *Chlorella–Aeromonas* pairing increased biomass by 22.31% and CO_2 fixation by 87% compared with monoculture (Chen et al., 2024). Microbial electrosynthesis (MES) applies this consortium logic to bio electrochemical systems, where electroactive microbes draw electrons from electrode to drive CO_2 reduction (Sun et al., 2025), electroactive microbial consortia built from *Methanobacterium*, *Shewanella*, *Acetobacterium*, *Sporomusa*, *Moorella*, and *Clostridium* convert CO_2 into methane, formate, acetate, butyrate, and ethanol, demonstrating a viable link between renewable electricity and biological carbon conversion. The larger gain from the *Chlorella–Aeromonas* pairing likely reflects elevated CO_2 conditions rather than superior consortium design, while microbial electrosynthesis, powered by electricity rather than light, offers a route free from land and sunlight constraints.

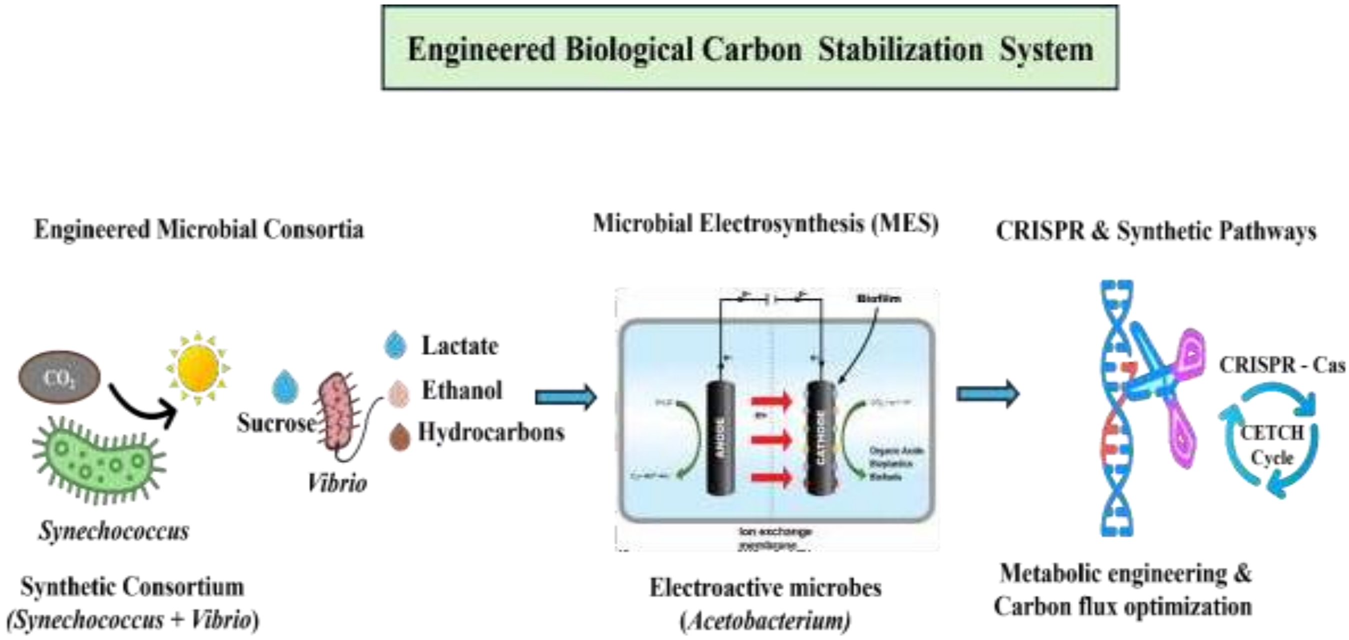

Figure 3. Engineered biological strategies for carbon stabilization, including microbial consortia, microbial electrosynthesis, and CRISPR-based metabolic engineering.

3.2.2 Metabolic Engineering and Synthetic Microbiology

Microbial and plant metabolic engineering enhances carbon sequestration by improving CO_2 capture and SOC stability (Mustafa et al., 2026). It optimizes the Calvin–Benson–Bassham cycle and introduces engineered pathways (Nayak et al., 2022), redirecting metabolic flux, enhancing key gene functions, and suppressing competing pathways to increase carbon allocation to biomass and storage (Sarjuni et al., 2022). Engineering RuBisCO and associated photosynthetic pathways improves CO_2 fixation, although photorespiration and enzyme limitations remain (Gakpo et al., 2024). Alternative pathways, the rTCA cycle and Wood–Ljungdahl pathway, are introduced into microorganisms, including *Escherichia coli* and cyanobacteria to bypass natural inefficiencies (X. Liu et al., 2022; Mustafa et al., 2026). A key advance is the reconstruction of a functional Calvin cycle in *Escherichia coli*, enabling CO_2 utilization and increased sugar intermediates. Beyond enhancing native pathways, engineered strains now incorporate entirely novel carbon-assimilation modules (Sarjuni et al., 2022). CRISPR-based genome editing enables precise regulation of metabolic pathways, improving carbon-use efficiency and biomass accumulation (Yu et al., 2022). Synthetic biology has further introduced wholly artificial fixation routes, including the CETCH cycle and reductive glycine pathway (Erb, 2024; Osmanoglu et al., 2021). Applications span both microbial and plant systems. In *Chlamydomonas reinhardtii*, CRISPR-Cas9 editing of *PEPC1* redirects carbon from starch toward lipid biosynthesis, increasing biomass (Hu et al., 2023). In plants, CRISPR has improved RuBisCO function and reduced photorespiratory losses (Boisset et al., 2023) while enabling integration of synthetic fixation pathways to increase carbon capture potential of plants (Wang et al., 2022). These strategies trade lower risk in native-pathway optimization for greater but less-proven gains in synthetic routes like CETCH. Collectively CRISPR-assisted metabolic engineering is advancing CO_2 fixation, biomass accumulation, and carbon sink development, with future integration of AI-guided design expected to accelerate progress toward scale carbon capture.

3.3 Advanced Soil Carbonation and Engineered Mineralization Amendments

3.3.1 Nano materials and functionalized clays

Nanostructured minerals and functionalized clays enhance CO_2 capture and carbonation through high surface area, tunable chemistry, and strong CO_2 affinity, which together accelerate reaction rates and support long-term carbon stabilization. Clay minerals differ markedly in their CO_2 adsorption capacity. Swelling clays such as montmorillonite and smectite generally outperform non-swelling clays owing to their expandable interlayer structures and higher adsorption capacity (Altaf et al., 2025). Engineered nanomaterials extend this capacity owing to a high surface-area-to-volume ratio and adjustable surface chemistry, enhancing adsorption efficiency, selectivity, and regeneration (AlShamaileh et al., 2024). MgO nanoparticles and amine-functionalized montmorillonite represent effective nanomaterials for improving CO_2 adsorption and carbonation efficiency (Hu et al., 2020). Carbon-based nanomaterials, including graphene oxide, CNTs, aerogels, and nanofibers, also provide high porosity, with capacities of 2.23 mol kg⁻¹ of activated carbon and 1.44 mol kg⁻¹ of CNTs (Lu et al., 2008).Engineered nanostructured adsorbents MOFs, POPs/COFs, carbon materials, and hybrids - show strong CO_2 capture potential, with MOFs offering both high capacity and porosity (4-8 mmol g^{-1}& 1000-3500 m² g^{-1}), while hybrid system additionally enable capture–conversion at moderate cost (Selvam et al., 2026). Nanomaterial-enhanced liquid absorbents Complement these solid sorbents: amines, ionic liquids, nanofluids improve CO_2 capture by enhancing absorption and mass transfer (Zhu et al., 2024). MEA offers a fast kinetics, but demands high regeneration energy; modified formulations address this partially, with AMP–ethylene glycol/ polar solvents blend raising capacity by 28.4%, and graphene oxide (0.1 wt%) in MDEA improving solubility by 9.1%, though aggregation and long-term stability and remain unresolved. Modified smectite clays (montmorillonite, saponite) form porous heterostructures via intercalation, pillaring, and calcination (550 °C, 6 h), yielding materials with enhanced porosity and CO_2 adsorption capacity (Franco et al., 2024). (Q. Liu et al., 2022) showed that amine-functionalized kaolinite enhances CO_2 adsorption (up to 17.0 ± 0.4 mL g^{-1} vs. 6.5 mL g^{-1} raw) due to increased surface area and chemisorption, highlighting the effectiveness of functionalized nano-clays for CO_2 capture. Overall, capacity and cost trade off consistently across these materials: MOFs and engineered nanomaterials offer the highest capacity but remain costly, while modified clays like kaolinite provide lower but more affordable gains.

3.3.2 Mineral-Biochar Composite for Carbon stabilization

Biochar, a carbon-negative material produced through biomass pyrolysis, enables long-term carbon storage (Biswal & Balasubramanian, 2025). Its high surface area and porosity improve soil properties, while stabilizing plant-derived CO_2; At scale, this potential is substantial- the IPCC recognizes biochar as capable of reducing emissions by up to 1.8 Pg CO_2–C yr^{-1} (Singh et al., 2023). Biochar composites, including metal, mineral, layered double hydroxide (LDH), carbonaceous, and microorganism–biochar, further enhance performance, with mineral biochar systems particularly effective for carbon sequestration and environmental remediation (Wang et al., 2022). This advantage is well supported empirically. $Ca(H_2PO_4)_2$ - treated biochar shows the stronger performance to date, raising retention by 15% and stability by 12 % , alongside increased activation energy, indicating greater resistance to degradation (Yang et al., 2025). In the same study, mineral doping in a different feedstock - biochar produced from corn stalks - achieved a 6% higher yield, 17.5% less carbon loss, a 138.2 mg kg⁻¹ increase in microbial biomass carbon and a 48.9 mg kg⁻¹ decline in dissolved organic carbon – collectively signalling stronger stabilization of labile carbon fractions (Yang et al., 2025). A comparable outcome emerges from Sepiolite-modified rice husk biochar reduced carbon mineralization and decreased dissolved organic carbon by 49.39% compared to unmodified biochar, highlighting significantly improved carbon retention and stabilization (Hou et al., 2024). Across feedstocks and additives, the consistent decline in dissolved organic carbon suggests mineral-shielding of labile carbon is a general mechanism, not specific to any one biochar type.

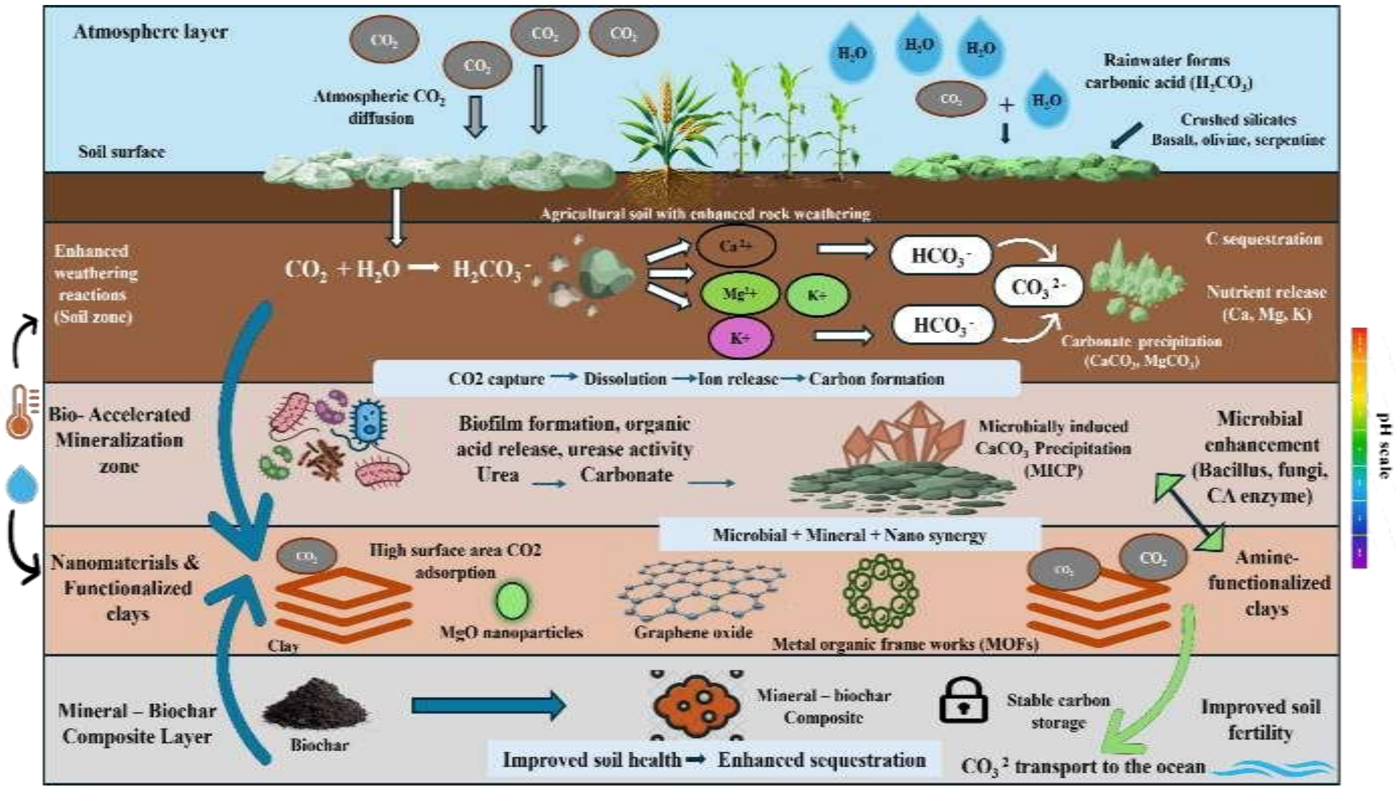

Figure 4. Enhanced rock weathering system integrating minerals, microbial processes, biochar and nanomaterials for CO_2 capture and soil carbon stabilization.

4. Emerging Technologies for Engineered Soil Carbon Systems

4.1 Sensors and Monitoring, Reporting, and Verification (MRV)

Reliable monitoring, reporting, and verification (MRV) systems are essential for quantifying soil carbon sequestration, validating greenhouse gas reductions, and supporting transparent carbon accounting (Thornbush & Govind, 2025). Digital MRV (DMRV) further enhances these capabilities by integrating remote sensing, field sensors, cloud computing, machine learning, and blockchain technologies to enable efficient, near-real-time monitoring and verification of soil carbon dynamics (Ecklu & Thomas, 2025). Applying MRV to soil carbon requires rapid and field- deployable monitoring tools, as conventional laboratory analyses are time-consuming and unsuitable for continuous assessment. Consequently, portable technologies such as infrared spectrometers, reflectometric probes, electrochemical sensors, and handheld CO_2 analyzers are increasingly used for near-real time soil carbon monitoring (Loria et al., 2024). Among these, non-dispersive infrared (NDIR) CO_2 sensors have drawn particular attention for their balance of accuracy and affordability, detecting CO_2 based on infrared absorption at characteristic wavelengths (Liang et al., 2023). An automated chamber built around an inexpensive MH-Z19 sensor showed strong correlation with commercial systems ($R^2 \approx 0.98–0.99$), with only a slight tendency to underestimate time flux (Verma et al., 2026), while under controlled conditions, NDIR sensors likewise produced reliable soil respiration estimates (9.23 mg C kg^{-1} day^{-1}) comparable to standard reference methods (Irving et al., 2024). Beyond carbon measurement, tracking and emission – driving conditions matter too: soil moisture and pH govern microbial activity and organic matter breakdown, emissions 40% for predicting flux (Hao et al., 2025). Both correlation-and accuracy-based validations confirm NDIR sensors as a reliable, low-cost alternative to lab-based carbon measurement.

4.2 Remote Sensing and Digital Carbon Mapping

While in-situ tools offer fine-scale precision, remote sensing (RS) enables continuous, cost-effective monitoring of SOC at landscapes to regional scales, supporting large scale spatial- mapping through satellite platforms such as Sentinel, Landsat, and hyperspectral sensors for MRV applications (Amoli et al., 2025). By capturing electromagnetic interactions with soil, RS provides high-resolution spectral data, with VNIR–SWIR spectroscopy (400–2500 nm) particularly sensitive to molecular vibrations, relevant to SOC estimation (Li et al., 2024). Remote sensing also enables temporal monitoring SOC dynamics under changing land use, climate, and management practices (Xu et al., 2026); and multi-source integration which combines field, proximal sensing, terrain, and climate variables to improves prediction accuracy across heterogenous landscapes (Sevilla et al., 2025), who assessed SOC in semiarid systems using Sentinel-2, UAV, and field data, reporting low SOC (0.45–1.30%) with NDVI as a key predictor; model performance was modest overall ($R^2_a d_j = 0.325$; RMSE = 0.156%) but improved notably under bare soil conditions ($R^2_a d_j = 0.561$; RMSE = 0.122%) compared to vegetated conditions ($R^2_a d_j = 0.424$). Addressing a related source of error, (Jiang et al., 2024) combined hyperspectral imagery with SAR data to correct SOC estimation errors caused by moisture and surface roughness, improving correlation accuracy by over 60% ($R^2_p = 0.743$ (RMSEP = 3.455 g kg^{-1}), though performance remained sensitive to bare-soil conditions. Furthermore, (Angelopoulou et al., 2025) reviewed AI-integrated multi-sensor Earth Observation-spanning optical, SAR, LiDAR and UAV platforms- for carbon monitoring, reporting high LiDAR accuracy ($R^2 > 0.9$) alongside persistent limitations for SOC <1% and unresolved challenges in detecting small changes or standardizing MRV protocols. Performance across these methods drops under vegetation and low SOC, showing multi-sensor fusion outperforms any single platform.

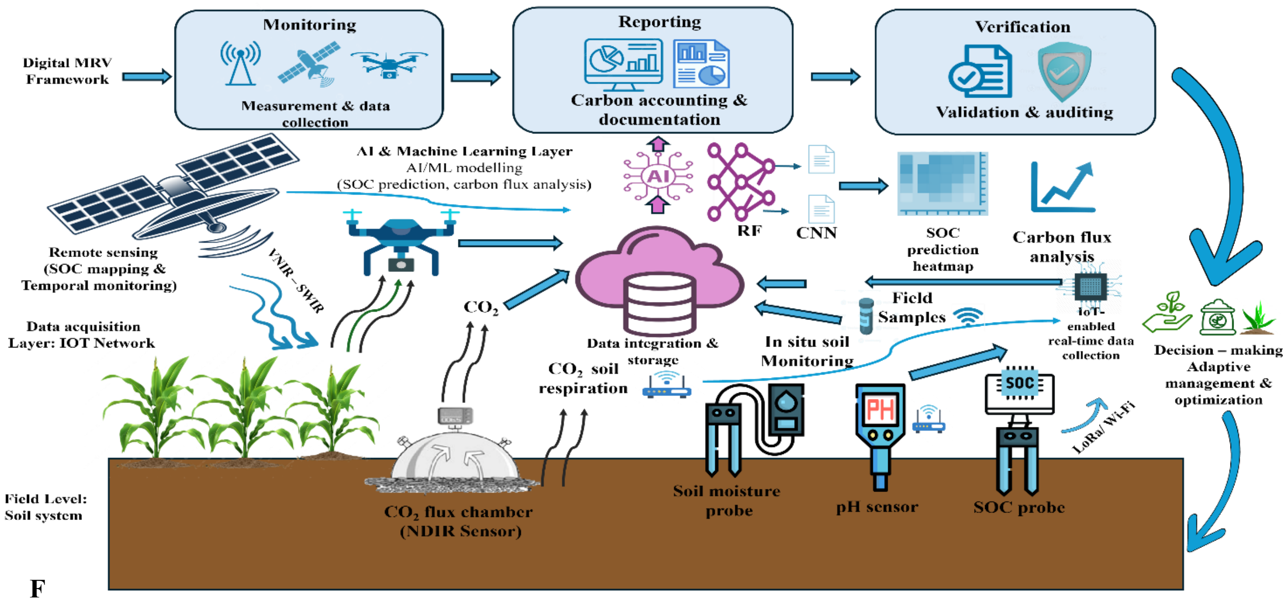

Figure 5. Digital monitoring, reporting, and verification (MRV) system integrating IoT, remote sensing, and AI for real-time soil carbon monitoring and decision-making.

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Table 1. Representative Technologies and Performance Outcomes in Engineered Soil Carbon Systems (ESCS)

ESCS approach	Technology / System	Key Findings	Reference
Enhanced Rock Weathering	Basalt rock powder	Carbon removal potential of 0.16 - 0.30 Gt CO_2 yr^{-1} across U.S. croplands	(Beerling et al., 2020)
	Tropical mafic rock powders	Carbon sequestration of 2.4 - 11.9 t CO_2 ha^{-1} yr^{-1}	(Vanderkloot et al., 2024)
Engineered Microbial Systems	*Synechococcus elongatus* (cscB) - *Vibrio natriegens* consortium	Engineered sucrose transfer increased CO_2 fixation by 31%	(Wang & Dai, 2023)
	Chlorella vulgaris HL02 - Aeromonas consortium	Biomass increased by 22.31% and CO_2 fixation by 87% compared with monoculture	(Chen et al., 2024)
	CRISPR-edited *Chlamydomonas reinhardtii* (PEPC1)	Redirected carbon from starch to lipids, increasing biomass accumulation	(Hu et al., 2023)
Advanced Soil Carbonation	Amine-functionalized kaolinite	CO_2 adsorption increased from 6.5 to 17.0 ± 0.4 mL g^{-1}	(Q. Liu et al., 2022)
	Metal - Organic Frameworks (MOFs)	CO_2 adsorption capacity of 4 - 8 mmol g^{-1} with 1000 - 3500 m^2 g^{-1} surface area	(Selvam et al., 2026)
	$Ca(H_2PO_4)_2$ - treated biochar	Carbon retention increased by 15% and stability by 12%	(Yang et al., 2025)
Digital Monitoring Technologies	Automated chamber with MH-Z19 NDIR CO_2 sensor	Strong agreement analyzers ($R^2 \approx 0.98 - 0.99$)	(Verma et al., 2026)
	Sentinel-2 + UAV+ field observations	Improved SOC prediction under bare-soil conditions ($R^2adj = 0.561$; RMSE = 0.122)	(Sevilla et al., 2025)
	Hyperspectral imaging + Synthetic Aperture Radar (SAR)	Improved SOC prediction by >60% (R^2_p= 0.743) through correction of moisture and roughness effects	(Jiang et al., 2024)

5. Challenges and Limitations of Engineered Soil Carbon Systems

5.1 Environmental and Technical Constraints

Enhanced rock weathering efficiency is strongly influenced by environmental factors, particularly soil pH, moisture, and microbial activity. Soil pH regulates mineral dissolution, with olivine and pyroxene weathering more rapidly under acidic conditions, whereas aluminium-rich minerals remain relatively stable in alkaline soils. Magnesium release may also be restricted by iron coatings but enhanced by chelating agents such as CDTA (Vandeginste et al., 2024). Soil moisture further controls mineral weathering and carbonate formation by regulating CO_2 - water - mineral interactions and the release of calcium and magnesium ions. While optimal moisture conditions promote carbonation, excessive drying or waterlogging can reduce reaction rates or alter soil redox conditions. In addition, microbial respiration and organic acid production accelerate carbonic acid formation and mineral dissolution, thereby influencing ion transport and overall carbon sequestration efficiency (Levy et al., 2024; Vandeginste et al., 2024). Together, these findings show ERW performance hinges less on mineral type and more on local soil chemistry and moisture regime, indicating that deployment strategies should be site-specific rather than standardized.

5.2 Bio safety, Ethical, and Regulatory Challenges

Environmental applications of CRISPR, synthetic microbial consortia, and other engineered biological systems offer significant opportunities for carbon sequestration but also raise important biosafety concerns. Major risks include off-target genome modifications, horizontal gene transfer (HGT), and potential containment failure following environmental release following environmental release (Gillett et al., 2025; Hoepers et al., 2024; Lerner et al., 2026). At the ecosystem level, these risks may disrupt native microbial communities, alter microbial diversity, and create unpredictable interactions within synthetic microbial populations, while the spread of engineered genes remains difficult to monitor using current surveillance frameworks (Arnolds et al., 2024; Maull et al., 2025; Zhang et al., 2024). Ethical and regulatory challenges further include the irreversible release of engineered organisms, dual-use concerns, and fragmented governance across countries. These issues highlight the need for robust biocontainment strategies, adaptive regulatory frameworks, and long-term environmental monitoring to ensure the safe and responsible deployment of engineered soil carbon technologies (Chemla et al., 2025; Eckerstorfer et al., 2025). These risks are distinct yet compounding, showing that biosafety oversight must address both the organism and the regulatory system around it.

6. Policy frameworks, Carbon Markets, and Adoption pathways

Supportive policy frameworks and well-regulated carbon markets are essential for enabling the large-scale adoption of engineered soil carbon systems as climate mitigation strategies. Robust MRV is a key bottleneck: inconsistencies in additionality, permanence, and baselines risk non-equivalent credits (Oldfield et al., 2022), and ERW's inherent time lags make standard annual crediting cycles a poor fit - field trials have shown overlapping CDR estimates of 0.53 t CO_2/ ha over 1.5 years across an 18-month window (Kanzaki et al., 2025; McBride et al., 2025). Modular, digitally enabled MRV systems could standardize measurement and speed up credit issuance, improving the case for investment (Batjes et al., 2024; Veen et al., 2025), but inconsistent federal- level requirements points to a broader need for unified standards (Lebling et al., 2024). Compliance pathways remain underdeveloped: Article 6 offers potential but lacks standardized methods (Cook et al., 2024), while weak offset integrity and wide price variability (US$1–1,000 per tonne) reflect additionality concerns that risk market credibility (Michaelowa et al., 2023; Wozny et al., 2022). Robust certification must distinguish net removals from avoided emissions and ensure permanence (Schenuit et al., 2023). Continued improvements in policy frameworks, certification systems, and carbon market mechanisms will be crucial for enabling the widespread adoption and long-term success of engineered soil carbon systems.

7. Future Directions

Future research should advance engineered biological, mineral, and digital technologies to improve the efficiency, scalability, and long-term stability of soil carbon sequestration. Synthetic biology is opening one path forward, with engineered microbiomes now capable of optimized carbon assimilation and more stable carbon formation (Gleizer et al., 2019; Liu et al., 2020). Parallel advances in AI-powered soil systems and digital twin frameworks are enabling real-time monitoring, predictive modelling, and adaptive management across diverse landscapes (Minasny et al., 2017; Smith et al., 2020). Integrated carbon–nutrient strategies, including carbon-stabilizing fertilizers, further improve microbial carbon use efficiency while reducing nutrient losses and greenhouse gas emissions (Lal, 2018; Oldfield et al., 2019). At broader scales, carbon farming within regenerative agriculture, supported by robust measurement, reporting, and verification (MRV) frameworks, offers a practical pathway for durable sequestration (Beerling et al., 2020; Paustian et al., 2016). Realizing scalable, climate-resilient carbon sequestration will ultimately depend on these strands converging-for instance, digital MRV systems verifying gains from synthetic biology or mineral based approaches rather than progressing in isolation.

8. CONCLUSION

Engineered soil carbon systems represent a shift from passive sequestration to actively designed carbon stabilization strategies. Advanced mineral carbonation, engineered microbial systems, and emerging digital technologies each enhance carbon persistence, measurability, and scalability. Advanced materials further strengthen carbon retention under variable environmental conditions. However, constraints such as soil carbon saturation and long-term stability uncertainties remain key challenges. Overall, continued progress across mineral, biological, and digital approaches offers a promising pathway for next-generation carbon capture, requiring continued field validation and adaptive implementation for sustainable climate mitigation.

Data availability

No new data were created or analysed in this study. Data sharing does not apply to this article.

Declaration of competing interest

The authors declare that they have no conflict of interest

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